An advanced road transport emissions model

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DOCTORAL DISSERTATION

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Sveučilište u Zagrebu
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Marko Rešetar

UNAPRIJEĐENI MODEL EMISIJA IZ CESTOVNOG TRANSPORTA

DOKTORSKI RAD

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“Genius is patience.”

Isaac Newton

ABSTRACT

This doctoral thesis aimed to develop an advanced road transport emissions model (ARTEM) by collecting, processing, and applying specific data, such as legislation data, results of periodic technical inspection of vehicles, on-board diagnostics (OBD) data, independent emission measurements, and surveys on target user groups. The quantitative research results focused on diesel passenger cars and harmful nitrogen oxide (NO_X) emissions. Moreover, it was pointed out that there are many vehicles on which illegal modifications to the emissions control system (ECS) are performed, and the impact of such manipulations on emissions is still not sufficiently investigated. Due to this, experimental tests of NO_X emissions on Euro 5 and Euro 6 diesel cars under laboratory conditions and on the road were performed. The results of experimental tests indicated that tampering with ECSs can cause a multiple increase in NO_X emissions, even more than two orders of magnitude. By processing the results of the experimental tests, new knowledge was obtained, and a new formula was set for calculating the NO_X emission factors (EFs) of manipulated vehicles. By determining the weight impacts of individual parameters that influence the formation of NO_X emissions, it was proven that the effect of ECS manipulation on the formation of NO_X emissions is by far the greatest. Considering the findings of the suggested ARTEM, three case scenarios were created to calculate NO_X emissions of the Euro 6 diesel car fleet. The worst-case scenario shows that NO_X emissions increased by 36% compared to the calculation with emission factors (EFs) from the COPERT database. To validate the presented model and ensure its wide application, an external evaluation, i.e. an inter-laboratory comparison of the results, is necessary.

PROŠIRENI SAŽETAK

Kao i kod većine ostalih sektora, sektor transporta na globalnoj razini bilježi kontinuirani porast potrošnje energije i emisija ispušnih tvari već dulji niz godina [1]. Tek manji pad utvrđen je kratkoročno nakon globalne ekonomske krize 2008. g., kao i za vrijeme pandemije koronavirusa [2]. Sektor transporta u svijetu generira otprilike 21 % stakleničkih plinova, od čega samo cestovni transport sudjeluje s visokih 79 % [3].

Iako za stakleničke plinove postoji relativno pouzdana procjena njihovog iznosa bazirana na temelju količine utrošenih energenata, za emisije štetnih tvari to nije slučaj [4]. Emisije štetnih tvari ovise o velikom broju parametara zbog čega ih nije moguće na brz i jednostavan način dovoljno točno procijeniti, već ih je potrebno mjeriti. Na temelju rezultata mjerenja izrađuju se novi, a ažuriraju postojeći modeli za procjenu emisija štetnih tvari. Postojeći modeli procjene emisija štetnih tvari iz cestovnog transporta baziraju se uglavnom na ispitivanjem određenim srednjim vrijednostima emisijskih faktora i uvjeta korištenja kao što su npr. prijeđeni put vozila, vrijeme rada motora, broj pokretanja motora itd. Istraživanja provedena posljednjih desetak godina ukazuju na nedostatke postojećih modela procjene emisija štetnih tvari i to uglavnom ukazujući na bitno veće vrijednosti emisijskih faktora u odnosu na one koji se trenutno koriste [5], [6], [7]. Međutim, osim emisijskih faktora značajnu ulogu u točnijoj procjeni emisija ima preciznije definiranje uvjeta korištenja vozila.

Glavni cilj doktorskog rada bio je izraditi unaprijeđeni model emisija iz cestovnog transporta kroz postupak prikupljanja, obrade i primjene specifičnih podataka, kao što su podaci o homologaciji, rezultati redovnih tehničkih pregleda vozila, podaci dostupni kroz dijagnostiku vozila (OBD), rezultati nezavisnih mjerenja emisija i ankete provedene nad korisnicima vozila. Doktorska disertacija se sastoji od više članaka objavljenih tijekom doktorskog studija u časopisima i zbornicima s konferencija, a koji zajedno čine jednu zaokruženu cjelinu koja daje novi znanstveni doprinos u odnosu na pojedinačne radove. Ključni rezultati provedenih istraživanja predstavljeni su u ovom radu. Razrađen je doprinos svakog pojedinog članka, odnosno istaknuta je njegova važnost za realizaciju cilja istraživanja. U konačnici potvrđene su postavljene hipoteze i istaknuti znanstveni doprinosi doktorskog rada u cjelini.

Doktorski rad je temeljen na kvantitativnim i kvalitativnim istraživanjima, kao i na eksperimentalnim ispitivanjima. Kvantitativno istraživanje obuhvatilo je više izvora podataka: bazu COPERT emisijskih faktora NO_X, bazu podataka tvrtke EMISIA SA za izračun emisija pomoću računalnog programa COPERT, bazu podataka Centra za vozila Hrvatske (CVH) o registriranim vozilima, granične vrijednosti emisija određene legislativom, rezultate tehničkih pregleda vozila u Republici Hrvatskoj (podaci o ispitivanju ispušnih plinova i OBD podaci), meteorološke podatke i rezultate ankete provedene nad korisnicima vozila. Rezultati kvantitativnih istraživanja usmjerili su pažnju na vozila s Dieselovim motorom i štetne emisije dušikovih oksida (NO_X). Utvrđeno je da postoji značajan broj vozila na kojima se obavljaju ilegalne preinake na sustavu za kontrolu emisija, a utjecaj takvih preinaka na emisije još uvijek nije dovoljno istražen. Zbog toga su provedena mjerenja emisija NO_X na Euro 5 i Euro 6 automobilima s Dieselovim motorom u laboratorijskim uvjetima, kao i u stvarnim uvjetima vožnje na cesti koristeći PEMS uređaj. Eksperimentalna ispitivanja uključivala su prikupljanje podataka o načinu korištenja vozila za vrijeme ispitnih vožnji: brzina i ubrzanje vozila, brzina vrtnje motora, stupanj prijenosa mjenjača, opterećenje vozila putnicima i teretom, geografske koordinate vozila koristeći GPS sustav, stupanj učinkovitosti sustava za naknadnu obradu ispušnih tvari, OBD podaci. Rezultati eksperimentalnih ispitivanja potvrdili su pretpostavke da manipulacije sustava za kontrolu emisija mogu uzrokovati značajno povećanje emisija NO_X. Obradom rezultata eksperimentalnih ispitivanja došlo se do novih spoznaja, te je postavljena nova formulacija za izračun emisijskih faktora NO_X manipuliranih vozila. Kvalitativnim istraživanjima utvrđeni su parametri iz stvarnih uvjeta vožnje koji značajnije utječu na stvaranje emisija NO_X. Mijenjajući vrijednosti tih parametara izračunati su faktori utjecaja tih veličina na emisije NO_X i dokazano je da je utjecaj manipulacija daleko najveći. U konačnici za tri moguća scenarija izračunate su emisije NO_X flote osobnih automobila s Dieselovim Euro 6 motorom u Hrvatskoj za proteklu 2023. godinu.

Doktorski rad je kroz izradu bio podijeljen u četiri faze:

1) Kvantitativna istraživanja,
2) Eksperimentalna ispitivanja,
3) Kvalitativna istraživanja — razvoj naprednog emisijskog modela,
4) Izračun emisija baziran na korištenju naprednog emisijskog modela.

Prva faza obuhvaća pregled znanstvene literature koja sadrži podatke o emisijskim faktorima i emisijama iz stvarnih uvjeta vožnje, sve u cilju točnije procjene emisija NO_X. Analizirani su dostupni podaci iz baza podataka tvrtki EMISIA SA i CVH o broju vozila, godišnje prijeđenom putu i starosti vozila tj. emisijskoj razini. Istražene su promjene u strukturi voznog parka Hrvatske tijekom perioda za koji postoje dostupni podaci iz baze podataka CVH. Na razini pojedinačnog vozila analizirani su podaci koji se prikupljaju prilikom tehničkih pregleda vozila:

starost vozila, prijeđeni put, emisijska (Euro) razina, tehnička ispravnost, rezultati ispitivanja ispušnih plinova, OBD podaci i dr. Emisijski faktori NO_X uspoređeni su s graničnim vrijednostima određenima od strane legislative. Koristeći računalni program COPERT izračunate su emisije NO_X, te su identificirana vozila koja prekoračuju granične vrijednosti istih. Također, istražena je baza podataka CVH o broju osobnih automobila koji su pristupili ispitivanju zbog izvršenih preinaka. Uz navedeno, korisnici vozila ispunjavali su ankete s pitanjima koja uključuju uvjete korištenja vozila. Osim toga, od strane Državnog hidrometeorološkog zavoda (DHMZ) zatraženi su meteorološki podaci potrebni za izračun emisija pomoću COPERT-a.

Druga faza obuhvaća eksperimentalna ispitivanja na vozilima. Ispitivanja uključuju ispitne vožnje tijekom kojih su se prikupljali različiti podaci kao što su brzina i ubrzanje vozila, brzina vrtnje motora, stupanj prijenosa mjenjača, stupanj učinkovitosti sustava za kontrolu emisija, geografske koordinate vozila koristeći GPS sustav, emisije i dr. Spajanjem uređaja za zapisivanje podataka (engl. *data logger*) na OBD priključnicu vozila, tijekom ispitnih vožnji očitavali su se i pohranjivali dostupni podaci s pojedinih elektroničkih upravljačkih jedinica ugrađenih u vozilu (engl. *Electronic Control Unit*). Ispitne vožnje uključivale su različite standardizirane vozne cikluse (ECE–15, EUDC, NEDC), proizvoljno kreirane vozne cikluse i režime vožnji kao što su gradski, izvangradski i vožnja autocestom. Ispitne vožnje uključivale su uvjete iz stvarnih vožnji, tj. uspoređivale su se emisije NO_X pri različitim uvjetima korištenja kao što su opterećenje vozila dodatnim teretom, stupanj prijenosa mjenjača i utjecaj isključivanja sustava za kontrolu emisija. Rezultati eksperimentalnih ispitivanja ukazali su da manipulacije odnosno isključivanje pojedinih sustava za kontrolu emisija mogu uzrokovati višestruko povećanje emisija NO_X, čak i više od dva reda veličine. Analizom rezultata eksperimentalnih ispitivanja došlo se do novih saznanja da emisije manipuliranih vozila po vrlo sličnoj zakonitosti ovise o prosječnoj brzini vožnje kao i emisije tehnički ispravnih vozila, dok se iste kvantitativno uvelike razlikuju. Temeljem tih saznanja kreirana je nova formula za izračun emisijskih faktora NO_X manipuliranih vozila.

Treća faza uključuje kvalitativna istraživanja — analizu podataka prikupljenih tijekom kvantitativnih istraživanja i eksperimentalnih ispitivanja, te pronalazak funkcijske ovisnosti emisija NO_X o različitim utjecajnim parametrima. Postupak određivanja emisija NO_X o različitim utjecajnim parametrima zapravo predstavlja razvoj naprednog emisijskog modela. Ovaj model uključuje točnije vrijednosti ulaznih podataka, otklanjajući nedostatke postojećih emisijskih modela, budući da bi se svakom vozilu dodjeljivali podaci specifični baš za razmatrano vozilo ili za vozila sličnog tipa. Tako npr. svako vozilo prijeđe drugačiji put na godišnjoj razini, ima drugačiju vlastitu masu, drugačije mase prevoženih putnika i tereta, drugačije sustave za kontrolu emisija i ostalo. Osim toga, geografsko područje i klimatski uvjeti nisu svugdje jednaki da bi se mogli pridružiti svakom vozilu na isti način. U ovoj fazi određeni su parametri za koje je eksperimentalnim ispitivanjima znanstveno dokazano da imaju daleko najveći utjecaj na stvaranje emisija NO_X, a koji nisu korišteni u postojećim modelima za izračun emisija. Kvalitativnim istraživanjima utvrđeno je da je najutjecajniji parametar koji koristi unaprijeđeni model neosporno manipulacija odnosno isključivanje sustava za kontrolu emisija.

U četvrtoj fazi, uzimajući u obzir otkrića predloženog unaprijeđenog emisijskog modela izrađena su tri moguća scenarija za izračun emisija NO_X. Koristeći postojeći emisijski model COPERT, izrađen je izračun emisija NO_X za flotu osobnih automobila s Dieselovim Euro 6 motorom u Hrvatskoj za proteklu 2023. godinu, te su se izračunati rezultati usporedili s rezultatima naprednog emisijskog modela. Rezultati naprednog emisijskog modela ukazali su na bitno veće vrijednosti emisija NO_X u odnosu na emisije izračunate COPERT-om. Najnepovoljniji scenarij ukazuje na povećanje emisija NO_X za 36 % u usporedbi s izračunom koji koristi emisijske faktore NO_X iz COPERT-ove baze podataka. Kako bi se predloženi model mogao validirati i kako bi se osigurala njegova široka primjena, potrebna je vanjska evaluacija, odnosno međulaboratorijska usporedba rezultata. Budući da se unaprijeđeni emisijski model bazira na emisijama svakog vozila zasebno, isti ukazuje na to koja vozila stvaraju značajno veće količine emisija NO_X od zakonski dopuštenih. Na temelju izračunatih rezultata mogu se donositi različiti zaključci i podloge za primjenu drugačijih mjera politika. Jedan od prijedloga je da se mjerama porezne politike destimulira korištenje takvih vozila, a umjesto dosadašnjih mjera koje potiču kupnju starijih rabljenih vozila potiče kupnja novih vozila sa značajno manjim emisijama ili vozila s nultom stopom emisija — električnih vozila.

KEYWORDS

COPERT

Emissions control system

Emission factor

Emissions model

Nitrogen oxides

Road transport

KLJUČNE RIJEČI

COPERT

Sustav za kontrolu emisija

Emisijski faktor

Emisijski model

Dušikovi oksidi

Cestovni transport

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

Symbol	Description
ARTEM	An advanced road transport emissions model
CLRTAP	Convention on long-range transboundary air pollution
CO	Carbon monoxide
COPERT	A computer program to calculate emissions from road transport
CVH	Centre for Vehicles of Croatia
DEF	Diesel exhaust fluid
DHMZ	Croatian Meteorological and Hydrological Service
DPF	Diesel particulate filter
DTC	Diagnostic trouble code
ECE	Economic Commission for Europe
ECS	Emissions control system
EEA	European Environment Agency
EF	Emission factor
EGR	Exhaust gas recirculation
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
ERMES	European research for mobile emission sources
EU	European Union
EUDC	Extra-urban driving cycle
EV	Electric vehicle
GPS	Global Positioning System
GVWR	Gross vehicle weight rating
HBEFA	Handbook emission factors for road transport
ICE	Internal combustion engine
MIL	Malfunction indicator lamp
MIRO	Mass in running order
MIT	Massachusetts Institute of Technology
MOVES	Motor vehicle emission simulator
NEDC	New European driving cycle
NO_X	Nitrogen oxides
OBD	On-board diagnostics
PC	Passenger car
PEMS	Portable emission measurement system
PHEM	Passenger car and heavy-duty vehicle emission model
PTI	Periodic technical inspection
RDE	Real driving emissions
SCR	Selective catalytic reduction
WLTP	Worldwide harmonised light vehicles test procedure

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Like most other sectors, the global transport sector has been experiencing a continuous increase in energy consumption and emissions for many years [1]. A small decline was observed in the short term after the 2008 global economic crisis and during the coronavirus pandemic [2]. The transport sector generates approximately 21% of total greenhouse gases, of which road transport alone accounts for a high 79% [3].

Although greenhouse gases already have a relatively reliable estimate of their amount based on the energy consumed, harmful emissions are different [4]. Harmful emissions depend on many parameters, so it is impossible to evaluate them quickly, but it is necessary to measure them. Based on the results of the measurements, new emissions models are developed, and existing models are updated to estimate emissions. Existing models for estimating harmful emissions from road transport are mainly based on mean values of emission factors (EFs) obtained by testing and conditions of use such as vehicle distance travelled, engine operating time, number of engine starts, etc. During the last decade, research has pointed to the shortcomings of existing models in assessments of harmful emissions, mostly indicating significantly higher EF values than those currently used [5], [6], [7]. However, besides EFs, a more precise definition of vehicle usage conditions plays a significant role in a more accurate emissions assessment.

1.1 Previous and related studies

After World War II, passenger car (PC) use significantly increased, leading to the appearance of an unusual form of air pollution — smog — in cities worldwide. Throughout the latter half of the 1940s and 1950s, considerable efforts were undertaken to characterise this unique form of smog and to understand its causes and effects [8], [9]. Systematic measures to protect the environment from pollution by motor vehicle exhaust began in California, United States of America (USA), in the early 1970s and spread to other countries worldwide in the following years. From then until now, there has been an era of continuous action and struggles to reduce pollutant emissions from motor vehicles [10], [11]. Various exhaust substances (compounds) harm human health [12], [13]. However, only some of them are restricted by law: carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_X), and particulate matter (PM) [14]. It is scientifically proven that inhaling such pollutants over a long time has serious consequences for human health [15]. The adverse effects of exhaust emissions on health are mostly related to cardiovascular and respiratory diseases [16]. Studies by the Massachusetts

Institute of Technology (MIT) show the correlation between the number of deaths from respiratory diseases and human exposure to the environment with pollutants above the permissible limits. According to these studies, more than 200,000 people die each year in the USA from diseases related to the harmful effects of combustion pollutants, including nearly 60,000 from the direct effects of harmful exhaust emissions from road traffic alone [17]. Cities with high traffic density on the roads are a real example of such harmful environmental conditions [18]. Reducing harmful exhaust emissions from road transport by improving the combustion processes and after-treatment systems is the most effective way for vehicle manufacturers to reduce the impact of these substances on the environment and human health.

To demonstrate and prove that the current technology used in exhaust systems to control vehicle exhaust emissions is justified, it is necessary to measure vehicle emissions regularly. For this reason, during the homologation tests, the vehicle is placed on the test rollers, and the emission test is carried out according to the appropriate pre-determined driving cycle [19]. In this process, the vehicle is fixed in a stationary position while the drive wheels of the vehicle rotate on rollers to simulate the vehicle driving [20]. An exhaust gas composition analyser is connected to the vehicle's exhaust pipe, which measures the emissions. With such measurements, in addition to the known driving conditions defined by the respective test cycle, the vehicle's emissions are determined, from which the EFs for each exhaust gas are then calculated. Numerous studies have shown that the average fuel consumption under real driving conditions is usually higher than that defined by the homologation test [21], [22], [23]. However, it has been proven that in addition to fuel consumption, pollutant emissions under real driving conditions also deviate significantly from the values measured under laboratory conditions [24], [25], [26], [27]. For these reasons, the Worldwide Harmonised Light-duty Test Procedure (WLTP) was introduced in September 2017 for new types of PCs, which is much more dynamic, lasts longer, and better describes real driving conditions on the road than the New European Driving Cycle (NEDC) that was applied until then [28], [29].

In addition to earlier research measurements, since 2017, emissions measurements for homologation tests have also been carried out with a portable emission measurement system (PEMS), which can measure emissions in real driving conditions [30], [31]. Such a device is installed on a vehicle that travels a certain distance while the device simultaneously measures emissions. In contrast to laboratory homologation tests, especially NEDC, real driving measurements with the PEMS are stochastic and include various influencing parameters [32]. The driving conditions achieved by PEMS measurements most closely correspond to real driving conditions when the vehicle is used on the road [33]. With the help of such tests, it is possible to calculate more realistic EFs [34], [35]. Besides that, detailed emissions analyses and their dependence on various parameters during driving are possible [36]. Such measurements provide more reliable EFs, which could be expressed as empirical functions between the emissions and the activities that cause them. They are usually expressed as the mass of an individual exhaust substance per kilometre travelled, g/km [6]. Therefore, it is extremely important to determine the EFs of individual vehicles or vehicle categories as accurately as possible so that the assessment of the total emissions of the vehicle fleet is as accurate as possible.

Due to the large number of registered vehicles, it is almost impossible to carry out complex emission tests for each vehicle type/variant/version under real driving conditions. Therefore, various traffic emissions models, such as the 'average speed', 'traffic situation', 'traffic variable', 'cycle variable', and 'modal' models, are used to determine EFs [37].

The evaluation of the raw data collected by various European test laboratories and the monitoring of the development of the main emissions models in Europe are carried out by the European Research on Mobile Emission Sources (ERMES) group [38]. Inventory models are tools for monitoring progress towards emission targets, such as those set in international agreements such as the 1979 Convention on Long-range Transboundary Air Pollution (CLRTAP) and the 2015 UN Paris Agreement on climate change. Since 1999, the Graz University of Technology has developed a microscale vehicle emission model — PHEM (Passenger car and Heavy-duty vehicle Emission Model). The data processed in PHEM are used to calculate work done and emissions [39]. The PHEM also provides EFs for the HBEFA (Handbook Emission Factors for Road Transport), one of the widely used tools to quantify emissions from road transport in Europe [40], [41]. The computer program that calculates emissions based on average driving speed, COPERT (Computer Program to calculate Emissions from Road Transport), also uses the EFs listed in HBEFA [42]. Many projects related to emissions assessment for European Union (EU) Member States, China, and Australia have been carried out using the COPERT [43], [44], [45]. The VERSIT+ statistical model for calculating emissions, based on a variable cycle, was developed by TNO (Netherlands Organisatie voor Toegepast Natuurwetenschapel Onderzoek) and uses data from laboratory measurements [46]. LIPASTO is a calculation system developed and maintained by VTT Technical Research Centre of Finland Ltd. [47]. It calculates transport emissions and energy consumption in Finland, covering road, rail, waterborne and air transport, and non-road mobile machinery. An overview of emissions models used in road transport in European countries is shown in Figure 1. The US Environmental Protection Agency (EPA) uses the computer program MOVES (Motor Vehicle Emission Simulator) to determine EFs and estimate emissions [48], [49]. Using computer programs saves the cost of expensive emission measurements and enables the comparison of emissions for different vehicle driving modes.

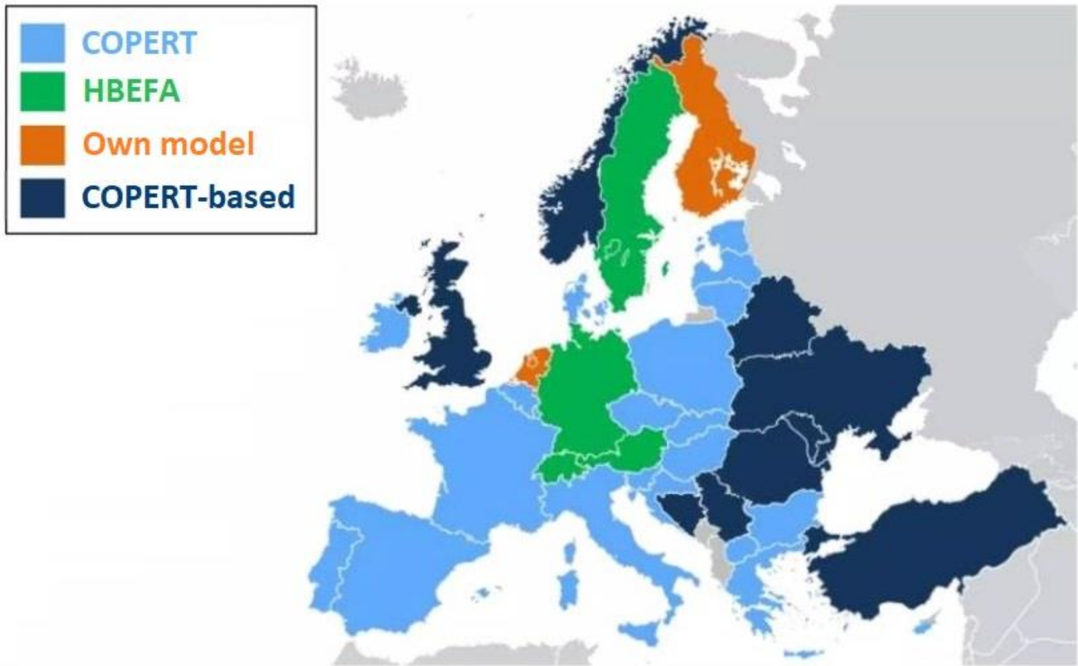


Figure 1. Road transport emissions models used in European countries (Source: ERMES)

Many parameters affect the formation of emissions from road transport [50], [51], [52], [53], [54], [55]. One of these parameters is also the age of the vehicle, i.e., the vehicle's total mileage, and studies have shown that emission levels increase with the age of the vehicle [56], [57]. The EFs used in legacy computer programs were developed using laboratory measurement data and standardised driving cycles. Recent studies on NO_X emissions measured with PEMS devices show considerable deviations in the EFs compared to the values used by outdated computer programs [5], [7]. Because of this, computer programs used to calculate emissions must be continuously validated based on the results of actual measurements and improved for new technologies installed in vehicles to determine emissions accurately.

Since urban environments are the most exposed to elevated exhaust pollutants from road transport, they receive the most attention [58], [59]. There are quite a lot of studies that point to high levels of air pollution in cities [60], [61]. In the last decade, many projects have aimed to introduce low-emission zones and reduce the number of motor vehicles in the centres of larger European cities to improve air quality in urban areas [62], [63], [64], [65]. While some introduced alternative urban mobility means, such as electric bicycles and scooters, others advocated banning high-polluting vehicles in city centres [66], [67], [68], [69]. In the last decade, car manufacturers have been introducing more and more models of electric vehicles (EVs) while simultaneously phasing out models powered by internal combustion engines. However, recent studies indicate that due to their increased mass, EVs generate significantly higher non-exhaust emissions than conventional vehicles [70], [71], [72]. Although the European Commission has decided to ban the sale of new petrol and diesel cars and vans until 2035, the trends in the market regarding the transition to EVs are not going according to plan, and it is almost certain that such goals will not be achieved within the stipulated time [73]. Therefore, some vehicle manufacturers are abandoning the plan to produce EVs exclusively and hope that in the coming years, there will be progress in the production of synthetic fuels (e-fuels) so that legislative bodies will still allow the sale of new vehicles with an internal combustion engine even after 2035 [74], [75]. Hydrogen has received increasing attention as a potential successor to fossil fuels [76], [77]. It can be a fuel source for fuel cells or internal combustion engines [78], [79], [80]. However, hydrogen also has disadvantages, such as transportation difficulties, lack of infrastructure, and the high cost of catalysts and hydrogen production. It is tasteless, odourless, extremely volatile and flammable. It also pollutes if not produced using renewable sources. Considering the current situation on the market and the progress achieved in recent years, the transition from conventional vehicles to vehicles powered by alternative clean fuels and electrification will likely take decades. Such findings indicate the need for further use and constant updating of emissions models, given new scientific discoveries in road transport emissions.

1.2 Motivation for conducting the research

When this study began, a regulation was in force requiring the application of the NEDC for homologation emissions tests under laboratory conditions. Previous research has demonstrated that emissions under real driving conditions deviate significantly from the values measured under laboratory conditions, particularly concerning pollutant emissions [24], [25], [26], [27]. This situation prompted the motivation to investigate real emissions and enhance road transport emissions calculation. The Dieselgate scandal and NO_X emissions cheating further increased the motivation to develop the ARTEM.

1.3 Objectives and hypotheses of the research

The main objective of the doctoral thesis is to improve the model for calculating vehicle exhaust emissions from road transport by collecting, processing, and applying specific data, such as legislation data, results of periodic technical inspections (PTIs) of vehicles, on-board diagnostics (OBD) data, results of independent emissions measurements, surveys on target user groups, etc.

The research hypothesis assumes that more accurate emissions models can be developed by collecting and processing vehicle usage data. Consequently, improving existing models for calculating vehicle exhaust emissions from road transport becomes feasible. Additionally, using data from various sources and applying the ARTEM to calculate vehicle emissions from road transport makes it possible to estimate vehicle emissions in the observed area for a certain period with greater accuracy than existing models.

1.4 Scientific contributions

Innovative elements of the doctoral thesis include a new formula for calculating the NO_X EFs of vehicles with a manipulated emissions control system (ECS) and a method for estimating the number of manipulated registered PCs.

Considering the vehicle's technical data and conditions of use, the proposed emissions model contributes to more accurate estimates of NO_X emissions at the individual vehicle level.

The research results show the influence of certain vehicle usage conditions on the formation of harmful emissions. Thus, with minor perturbations of the input data, it is possible to predict how the emissions will change.

In addition to an individual vehicle level, the ARTEM enables a more accurate calculation of NO_X emissions for the vehicle fleet. Concerning predicting changes in the vehicle fleet, it provides more accurate estimates of NO_X emissions for future periods.

As a scientifically based tool, the ARTEM can propose future measures and policies, thus compensating for the lack of current strategic planning regarding fleet management and its environmental impact.

2 OVERVIEW AND DISCUSSION

The doctoral dissertation comprises several articles published during the doctoral studies in journals and conference proceedings, forming a totality that offers a new scientific contribution compared to individual works. This section provides a brief overview of the research's key findings. It elaborates on the contribution of each article individually, highlighting its significance in achieving the research objectives. Ultimately, the highlighted hypotheses are validated, and the overall contributions of the entire doctoral thesis are emphasised.

The doctoral thesis is grounded in quantitative and qualitative research and experimental tests. Quantitative research draws from various data sources, including the COPERT NO_X EF database, the EMISIA SA database for calculating emissions using the COPERT computer program, the CVH (Centre for Vehicles of Croatia) database on registered vehicles, emission limit values determined by legislation, results of technical inspections of vehicles in the Republic of Croatia (including tailpipe and OBD tests), meteorological data, and the results of a survey of vehicle users. Experimental tests involve collecting data on vehicle usage during test drives, covering variables such as vehicle speed and acceleration, engine speed, gear ratio, vehicle load with passengers and cargo, vehicle location using the Global Positioning System (GPS), efficiency level of the exhaust after-treatment system, and OBD data. Additionally, NO_X emission values were measured during test drives in both laboratory and real driving conditions. Qualitative research has identified parameters from real driving conditions that significantly influence NO_X emissions. By altering the values of these parameters, the influence factors of these parameters on NO_X emissions were calculated.

The doctoral thesis is essentially divided into four phases:

1) Quantitative research,
2) Experimental tests,
3) Qualitative research — development of the ARTEM,
4) Calculation of emissions based on the findings of the ARTEM.

The first phase includes a review of the scientific literature containing data on EFs and emissions from real driving conditions, aiming at a more accurate assessment of NO_X emissions. The available data from the EMISIA SA database on the vehicle population, the annual distance travelled, and the age of the vehicle (emission standard) were analysed. The changes in the Croatian road vehicle fleet structure for the period during which data from the CVH database is available were investigated. At the level of an individual vehicle, the data collected during PTIs of vehicles were studied: vehicle age, distance travelled, Euro emission standard, technical correctness, tailpipe and OBD test results, etc. NO_X EFs were compared with the limit values determined by the legislation. Using the computer program COPERT, NO_X emissions were calculated, and vehicles exceeding the limit values of NO_X emissions were identified. The CVH database was used to investigate the population of modified PCs. Such modifications include replacing the powertrain, brakes, suspension, exhaust components, etc. In addition to the above, vehicle users filled out surveys with questions that included the conditions of vehicle use. In addition, the Croatian Meteorological and Hydrological Service (DHMZ) provided the meteorological data necessary for calculating emissions using COPERT.

The second phase includes experimental tests on vehicles. These tests include test drives during which various data were collected, such as vehicle speed and acceleration, engine speed, gear ratio, ECS working parameters, vehicle position using the GPS, and emissions. By connecting the data logger to the OBD vehicle socket, available data from individual electronic control units (ECUs) were read and stored during the test drives. Test drives included various standardised driving cycles (ECE-15, EUDC, NEDC), arbitrarily created driving cycles, and urban, rural, and motorway driving modes. Test drives included conditions from real drives — NO_X emissions were compared under different conditions of vehicle use, such as loading the vehicle with additional cargo, different gear ratios, and the impact of deactivating some of the ECS components.

The third phase includes qualitative research, which analyses data collected during the quantitative research and experimental tests to determine the functional dependence of NO_X emissions on various influencing parameters. This procedure represents the development of the ARTEM. This model requires more accurate input data, eliminating the shortcomings of existing emissions models, as each vehicle would be assigned data specific to the observed vehicle or vehicles of a similar type. For example, each vehicle travels a different route annually and has a different weight, mass of transported passengers and cargo, various ECSs, etc. Additionally, geographical areas and climatic conditions vary, influencing each vehicle differently. In this phase, the parameters scientifically proven by experimental tests to have the greatest influence on the formation of NO_X emissions are identified.

In the fourth phase, the calculation of NO_X emissions for the Euro 6 diesel PC fleet in Croatia for the past year, 2023, was conducted using the existing emissions model COPERT. The results were then compared with those of the ARTEM. The outcomes from the ARTEM showed up to 36% higher NO_X emissions than COPERT. As the ARTEM is based on the emissions of each vehicle individually, it identifies which vehicles generate significantly higher amounts of NO_X

emissions than legally allowed. These results provide a basis for drawing conclusions and implementing various policy measures. One proposal is to implement tax policy measures to discourage the use of such vehicles. Instead of the current measures that encourage the purchase of older used vehicles, there is a suggestion to incentivise the purchase of new vehicles with significantly lower emissions or zero-emission vehicles like EVs.

2.1 Quantitative research

In addition to the previous review of the scientific literature that studies emissions from road transport, covered in Section 1, the initial phase of the doctoral thesis includes quantitative research. This research involves several data sources, including assessing the mass of NO_X emissions from Croatia's PC fleet based on the available data. The feasibility of applying data from various sources listed below was analysed, and NO_X emissions were calculated using a set of reasonably acceptable data.

2.1.1 *NO_X EF database*

COPERT uses EFs listed in the EMEP/EEA air pollutant emission inventory guidebook [4]. It is a continuously updated guidebook concerning new technologies implemented in new vehicles. The data on EFs are most important for calculating emissions. Three methods are described in the guidebook above, and only the most advanced Tier 3 method was used during the doctoral studies. According to the Tier 3 method, the total emissions based on the temperature of the engine and aftertreatment systems are divided into hot and cold, and according to different driving regimes, they are further divided into urban (U), rural (R) and motorway (M), Equation (1).

$$E_{\mathrm{TOTAL}} = E_{\mathrm{COLD}} + E_{\mathrm{HOT}} = E_{\mathrm{URBAN}} + E_{\mathrm{RURAL}} + E_{\mathrm{MOTORWAY}} \tag{1}$$

Where:

E = General term for any gaseous component (g).

Cold-start emissions are calculated as an extra emission over the emissions that would be expected if all vehicles were only operated with hot engines and warmed-up aftertreatment components. A relevant factor corresponding to the cold over hot emissions ratio is applied to the fraction of kilometres driven with a cold engine. This factor varies from country to country. Driving behaviour (varying trip lengths) and climatic conditions affect the time required to warm up the engine and the aftertreatment components and, consequently, affect the fraction of a trip driven with a cold engine. Because of that, cold-start emissions are not considered in

Sections 2.2 and 2.4 to simplify comparing results for different driving conditions. However, the guidebook provides a detailed description and formulas for calculating cold-start emissions, which were used only to determine the influence of average monthly air temperatures on NO_X emissions (Section 2.3.1).

The most important data required to assess hot NO_X emissions of the PC fleet are the vehicle population, the average annual mileage and the NO_X EF, Equation (2).

$$E_{\mathrm{HOT;NO_X}} = \sum\nolimits_{k,r} \left(N_k \times M_{k,r} \times EF_{\mathrm{HOT;NO_X},k,r}\right) \tag{2}$$

Where:

$E_{\mathrm{HOT;NO_X}}$ = Total hot NO_X emission (g),

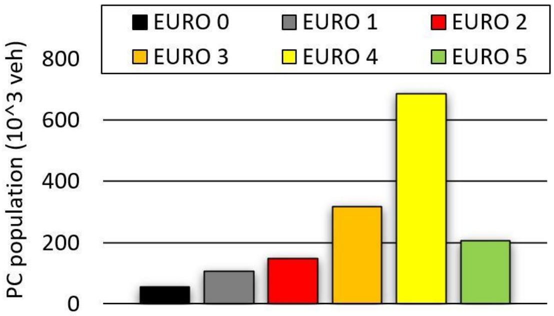
N_k = Vehicle population of emission standard *k* in operation in a year concerned,

$M_{k,r}$ = Mean annual mileage per vehicle (km), driven on roads of type *r* by vehicles of emission standard *k*,

$EF_{\mathrm{HOT;NO_X},k,r}$ = NO_X EF (g/km), relevant for the vehicle emission standard *k* (Euro 0/1/2/3/4/5/6), operated on roads of type *r* (U/R/M).

2.1.2 *Input data from the EMISIA SA database and the first estimate of NO_X emissions*

Since the only comprehensive data required for calculating PC NO_X emissions in Croatia were those of the company EMISIA SA, they were used for the initial assessment of emissions using the computer program COPERT 4. The data above were requested and delivered in 2015 and contained values from 2000 to 2014. Therefore, 2014 was used for the calculation, Figure 2.



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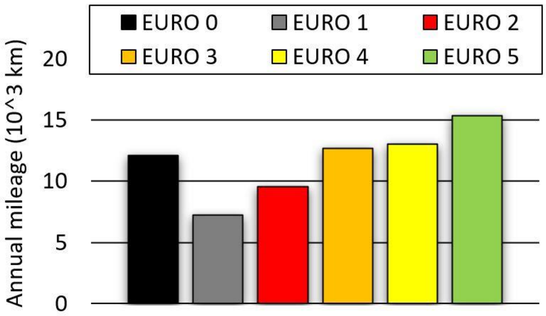

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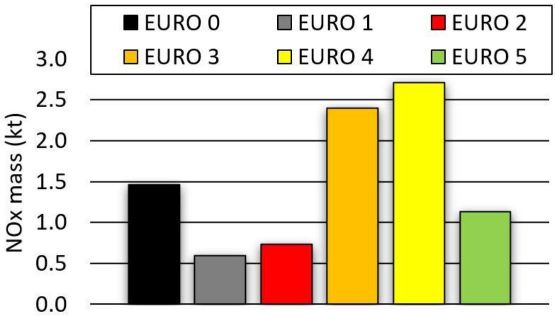


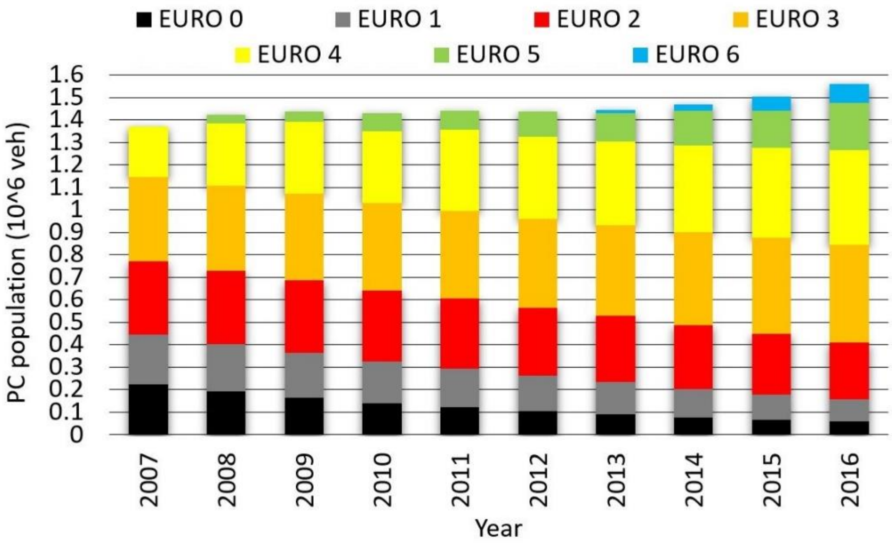
(c)

Figure 2. PC population (a) and an annual mileage of PCs (b) for the Republic of Croatia in the year 2014 based on the EMISIA SA database for Euro 0–Euro 5 emission standard, and total NO_X mass of PCs (c) calculated by the COPERT 4.

An insight into the distribution of the PC population according to the Euro emission standard revealed a significant deviation in the number of Euro 4 vehicles compared to other categories. Therefore, the possibility of using data from other sources was explored to justify doubts about the credibility of the above-stated data.

2.1.3 *Input data from the CVH database and the second estimate of NO_X emissions*

The CVH has been collecting data such as vehicle population and results of technical inspections of vehicles since 1971. However, data storage in the CVH digital database began in 2007. Therefore, data on vehicle population, vehicle age — Euro emission standard, roadworthiness, results of the tailpipe test, as well as changes in the structure of the Croatian road vehicle fleet during the period for which there are available data were researched and processed, and these are presented in *JOURNAL PAPER I (Changes and trends in the Croatian road vehicle fleet — Need for change of policy measures)*. Equation (2) highlights the importance of three main parameters in calculating annual NO_X emissions: vehicle population, mean annual mileage and NO_X EF. The accuracy of the calculation is directly proportional to the proximity of these parameters to the actual values. This article is important for realising the research goal because, for the first time, the PC population in Croatia has been processed according to the Euro emission standard, Figure 3.



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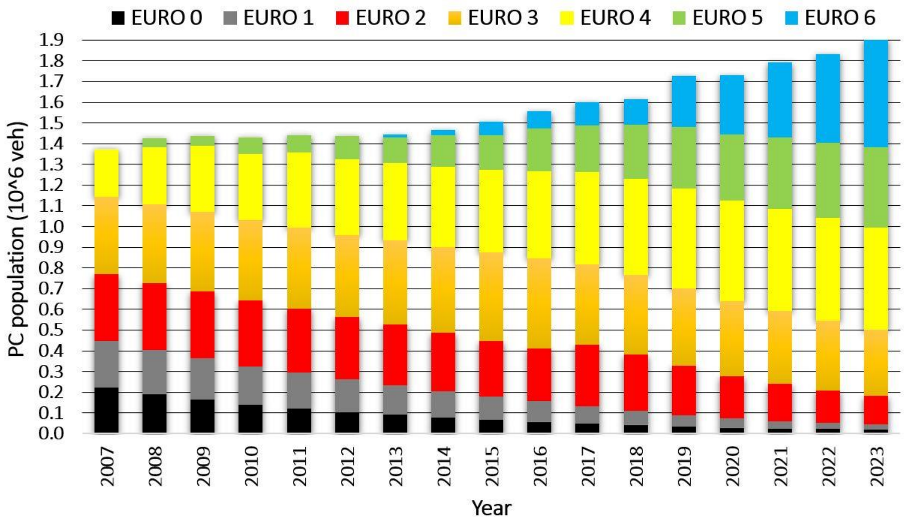
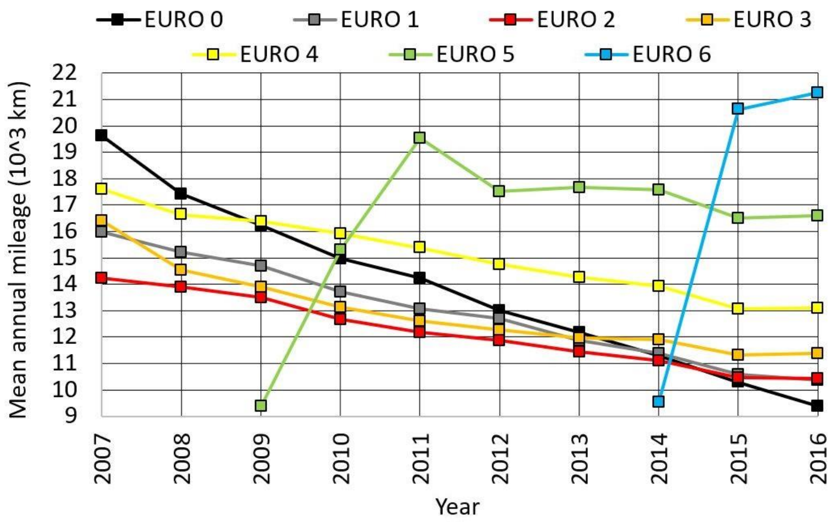


(b)

Figure 3. PC population in Croatia according to the Euro emission standard from 2007 to 2016 — JOURNAL PAPER I (a), and updated data from 2007 to 2023 (b).

It should be noted that the COPERT nomenclature is much more extensive than the division only to the Euro emission standard, as shown in Figure 3. It additionally divides PCs by fuel and engine capacity. In addition, the article details the negative aspects of policy measures that are still implemented in Croatia today, consequently increasing the age of the vehicle fleet, which is in direct correlation with technical malfunctions and emissions. In addition to the vehicle population, it was necessary to determine the mean annual mileage of PCs. Since the state of the odometer for each motor vehicle is recorded and stored in the CVH database during a PTI, an internal method was developed to determine the average annual mileage according to the COPERT nomenclature. The values are presented in *CONFERENCE PAPER I (Road transport emissions of passenger cars in the Republic of Croatia)*. The importance of this article for realising the research goal is that at the level of each vehicle individually, according to the Euro emission standard, for the first time, the average annual mileage by PCs in Croatia has been processed, Figure 4.



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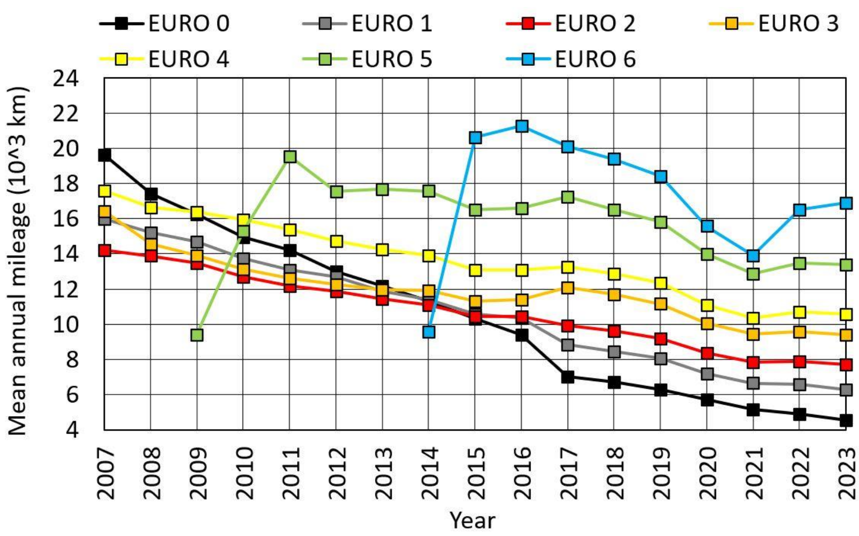
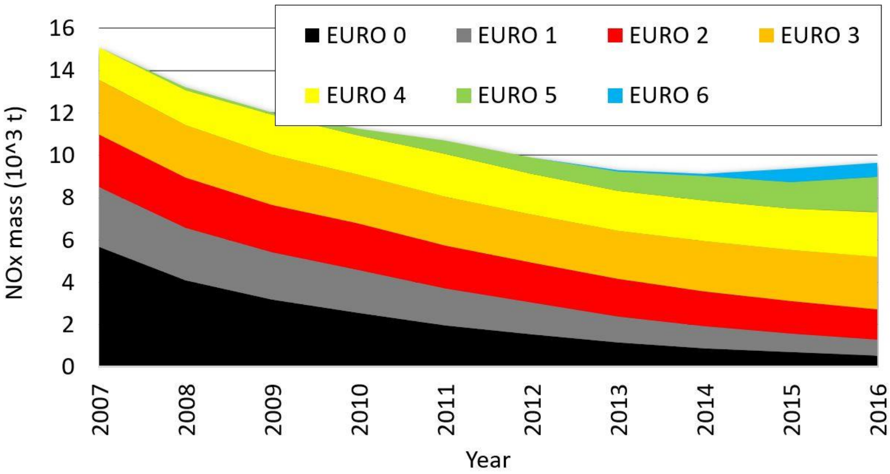


(b)

Figure 4. Mean annual mileage of PCs according to the Euro emission standard from 2007 to 2016 — CONFERENCE PAPER I (a), and updated data from 2007 to 2023 (b).

From 2007 to 2016, it is evident that the average annual mileage by Euro 0 to Euro 4 vehicles decreased, while for Euro 5 and Euro 6 vehicles, it generally increased or stagnated. It is evident that the driving intensity of older vehicles is decreasing, while newer vehicles are used more intensively compared to older vehicles. During the period above, the average annual mileage of Euro 0 vehicles was more than halved, from 19,620 km to 9400 km. In contrast, Euro 6 vehicles recorded the highest mileage, with 21,270 km in 2016. Considering the updated data from 2016 to 2023, the average annual mileage for vehicles of all the Euro emission standards tended to fall. In 2020 and 2021, the consequences of reduced activities due to the coronavirus pandemic significantly reduced the average annual mileage, especially for newer vehicles. After the pandemic, vehicle activities increased, causing higher mileage, especially for Euro 6 vehicles.

Another important contribution of this article should be highlighted, which is the fulfilment of the prerequisites for using COPERT to calculate the annual emissions of PCs in Croatia. Thus, in *CONFERENCE PAPER I*, using PC population and mean annual mileage from the CVH database, as well as EFs and other predefined input data from the newer version of the COPERT 5 program, emissions of pollutants CO, NO_X, PM10, NH_3, VOC, NMVOC, greenhouse gas CO_2 and fuel consumption were calculated for the period from 2007 to 2016. Figure 5 shows the graph from which the calculated mass of NO_X emissions can be determined.



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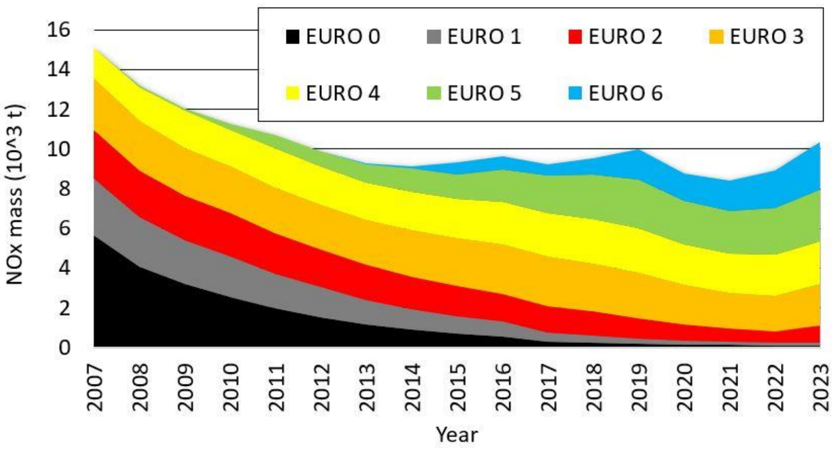


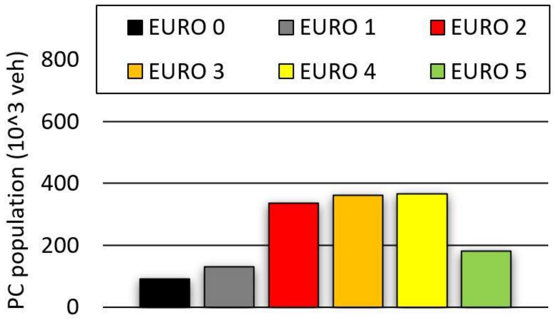
(b)

Figure 5. NO_X emissions of PCs according to the Euro emission standard from 2007 to 2016 — CONFERENCE PAPER I (a), and updated data from 2007 to 2023 (b).

From 2007 to 2016, the largest reduction in NO_X emissions from the Croatian PC fleet, by as much as 85%, was recorded for Euro 0 vehicles. A slightly milder reduction in NO_X emissions was recorded by Euro 1 and Euro 2 vehicles, while Euro 3 and Euro 4 vehicles showed no significant change. NO_X emissions from Euro 5 and Euro 6 vehicles are increasing, which is expected due to the growth in their population and the general increase in their annual distance travelled. From 2007 to 2016, NO_X emissions from the entire fleet decreased from 15.1 to 9.7 kt. Considering updated data from 2016 to 2023, Euro 0/1/2 vehicles recorded a further reduction in NO_X emissions, while Euro 3 and Euro 4 vehicles still showed no significant reduction. In 2020 and 2021, the consequences of reduced activities due to the coronavirus pandemic caused reduced emissions. After the pandemic, NO_X emissions in 2023 reached the values recorded in 2011.

2.1.4 *Selection of a suitable data source on the number of vehicles and the mean annual distance travelled*

By comparing the data on the PC population and their average annual mileage for 2014, it was found that there are significant discrepancies between the EMISIA SA (Figure 2) and CVH (Figure 6) databases, especially in the number of Euro 4 vehicles.



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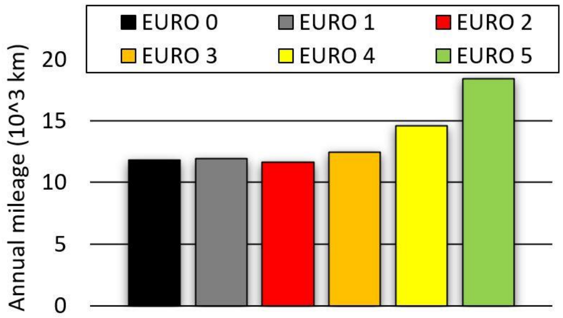

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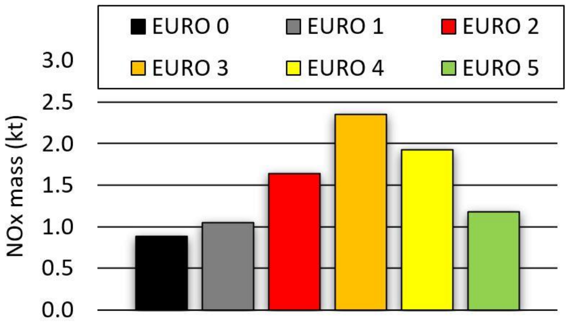


(c)

Figure 6. PC population (a) and an annual mileage of PCs (b) for the Republic of Croatia in the year 2014 based on the CVH database for Euro 0–Euro 5 emission standard, and total NO_X mass of PCs (c) calculated by the COPERT 4.

Although the total NO_X emissions of the entire PC fleet are approximately the same for both data sources, EMISIA SA — 9.028 kt and CVH — 9.133 kt, the distribution according to the Euro emission standard is quite different. The largest discrepancy in NO_X emissions between the EMISA SA and CVH databases was found for Euro 2 vehicles, followed by Euro 4, Euro 0 and Euro 1. For Euro 3 and Euro 5 vehicles, there is no significant difference between the EMISA SA and CVH databases. As the CVH data is collected and supplemented every year during PTI and vehicle registration, it can be safely said that it is a reliable source of data, which is why it was decided that it will be used for all future research.

2.1.5 *Limit values of NO_X emissions of PCs defined by legislation*

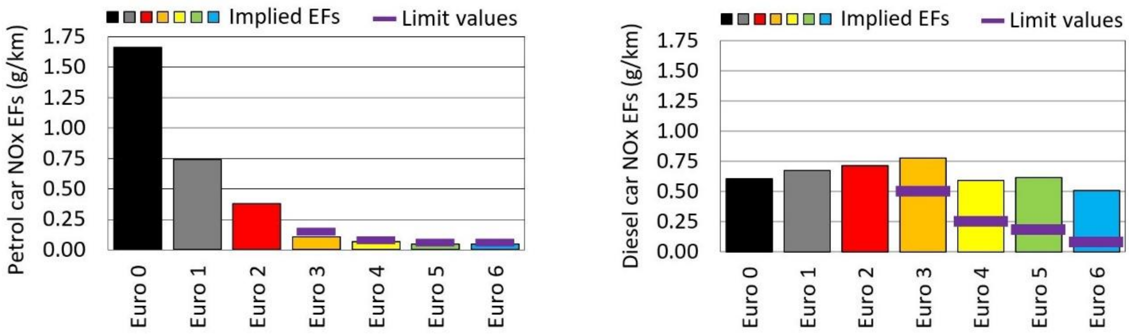
Due to their negative impact on the environment and human health, harmful exhaust emissions for new vehicles have been limited by EU regulations since 1992. For Euro 1 and Euro 2 vehicles, the NO_X values are not separately limited, but the limit values are expressed as the sum of NO_X and unburned hydrocarbons. Since the entry into force of the Euro 3 emission standard, the values of NO_X emissions have been limited and are shown in Table 1.

Table 1. Limit values of NO_X emissions of new PCs defined by EU legislation [81], [82], [83].

Emission standard	**NO_X (g/km)**	
	PETROL	**DIESEL**
Euro 3	**0.15**	**0.50**
Euro 4	**0.08**	**0.25**
Euro 5	**0.06**	**0.18**
Euro 6	**0.06**	**0.08**

2.1.6 *Identification of vehicles that exceed the legislation limit values of NO_X*

If all vehicles during their lifetime emitted NO_X emissions below the limit values listed in Table 1, then there would be no need to measure emissions and develop models for estimating emissions. In that case, NO_X emissions could be calculated using Equation (2). However, measuring emissions in real driving conditions determined that some vehicles emit significantly higher emissions than those stated in the legislation. The study results for detecting high-polluting vehicles in the PC fleet are presented in *CONFERENCE PAPER II (The influence of passenger car population and their activities on NO_X and PM emissions — Data from Croatia)*. For the fleet of petrol and diesel PCs according to the Euro emission standard, the implied EFs were calculated and compared with the legislation limit values. The implied NO_X EF is the total NO_X emissions of cars with the relevant Euro emission standard, divided by their total annual activity — mileage. Figure 7 shows the key research results — implied EFs for petrol and diesel PCs for Croatia in 2016.



(a) *(b)*

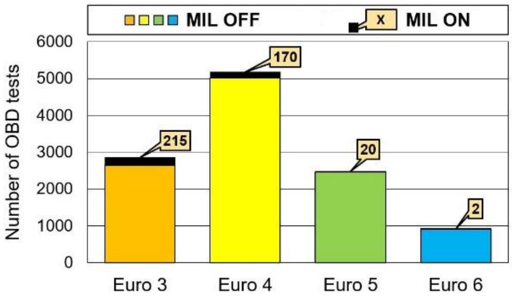
Figure 7. Implied NO_X EFs and the legislation limit values for petrol (a) and diesel (b) PCs according to the relevant Euro emission standard (CONFERENCE PAPER II).

Euro 0 petrol cars have the biggest implied NO_X EF, but the number of these vehicles is negligible compared to other PC categories. Although diesel Euro 6 implied NO_X EF is the lowest in the total diesel PC category, its value exceeds the Euro 6 emission limit by more than six times. Over the past ten years, many studies have shown that most Euro 6 diesel vehicles exceed the NO_X emission limit several times [5], [84], [85]. While there is visible progress in reducing NO_X emissions by introducing newer Euro emission standards for petrol cars, this is different for diesel cars. This article's contribution to achieving the research objective is that its scope is focused on diesel cars.

2.1.7 *Tailpipe and OBD test results collected during PTI*

Due to resolution or measurement precision limitations, existing emission analysers used in PTI stations often cannot measure the CO volume fraction of Euro 6 petrol engine vehicles nor the opacity of the Euro 6/VI diesel engine vehicles. According to Directive 2014/45/EU, for roadworthiness tests, the OBD test can be equivalent to standard tailpipe emission testing for vehicles of emission standard Euro 6/VI. Effective January 1, 2019, OBD testing methods have been implemented in Croatia. Data on the PC fleet that underwent PTI in January 2019 was gathered from the CVH database. Tailpipe and OBD test results were processed for petrol and diesel cars and shown at *CONFERENCE POSTER I (Primary results of OBD tests collected during PTI of vehicles in Croatia)*. What is checked during PTI for petrol cars is CO (vol.%) at neutral and fast idle and lambda value, and for diesel cars — smoke opacity (m^{-1}). If attention is paid to the results of tailpipe tests, NO_X emissions are not checked for either petrol or diesel cars. The key results of this study indicate that the application of OBD tests can identify those

Euro 3–Euro 6 vehicles in which the malfunction indicator lamp (MIL) is activated, which could cause excess pollution, Figure 8.



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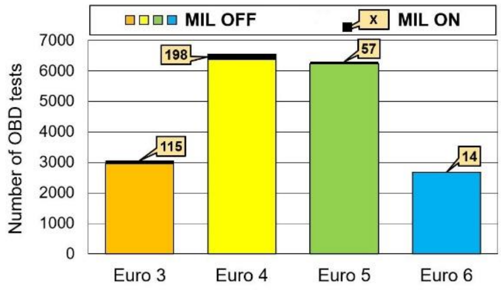


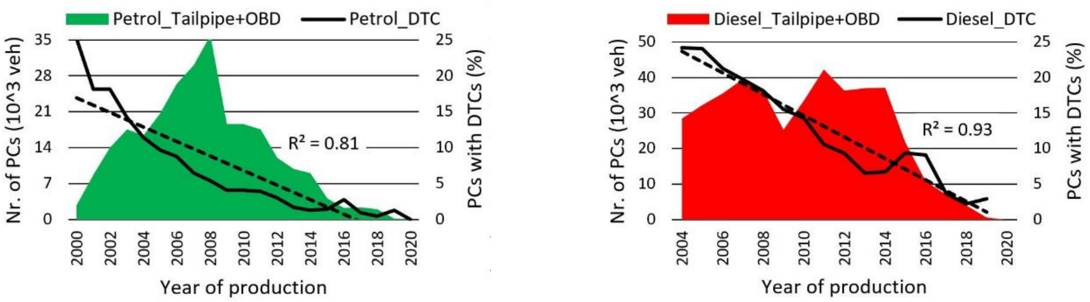
(b)

Figure 8. The number of performed OBD tests resulting in MIL OFF and ON status for petrol (a) and diesel (b) cars (CONFERENCE POSTER I).

The results indicate that the MIL was activated in Euro 3/4/5/6 petrol cars in 7.5/3.3/0.8/0.2%. In diesel Euro 3/4/5/6 cars, the MIL was activated in 3.8/3.0/0.9/0.5%. It can be concluded that both petrol and diesel cars with lower emission standards are more prone to malfunctions. The contribution of this article to the realisation of the research goal is that, for the first time, the possibilities of using OBD data to detect technically defective vehicles that cannot be detected by conventional test methods — such as the tailpipe test — have been explored. Such vehicles are often high-polluting and do not meet the legislation emissions limit value. If we take into account the number of all Euro 6 petrol/diesel cars that passed the OBD test — MIL status OFF and Readiness status OK — but did not pass the tailpipe test, there are a total of two/three such vehicles, or statistically 0.1% of them. Such a result proves that OBD tests can be an effective substitute for conventional testing of tailpipe emissions in Euro 6 vehicles.

2.1.8 *Proposal for wider application of OBD data for PTI purposes*

After the initial research on the possibilities of using OBD data during PTIs, conducted in January 2019, research on the wider application of OBD data followed. The OBD test results were collected and processed during PTIs of vehicles in Croatia in 2020. The study included petrol and diesel cars that passed the tailpipe test, on which an OBD test was also performed. The results are presented in the *CONFERENCE PAPER III (A new method for emission control system malfunction detection during the periodic technical inspection)*. The population of cars that passed the tailpipe test, where an OBD test was also performed, and the percentage of cars where at least one diagnostic trouble code (DTC) was found, according to vehicle year of production, are shown in Figure 9.



(a) (b)

Figure 9. The population of petrol (a) and diesel (b) cars that passed the tailpipe test, where an OBD test was also performed, and the percentage of cars where at least one DTC was found, according to vehicle year of production (CONFERENCE PAPER III).

The key finding of this research is that a stored DTC was found in as many as 11.5% of the tested cars. This discovery has practical implications — it suggests a new and more efficient method for detecting potentially defective vehicles. The OBD test is proposed to be mandatory for all vehicles with a European on-board diagnostics (EOBD) system. Additionally, introducing the number of DTCs as a mandatory data point, which will be crucial for passing the roadworthiness test, is recommended.

From the graphs in Figure 9, it can be determined that with the age of the vehicle, the proportion of those vehicles with DTCs found increases. By comparing petrol and diesel cars, it is evident that diesel cars have a significantly higher proportion of vehicles with DTCs found. The contribution of this article to the realisation of the research goal is that it was also concluded by applying OBD tests that diesel cars are more prone to breakdowns and that they are justified candidates for further research on harmful emissions.

2.1.9 *Modifications made to PCs*

The Testing Department at the CVH tests and approves vehicles and their modifications. Modifications on PCs performed from 2007 to 2017 were investigated, and the key results were presented in *CONFERENCE PAPER IV (Non-professional modifications of passenger cars)*. In addition to the impact on traffic safety, some modifications could also affect exhaust emissions. Even properly executed modifications can increase emissions. Modifications that increase the vehicle's frontal area or weight cause an increase in emissions. Examples of such modifications are the installation of bumpers, spoilers, larger wheels, replacement of the powertrain, transmission, and braking system with a more robust version, etc. If the vehicle is equipped with a mechanical coupling, the mass of the vehicle combination when towing a trailer could increase significantly. However, except for technically and legally acceptable modifications, the testing reveals a significant number of those that were not professionally done, which increases emissions. Such modifications most often occur during powertrain replacement, when individual components of the ECS are physically permanently modified, removed from the vehicle, or disabled by software manipulation.

PTIs of vehicles are the first filter where vehicle owners are informed about whether non-professional modifications have been made to their vehicles or not, and they are instructed on how to eliminate defects. In this way, a significantly reduced number of vehicles approach the testing, most of which pass. By processing the data from 2018 to 2023, it was determined that 1% of the total number of registered PCs annually undergo testing due to various modifications.

Given that vehicle modifications can generally affect their emissions, this article's contribution to realising the research goal is to investigate the number of PCs tested due to the modifications carried out and determine the share of non-professional modifications on such vehicles. The results presented in *CONFERENCE PAPER IV* indicate that certain modifications are performed on many vehicles, and the impact of such modifications on emissions has not yet been sufficiently investigated. Therefore, the need to conduct experimental tests measuring vehicle emissions on which some modifications were made is justified.

2.1.10 *Survey on the manner and conditions of vehicle use*

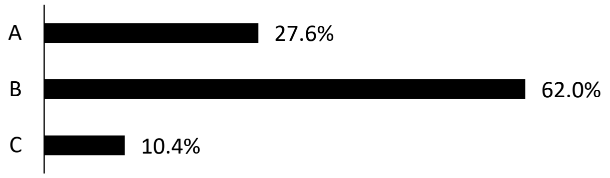
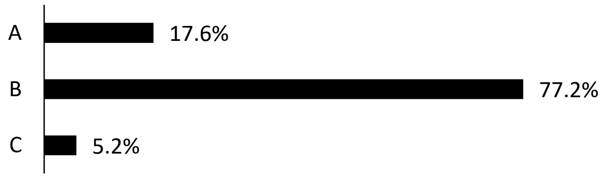
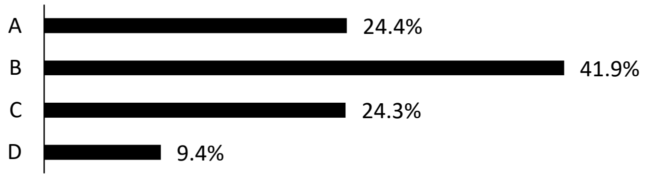
A short survey on drivers' habits and how they drive and maintain their cars was prepared for PC users in Croatia to achieve the goals and prove the research hypotheses with higher reliability. The survey was anonymous, created using Google Forms, and accessed by scanning the QR code or directly entering the URL in the web browser, Figure 10.

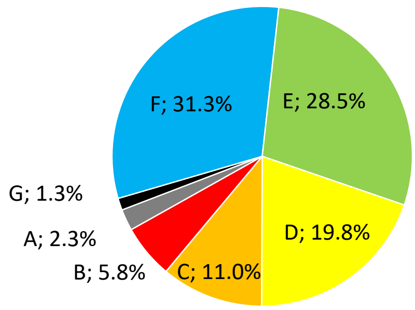
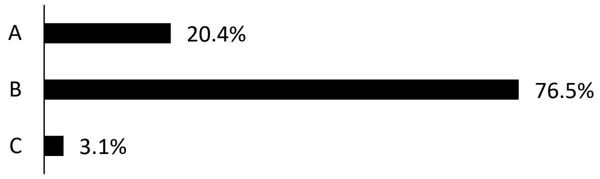
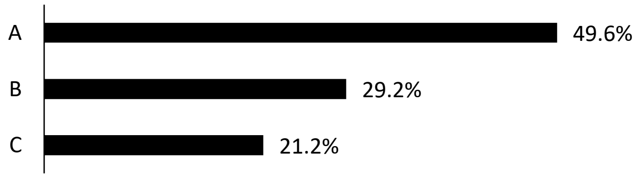
Figure 10. Instructions on how to access the survey.

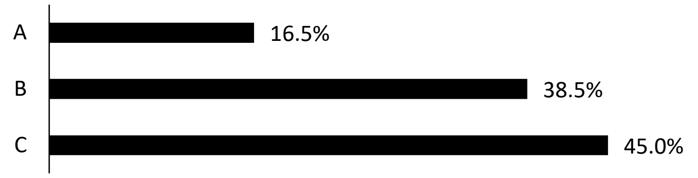
At the time of the final processing of the results, 2703 respondents had completed the survey. Table 2 comprehensively summarises the survey questions and respondents' answers.

Table 2. Survey questions and respondents' answers.

QUESTIONS	ANSWERS
1. How often do you visit workshops to maintain your car?	A) Regularly — at least once a year B) Only in case of technical difficulties C) Only when there is a major breakdown that makes driving the vehicle impossible
	

2. In which mode do you drive your car most of the time?	A) Urban B) Rural (mostly driving on local roads) C) Motorway (mostly driving on motorway)
	
3. How many kilometres per year do you drive your car?	A) Less than 10,000 km/year B) Between 10,000 and 30,000 km/year C) More than 30,000 km/year
	
4. What speed do you drive concerning road speed limits?	A) I always drive under the limit B) I drive slightly over the limit on average, just enough to avoid speeding tickets C) I don't pay too much attention to speed limits (usually, I'm in a hurry somewhere with or without reason)
	
5. What is the current status of your car's odometer?	A) Less than 100,000 km B) Between 100,000 and 200,000 km C) Between 200,000 and 300,000 km D) More than 300,000 km
	

<table>
<tr><td rowspan="2">6. What is the Euro emission standard of that car?</td><td>A) ≤ Euro 1
B) Euro 2
C) Euro 3
D) Euro 4
E) Euro 5
F) Euro 6
G) EV</td></tr>
<tr><td>
</td></tr>
<tr><td rowspan="2">7. Have any of your cars ever been modified concerning the ECS (e.g. blocking the EGR valve, removing the catalyst or DPF, removing the lambda sensor, turning off the AdBlue system, etc.)?</td><td>A) Yes
B) No</td></tr>
<tr><td>
</td></tr>
<tr><td rowspan="2">8. Is the specified car:</td><td>A) Petrol?
B) Diesel?
C) LPG/CNG?</td></tr>
<tr><td>
</td></tr>
<tr><td rowspan="2">9. Why did you decide on such a modification?</td><td>A) Due to the engine issue or ECS failure
B) Only as a precondition for increasing the engine power (chip tuning)
C) Other</td></tr>
<tr><td>
</td></tr>
</table>

10. What was the car's age at the time of such modification?	A) Less than five years B) Between five and ten years C) More than ten years
	
11. Did such a modification cause the car to fail the emissions test during the PTI?	A) Yes B) No C) I don't know (the car has been deregistered or sold)
	

The survey results shown in Table 2 refer, in general, to the category of PCs in Croatia. Section 2.3 discusses applying relevant survey results to a specific segment of the PC fleet.

2.1.11 *DHMZ database on environmental information*

DHMZ environmental data on average minimum and maximum monthly temperatures were used to calculate annual emissions using COPERT. Table 3 contains meteorological data for 2023 for the four largest Croatian cities.

Table 3. Average minimum and maximum monthly temperatures in 2023 for the four largest Croatian cities (Source: DHMZ).

MONTH	Average minimum/maximum air temperature (°C)			
	ZAGREB	SPLIT	RIJEKA	OSIJEK
Jan	-4.7 / 17.7	1.0 / 16.1	-0.5 / 16.1	-2.8 / 16.7
Feb	-8.1 / 18.4	-0.5 / 15.4	-5.6 / 18.4	-7.5 / 19.0
Mar	-2.5 / 23.4	5.6 / 20.0	2.1 / 20.3	-2.7 / 25.1
Apr	-2.2 / 23.3	5.1 / 22.3	1.2 / 23.5	-1.5 / 22.9
May	7.0; 28.3	12.7 / 28.7	10.2 / 28.5	6.2 / 27.6
Jun	11.4 / 34.3	16.7 / 32.4	15.9 / 33.5	10.4 / 35.8
Jul	11.2 / 36.4	19.7 / 37.2	15.5 / 36.5	11.8 / 36.6
Aug	10.9 / 35.5	17.8 / 36.1	14.9 / 36.9	10.6 / 38.2
Sep	9.5 / 30.4	16.2 / 30.8	14.5 / 31.0	10.4 / 32.6
Oct	2.0 / 29.2	12.0 / 26.7	5.5 / 27.5	0.2 / 28.4
Nov	-5.0 / 20.0	4.2 / 21.3	2.0 / 21.3	-2.6 / 20.4
Dec	-6.5 / 16.1	4.2 / 18.7	-0.6 / 17.9	-4.6 / 18.9

To simplify the emissions calculation, the mean data values of all four cities were used for the entire country instead of city-specific data (see Table 6).

2.2 Experimental tests

Section 2.1 presents the quantitative research results, enabling the calculation of emissions at the level of an individual vehicle and contributing to a more accurate assessment of vehicle fleet emissions using data from reliable sources. However, the results presented in *CONFERENCE PAPER IV* indicate a significant number of vehicles on which certain modifications are performed, and the impact of such modifications on emissions is still not sufficiently investigated. Since repairs and replacements of exhaust system components, such as DPFs, EGR valves, NO_X sensors, SCR catalysts and DEF systems, are relatively expensive, vehicle owners often choose the tampering method. Therefore, there is a justified need to conduct experimental tests to measure the emissions of vehicles on which some modifications have been made, especially if such modifications directly impact emissions. The survey results presented in Section 2.1.10 indicate that many vehicles have illegally modified ECSs, further confirming the justified need for measuring emissions from tampered vehicles. In the case of vehicles produced in the last two decades, it is very difficult or almost impossible to determine illegal modifications on ECSs without major physical disassembly. In addition, the OBD tests carried out during the PTI cannot always determine technical malfunctions or manipulations.

By reprogramming individual computer units in the vehicle, the activation of the "check engine" warning and the occurrence of DTCs can be avoided. Therefore, it is unsurprising that most unauthorised repair shops offer services such as ECU remap, chip tuning, EGR OFF, DPF OFF, DEF OFF, etc. Because of that, the most reliable method to detect potential tampering is emissions measurement.

Since quantitative research results indicate that diesel PCs produce NO_X emissions that exceed the limit values determined by legislation and that diesel cars are more prone to manipulation, experimental tests were carried out on Euro 5 and Euro 6 diesel cars. The Euro 5 vehicle was measured in laboratory conditions, and the Euro 6 vehicle was measured in real driving conditions on the road.

2.2.1 *Measurement of NO_X emissions of Euro 5 diesel car with a manipulated EGR valve under laboratory conditions*

Every year, a significant number of vehicles in which the EGR valve has either been removed or physically blocked are identified during a PTI. These are usually older vehicles with a pneumatically activated EGR valve. It can be assumed that the situation is similar in newer vehicles. However, in newer vehicles, such manipulations are quite difficult or nearly impossible to detect without special equipment. In some cases, visual inspections or vehicle diagnostics cannot determine the manipulations of the emissions control system (ECS). The EGR is a known method of reducing NO_X, but the impact of its deactivation on emissions has not been quantified. Due to this, an evaluation of the effect of EGR valve manipulation on NO_X emissions in a Euro 5 diesel PC under stationary and transient engine operating conditions measuring emissions on a chassis dynamometer was performed. The research results are presented in *JOURNAL PAPER II (Increase in nitrogen oxides due to exhaust gas recirculation valve manipulation)*. Test drives included standardised driving cycles — ECE-15, EUDC, and NEDC — and arbitrarily created driving cycles depending on driving speed and gear ratio. During the test drives using the OBD data logger, various data such as engine RPM, vehicle speed and acceleration, gear ratio, tractive force, air flow rate, exhaust mass flow rate, environmental conditions, EGR valve position, accelerator pedal position, emission values and others were collected. The measurements were performed during eight driving cycles and engine idle runs, and in all cases, a significant increase in NO_X emissions was found when the EGR valve was deactivated. NO_X emissions increased between 176% and 407%, depending on the cycle driven, Table 4.

Table 4. NO_X emissions and relative increase in NO_X emissions with deactivated EGR concerning the cycle driven.

Cycle	NO_X (mg/km)		NO_X increase (%)
	EGR ON	**EGR OFF**	
ECE-15	941	3377	259
EUDC	630	3196	407
NEDC	748	3267	337
Gear I-II	1625	5564	242
Gear II-III-IV	1300	3646	180
Gear IV-V-VI (80 km/h)	1022	2822	176
Gear IV-V-VI (100 km/h)	1072	3060	185
Gear V-VI	1197	3673	207

The measurements with an activated and deactivated EGR valve were performed under the same test conditions. Therefore, the Tier 3 approach can be applied to the results of this study before and after the manipulation of the EGR valve. A similar functional dependence of NO_X EFs on driving speed was also found in the case of measurements with deactivated EGR, Figure 11.

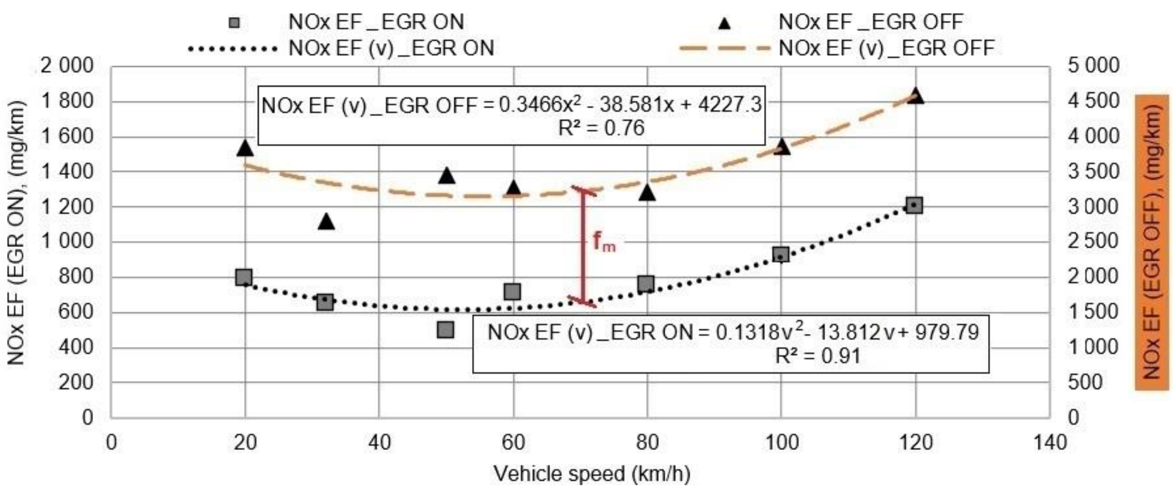


Figure 11. Comparison of NO_X EFs and their speed-dependent functions for the case when the EGR valve was activated and deactivated, respectively.

An important finding is that the NO_X EF function with a deactivated EGR valve is significantly higher than the NO_X EF function with an activated valve. With an activated EGR valve, the NO_X EF function based on the quadratic regression model fits the measured data with a coefficient of determination R^2 = 0.91. A slightly lower data matching was obtained for the deactivated valve, R^2 = 0.76. From the graph in Figure 11, it can be concluded that both polynomials are qualitatively very similar. This conclusion leads to the following hypothesis:

The EF of a vehicle with a deactivated EGR valve could be determined relatively accurately if the EF of a vehicle with an activated EGR valve is known. For a test vehicle with the EGR valve deactivated, NO_X EF can be calculated by applying Equation (3):

$$EF^{\mathrm{D}}_{\mathrm{NO_X}}(v) = EF^{\mathrm{A}}_{\mathrm{NO_X}}(v) + f^{\mathrm{M}}(v) \tag{3}$$

Where:

$EF^{\mathrm{D}}_{\mathrm{NO_X}}(v)$ = NO_X EF speed-dependent function for EGR OFF case (g/km),

$EF^{\mathrm{A}}_{\mathrm{NO_X}}(v)$ = NO_X EF speed-dependent function for EGR ON case (g/km),

$f^{\mathrm{M}}(v)$ = speed-dependent function of increased emissions due to manipulation (g/km).

For the test vehicle, the factor of increased emissions due to the manipulation varied between 1800 and 3939 mg/km, depending on the driving cycle specified in Table 4. This work's important contribution to achieving the research goal is discovering a functional relationship between NO_X emissions of vehicles with an activated and deactivated EGR valve. The results point to the need for a correction of the NO_X EFs, which should include the factor of increased emissions due to manipulations. This finding could be implemented into existing emissions calculation models if measurements are applied to a wider range of vehicles.

2.2.2 *Measurement of NO_X emissions of Euro 6 diesel car with manipulated ECSs under real driving conditions*

In addition to older vehicles, newer vehicles are also subject to the deterioration and failure of ECSs. Diesel vehicles are more prone to breakdowns, especially if they are mainly used in urban traffic. Due to the high maintenance and replacement cost, such systems are often subject to tampering. Manipulations of ECSs of in-use vehicles are still a taboo subject that science and legislation do not address sufficiently. Extensive research was conducted on a Euro 6 diesel car with a combination of manipulated ECSs to determine the influence of ECS manipulations on NO_X emissions under real driving conditions. The research results are presented in *JOURNAL PAPER III (An estimate of the NO_X emissions of Euro 6 diesel passenger cars with manipulated emission control systems)*. The test drives included different conditions of vehicle use, such as loading the vehicle with an additional load, changing gear ratios, and experiencing the effect of deactivating the ECS.

Tests were performed on three different routes:

1) Constant speed route (10–80 km/h),
2) Constant speed route (90–140 km/h),
3) Real driving emissions (RDE) route.

Tests were performed for two different vehicle masses:

1) Mass in running order (MIRO),
2) Gross vehicle weight rating (GVWR).

Tests were conducted for seven different ECS operating modes:

1) All ECS active,
2) DEF OFF,
3) HP EGR OFF,
4) LP EGR OFF,
5) HP EGR inactive and DEF OFF,
6) LP EGR inactive and DEF OFF,
7) HP & LP EGR inactive and DEF OFF.

Applying Equation (3) to all seven ECS scenarios for driving on the RDE route, the speed-dependent functions of the increased emissions due to manipulation, and NO_X increase factors for the overall RDE trip and separately for urban (U) / rural (R) / motorway (M) sections, were calculated, Table 5.

Table 5. Speed-dependent functions of increased emissions due to manipulation of certain ECSs of the tested vehicle — $f_i^M(v)$ — for the case of MIRO, along with NO_X increase factors for the overall RDE trip and separately for U/R/M sections.

ECS scenario	$f_i^M(v)$ **(g/km)**	**NO_X increase factor (-)**			
		Total RDE trip	U 30 km/h	R 70 km/h	M 110 km/h
1) All ECSs active	0	1	1	1	1
2) DEF OFF	$0.0008v^2 - 1.1199v + 306.95$	26	21	34	33
3) HP EGR OFF	$0.0976v^2 - 15.737v + 1053.2$	58	51	67	64
4) LP EGR OFF	$0.0727v^2 - 11.718v + 937.04$	56	49	73	67
5) HP EGR OFF & DEF OFF	$0.1069v^2 - 10.794v + 1516.7$	144	99	200	208
6) LP EGR OFF & DEF OFF	$0.1184v^2 - 10.23v + 1378.7$	139	90	193	216
7) HP and LP EGR OFF & DEF OFF	$0.1354v^2 - 14.061v + 1573.8$	142	98	195	213

NO_X EF speed-dependent functions for seven different ECS scenarios were calculated and compared with the NO_X EF curve for the most degraded emission standard Euro 0 appropriate for that car size, Figure 12.

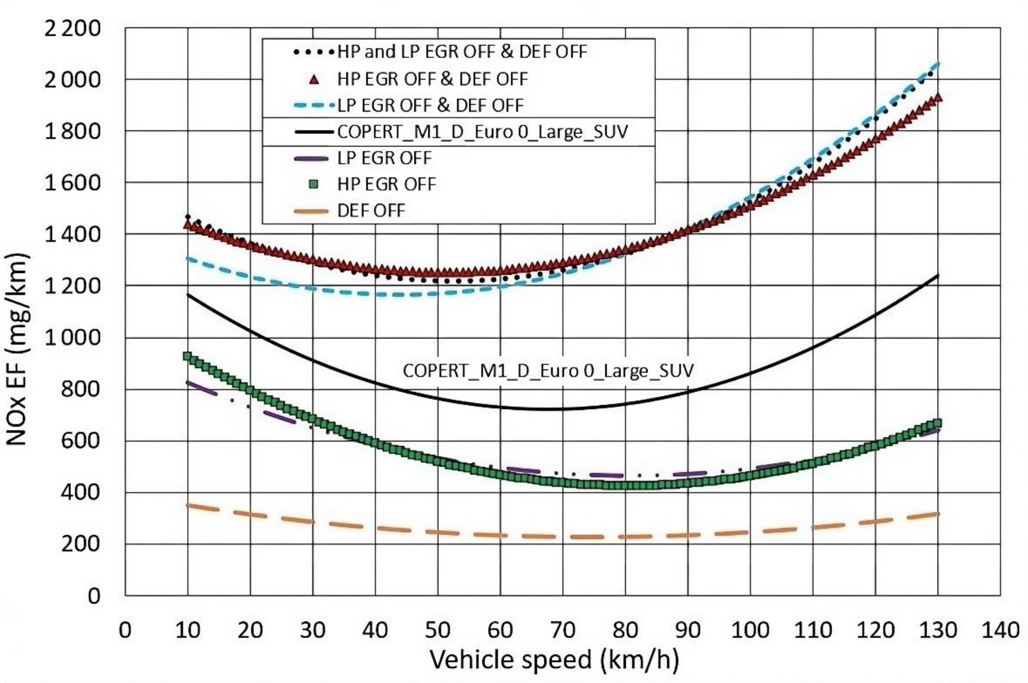


Figure 12. Comparison of the hot NO_X EFs of the test vehicle with manipulated ECSs with the COPERT hot NO_X EF of a large/SUV diesel PC of the Euro 0 emission standard.

When all ECSs were active, the NO_X emissions when driving at a constant speed from 10 km/h to 140 km/h were not significantly different from those when driving the RDE route. However, when the ECSs were deactivated, there was a significant difference between the emissions at a constant speed and the RDE route. This study's contribution to achieving the research objective is that it has been proven that driving dynamics on the RDE route contribute to increased NO_X emissions in vehicles with deactivated ECSs. Given these results, the RDE data should be used instead of the constant speed data to calculate emissions from manipulated vehicles. The results from *JOURNAL PAPER III* also contribute to a better understanding of how the influence of the increase in vehicle mass on the rise in NO_X emissions is negligible compared to the increase caused by the manipulations of the ECS. The significance of this study for realising the research goal is that the emissions of vehicles with different combinations of deactivated ECSs were quantified in real driving conditions, and it was pointed out that such modifications can cause a multiple increase in NO_X emissions, even more than two orders of magnitude.

2.3 Qualitative research — scientific discoveries and development of the ARTEM

Statistical data such as average monthly air temperatures, proportion of the distance travelled in a particular driving mode, average driving speed, change in gear ratio, change in vehicle weight and deactivating individual ECSs were used to determine the factors affecting NO_X emissions from vehicles. In addition to the above, vehicle users filled out surveys with questions that included the conditions of vehicle use.

2.3.1 *The influence of average monthly air temperatures on NO_X emissions*

Air temperature affects cold-start emissions that occur during the warm-up phase of the engine and exhaust aftertreatment devices, and such conditions are specific to urban driving. COPERT v.5.7.2 was used to assess the impact of changes in average monthly air temperatures on vehicle NO_X emissions. NO_X emissions were calculated for the environmental conditions listed in Table 6.

Table 6. Average minimum and maximum monthly temperature in Croatia in 2023 — data based on average values for the four largest Croatian cities listed in Table 3.

MONTH	Average minimum/maximum air temperature (°C)
	CROATIA
Jan	-1.8 / 16.7
Feb	-5.4 / 17.8
Mar	0.6 / 22.2
Apr	0.7 / 23.0
May	9.0; 28.3
Jun	13.6 / 34.0
Jul	14.6 / 36.7
Aug	13.6 / 36.7
Sep	12.7 / 31.2
Oct	4.9 / 28.0
Nov	-0.4 / 20.8
Dec	-1.9 / 17.9

Then, the average minimum and maximum monthly temperatures were changed by ±5 °C, and the total — cold and hot — annual NO_X emissions and their positive or negative increase are shown in Table 7. Considering the entire fleet of PCs, the reduction of average monthly temperatures of five degrees Celsius would cause an increase in NO_X emissions by 2.29%. In comparison, an increase in average monthly temperatures of five degrees Celsius would cause a decrease in NO_X emissions by 3.07%. Considering only diesel Euro 6 PCs, a change in average monthly temperatures of ±5 °C would change NO_X emissions by ±0.78%.

Table 7. Total NO_X emissions and their relative increase for standard (STD) temperatures according to Table 6, as well as the STD temperatures changed by ±5 °C.

Temperature (°C)	All PCs		Diesel Euro 6 PCs	
	NO_X emissions (t)	Rel. NO_X emissions increase (%)	NO_X emissions (t)	Rel. NO_X emissions increase (%)
STD - 5 °C	10,571	+2.29	2313	+0.78
STD	10,334	-	2295	-
STD + 5 °C	10,017	-3.07	2277	-0.78

2.3.2 *The influence of vehicle distance travelled and average driving speed in the U/R/M section on NO_X emissions*

Seven possible scenarios were created to determine the influence of the vehicle distance travelled and the average driving speed in a particular U/R/M mode, as listed in Table 8. The data for scenario I were obtained as the mean values of all RDE drives performed as part of experimental tests using the PEMS device. The data for the other scenarios were chosen arbitrarily by changing U/R/M values. In scenarios II–IV, the distance travelled by the vehicle was varied, and in scenarios V–VII, the impact of changing average driving speed was investigated.

Table 8. List of possible scenarios with the share of the distance travelled and the average driving speed for the U/R/M section.

Case scenario	URBAN PEAK		URBAN OFF-PEAK		RURAL		MOTORWAY	
	Distance (%)	Speed (km/h)	Distance (%)	Speed (km/h)	Distance (%)	Speed (km/h)	Distance (%)	Speed (km/h)
I (RDE)	6.6	10	27.8	42	33.4	75	32.2	113
II	10	10	40	42	25	75	25	113
III	5	10	20	42	50	75	25	113
IV	5	10	20	42	25	75	50	113
V	6.6	10	27.8	37	33.4	70	32.2	108
VI	6.6	10	27.8	47	33.4	80	32.2	118
VII	6.6	10	27.8	52	33.4	85	32.2	123

For the seven possible scenarios listed in Table 8, using COPERT v.5.7.2., NO_X emissions and their annual increase compared to Scenario I were calculated and shown in Table 9. Considering the entire PC fleet, a relative NO_X emissions increase varies from -4.3% to +5.3%. Considering only diesel Euro 6 PCs, a relative NO_X emissions increase could range from -4.3% to +4.7%.

Table 9. NO_X emissions and their relative increase for seven case scenarios from Table 8.

Case scenario	PCs		Diesel Euro 6 PCs	
	NO_X emissions (t)	Rel. NO_X emissions increase (%)	NO_X emissions (t)	Rel. NO_X emissions increase (%)
I	10,334	-	2295	-
II	10,557	+2.2	2360	+2.8
III	9889	-4.3	2196	-4.3
IV	10,617	+2.7	2341	+2.0
V	10,200	-1.3	2278	-0.7
VI	10,579	+2.4	2336	+1.8
VII	10,880	+5.3	2402	+4.7

2.3.3 *The effect of gear selection strategy on NO_X emissions*

Various tests were conducted under laboratory conditions to determine the effect of the gear selection strategy on NO_X emissions. The test results are presented in *JOURNAL PAPER II*. Table 10 compares NO_X EFs at steady-state engine load conditions while driving at a constant speed on a chassis dynamometer for different gear ratios.

Table 10. Comparison of NO_X emissions when driving at 50/80/100/120 km/h in different gears with the EGR valve ON and OFF, respectively.

Vehicle Speed (km/h)	Gear	EGR ON		EGR OFF	
		NO_X (mg/km) at EGR valve position (%)	Rel. NO_X increase (%)	NO_X (mg/km)	Rel. NO_X increase (%)
50	III IV	492 at 35 384 at 26	-11	3534 3464	-2
80	IV V	753 at 32 786 at 26	+4	2637 2926	+11
100	V VI	722 at 28 917 at 21	+27	3267 3865	+18
120	V VI	1225 at 23 1206 at 22	-2	4514 4587	+2

When the EGR system is active, no direct correlation can be established between the transmission gear selection and NO_X emissions because changing the gear changes the engine load, consequently changing the position of the EGR valve, which significantly affects NO_X emissions. When the EGR system is deactivated, it can be determined that the relative change in NO_X emissions due to gear shifting is much smaller than the change in NO_X emissions caused by EGR deactivation. As gear selection largely depends on the driver's habits, including this parameter in the emissions model is not scientifically justified because it is almost impossible to describe it mathematically. Measurements are required under real driving conditions to eliminate the influence of gear selection on emissions, where the driving dynamics and longer duration of the RDE cycle reduce the influence of gear selection on emissions.

2.3.4 *The effect of vehicle mass on NO_X emissions*

It is known that with an increase in vehicle mass, fuel consumption increases, and consequently emissions. The goal was to determine how much higher the NO_X emissions of a vehicle on the RDE route are if its MIRO is increased by the amount of the permitted carrying capacity, i.e. when the vehicle mass is equal to the GVWR. Using the example of five different ECS scenarios, the impact of increasing vehicle mass was investigated, and the NO_X EF values and their relative change are shown in Table 11.

Table 11. NO_X EFs and relative NO_X increase caused by increasing vehicle mass from MIRO to GVWR for five ECS scenarios.

ECS scenario	**NO_X EF (mg/km)**		**Rel. NO_X increase (%)**
	MIRO	GVWR	
All ECSs active	10.02	14.72	+47
DEF OFF	240.68	262.37	+9
HP EGR OFF	582.18	538.37	-8
HP EGR OFF & DEF OFF	1438.63	1386.64	-4
LP EGR OFF & DEF OFF	1396.74	1433.83	+3

From the above results and those presented in *JOURNAL PAPER III*, it can be concluded that the influence of increasing vehicle mass on NO_X emissions is relatively more visible when the ECSs were activated than when they were deactivated. However, since the values of NO_X emissions for the case when all ECSs were activated are small in absolute values, it can be concluded that the influence of increasing vehicle mass on NO_X emissions is negligible compared to the increase caused by ECS manipulations. In addition to the above, the vehicle's load largely depends on the driver's habits. Therefore, including this parameter in the emissions model is almost impossible to describe mathematically. Statistics show that the number of registered PCs in Croatia has increased by half a million in the last ten years, indicating that vehicles have become more accessible to residents. Today, on average, every second inhabitant owns a PC, and in most cases, only the driver is transported by vehicle. For the reasons stated above, the influence of vehicle mass was not considered when developing ARTEM.

2.3.5 *The effect of ECS manipulation on NO_X emissions*

By processing the results of experimental tests of the test vehicle in laboratory conditions for the case of an activated and deactivated EGR valve, NO_X EF polynomials were created as a function of average driving speeds. By comparing these polynomials, their mutual dependence was established, and a formula was created for calculating the emissions of vehicles with a deactivated EGR valve, Equation (3). According to the measurement results, NO_X emissions increased by up to 407% when the EGR was deactivated. The above findings motivated a detailed investigation of manipulations of different ECSs in real road driving conditions. The results of that research confirmed the previous study's hypothesis and reconfirmed that Equation (3) is valid. For the six scenarios where ECSs were disabled, NO_X emissions on the RDE route increased from 26 to 144 times compared to those in which ECSs were active, Table 5. For the test vehicle used in real driving conditions, the NO_X emissions (mg) and NO_X EFs (mg/km) were calculated for U/R/M sections and compared with the values calculated by COPERT, Figure 13.

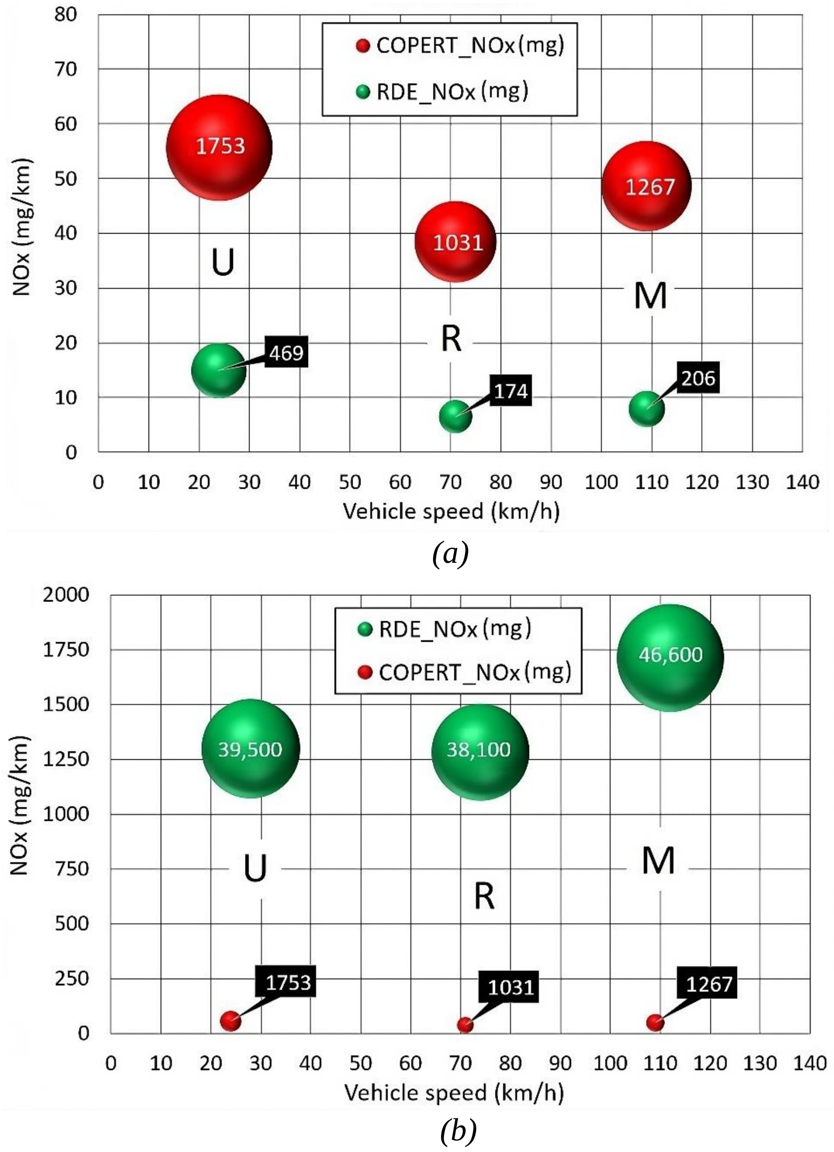


Figure 13. Comparison of the test vehicle's RDE NO_X emissions when ECSs were active (a) and inactive (b) with the COPERT calculation.

In the scenario where all ECSs were active, the RDE NO_X emissions were lower than the COPERT estimate by a factor of 3.7/5.9/6.2 for the U/R/M driving mode, Figure 13(a). In this case, the COPERT specification shows an overestimated value, but be aware that the COPERT estimate is based on measurements carried out on many cars. In the scenario where the NO_X ECSs were inactive, the RDE NO_X emissions were higher than the COPERT calculations by an increase factor of 23/37/37 for the U/R/M driving mode, Figure 13(b).

The doctoral thesis, which consists of several published papers, contributes to the scientifically proven fact that the effect of ECS manipulation on the creation of NO_X emissions is far greater than all other influential parameters presented so far. Therefore, the survey results presented in Section 2.1.10 had to be processed in more detail to define the impact of such manipulations on the emissions of the vehicle fleet concerning the measure of the vehicle owners' tendency to manipulate.

2.3.6 *Detailed analysis of survey results and their application to the fleet segment*

A simple random sampling technique was used to estimate the number of manipulated PCs in the Croatian fleet as accurately as possible. An anonymous survey was conducted among PC owners by completing a Google form. The survey flyer with an access QR code was available to vehicle owners nationwide at PTI stations. In this way, an attempt was made to reduce bias regarding geographical location so that the sample did not come from only one region. A total of 2738 people participated in the survey, of which 2703 were owners of PCs with an internal combustion engine (ICE). Since no survey can be 100% accurate, the degree of uncertainty in the survey results is called the margin of error and is calculated using Equation (4).

$$MoE = z\frac{\sigma}{\sqrt{n}}\sqrt{\frac{(N-n)}{(N-1)}} = z\sqrt{\frac{p(1-p)}{(N-1)\frac{n}{(N-n)}}} \cong z\frac{\sigma}{\sqrt{n}} \cong z\sqrt{\frac{p(1-p)}{n}} \qquad (4)$$

Where:

MoE = margin of error (%),

z = 1.96; z-value that corresponds to confidence level 95%,

σ = standard deviation of the sample,

n = 2703; sample size,

p = sample proportion (%),

N = 1,908,302; population size, i.e., number of registered PCs with an ICE in Croatia in 2023.

In addition to determining the margin of error, to determine the heterogeneity of the survey results, the number of PCs whose owners participated in the survey was compared with the number of registered PCs in Croatia in 2023, according to the Euro emission standard, Figure 14.

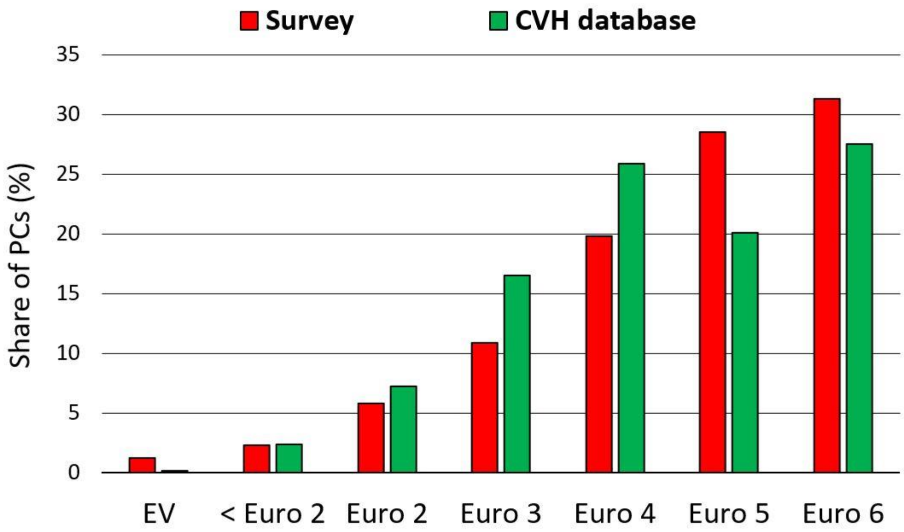


Figure 14. The percentage of PCs owned by survey respondents (red) and the percentage of PCs registered in Croatia in 2023 (green), according to the Euro emission standard.

The results show no major relative discrepancies between the survey and the CVH database. The Euro 5 classification has a slightly larger deviation. Namely, the population of Euro 5 PCs in the Croatian fleet in 2023 is less than Euro 4 or Euro 6, which is a strong reminder of the lasting impact of the global economic crisis that began in 2008. This crisis has significantly reduced the registrations of new Euro 5 cars in the coming period. Since 2014, the production of Euro 5 cars has stopped, and Euro 6 has been introduced.

Considering answers 6, 7, and 8 from Table 2, the distribution of the population of manipulated vehicles according to the Euro emission standard was determined, Figure 15.

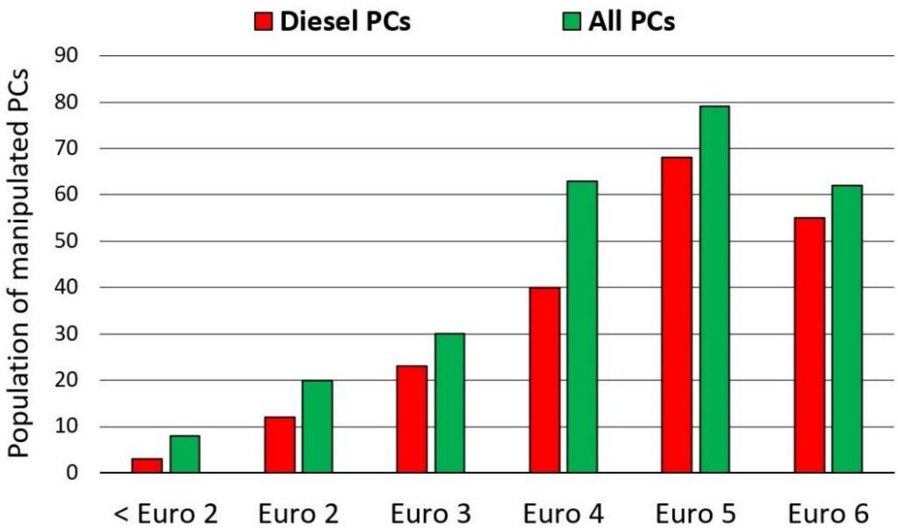


Figure 15. Distribution of the population of manipulated PCs based on the survey results, according to the Euro emission standard for diesel cars only (red) and all PCs (green).

Figure 15 shows that the diesel car category has the highest number of manipulated PCs. The presented results confirm the conclusions of quantitative research and the assumptions of experimental tests that diesel cars are more prone to malfunctions and ECS manipulations. Since newer — Euro 5 and Euro 6 — diesel PCs are equipped with multiple ECSs, they are more prone to manipulations than older vehicles.

In a sample of 2703 respondents — owners of a PC with ICE, 262 had carried out certain manipulations on the ECSs. This sample's proportion is 9.69%, and the margin of error is ±1.11% at a 95% confidence level. Applying this to the total population of 1,908,302 PCs with ICE registered in Croatia in 2023, the total number of PCs with manipulations on the ECSs would be 184,970. Of the 262 respondents who performed certain manipulations on their vehicles, 201 are owners of diesel PCs. This sample's proportion, i.e., the share of diesel PCs with manipulated ECSs in the total PC fleet, is 7.44%, and the margin of error is ±0.99% at a 95% confidence level. Applying this to the total population of 1,082,934 diesel PCs registered in Croatia in 2023, the total number of diesel PCs with manipulations on the ECSs would be 141,905 (13.10%). Of the 201 respondents who did certain manipulations on their diesel PCs, 55 are owners of Euro 6 diesel PCs. The sample proportion for this sample is 2.04%, and the margin of error is ±0.53% at a 95% confidence level. Applying this to the total population of 295,903 Euro 6 diesel PCs registered in Croatia in 2023, the total number of Euro 6 diesel PCs with manipulations on the ECSs would be 38,830 (13.12%). The results of the survey and other processed data are shown in Table 12. It should be noted that diesel plug-in hybrid EVs are also included in the above statistics.

Table 12. Survey results and the processed data for manipulated PCs.

N = 1,908,302; n = 2703	n	p (%)	MoE (%)	N	N (%)
Manipulated PCs with an ICE	262	9.69	±1.11	184,970	9.69
Manipulated Diesel PCs	201	7.44	±0.99	141,905	13.10
Manipulated Euro 6 Diesel PCs	55	2.04	±0.53	38,830	13.12

The Euro 6 vehicle category is divided into three subcategories: Euro 6 a/b/c, Euro 6 d-TEMP, and Euro 6 d. The largest share of vehicles is represented in the Euro 6 a/b/c subcategory (69.85%), followed by Euro 6 d-TEMP (17.30%) and Euro 6 d (12.85%). Assuming a uniform distribution of manipulated vehicles within the Euro 6 diesel subcategory and based on the number of manipulated Euro 6 diesel cars determined in Table 12, the number of manipulated vehicles is calculated and shown in Table 13.

Table 13. The number of Euro 6 diesel PCs in the Croatian road vehicle fleet in 2023 and the number of manipulated Euro 6 diesel cars distributed to Euro 6 a/b/c/, Euro 6d-TEMP and Euro 6d subcategories.

Diesel PCs	Vehicle population (-)	
	Total	Manipulated
Euro 6 a/b/c	206,681	27,122
Euro 6 d-TEMP	51,204	6719
Euro 6 d	38,018	4989
All Euro 6	295,903	38,830

Analysing the answers of the owners of manipulated Euro 6 diesel cars to the remaining questions from the survey, the following conclusions are reached:

- All 55 respondents answered that they maintain their vehicle regularly, i.e. at least once a year,
- 40% of respondents drive most of the time in urban mode, 49% in rural mode, and only 11% in motorway mode
- Only 11% of respondents drive less than 10,000 km per year, 56% of them between 10,000 and 30,000 km, and even 33% of them over 30,000 km,
- Only 11% of respondents stated that they drive at the speed limit, 73% of them slightly higher, and even 16% of them do not respect the speed limit on the roads at all,

- As many as 56% of respondents decided to manipulate the ECS due to ECS or engine failure, 31% of them as a prerequisite for chip-tuning, and 13% of them for some other reasons,
- 25% of respondents own a vehicle less than five years old, 64% of them have a vehicle between five and ten years old, and 11% of them have a vehicle older than ten years,
- Only 15% of respondents did not pass the PTI with this type of vehicle, while as many as 78% passed. In comparison, 7% said they sold or deregistered a vehicle before PTI.

2.3.7 *Development of the ARTEM*

The original idea of the doctoral thesis was to develop an ARTEM that could calculate emissions more accurately than existing models and calculate emissions at the individual vehicle level. The plan was to use the COPERT EFs and the annual vehicle distance travelled from the CVH database to calculate the emissions of each vehicle individually using the COPERT model. Such calculation would be possible using the Tier 2 approach. However, a more advanced Tier 3 approach was already released, which included additional parameters for a more precise calculation of emissions. The Tier 3 approach divides emissions into cold and hot and into the driving modes in which they are produced (U/R/M). It also expresses EFs as functions of mean vehicle speed. For the Tier 3 approach to be applied at the individual vehicle level, knowing the average driving speed and distance travelled by each vehicle in the U/R/M driving mode would be necessary. Unfortunately, this data is not available for individual vehicles. Because of this, research focused more on a hot topic at that time — the "Dieselgate" scandal and NO_X emissions cheating.

The parameters that have the greatest influence on the formation of NO_X emissions can be divided into three basic groups — environmental, driver behaviour, and vehicle condition parameters. Environmental parameters such as average minimum and maximum monthly air temperatures are discussed in Section 2.3.1. The processed results show that changing the average temperatures by ±5 °C can increase total NO_X emissions by 2.29% or decrease by 3.07%. When meteorological data for the four largest Croatian cities are considered (see Table 3), the change in average monthly temperatures in Table 6 by ±5 °C becomes realistic.

Driver behaviour parameters include vehicle distance travelled and average driving speed in the U/R/M section, gear selection strategy, vehicle mass, etc. When talking about drivers' habits, including these parameters in the emissions model is not scientifically justified because it is impossible to describe them mathematically in a simple way. However, considering the average driving speed and distance travelled in the U/R/M mode, using the COPERT, NO_X emissions were calculated for several realistic vehicle usage scenarios. Considering the entire PC fleet, the relative NO_X emissions increase varies from -4.3% to +5.3%.

Vehicle condition parameters include items such as vehicle maintenance, primarily engine and exhaust aftertreatment systems, which have an extremely significant impact on EFs. Section 2.2 shows the influence of parameters such as deactivating the EGR and DEF systems. With these manipulations, NO_X emissions increased up to 144 times compared to the vehicle conditions when these systems were active.

The discoveries made as part of quantitative research and by conducting experimental tests in the laboratory and under real driving conditions led to new knowledge about the impact of ECS manipulations on NO_X emissions. Moreover, a new formula for calculating NO_X EFs is introduced, which has the potential to enhance our understanding and management of NO_X emissions significantly. See Equation (3).

To create the model based on Equation (3), RDE measurements according to the procedure in Section 2.2.2 on a larger number of vehicles with different Euro emission standards and ECSs must be performed to obtain reliable and validated values of the function $f_i^{\mathrm{M}}(v)$. In that case, NO_X EFs with deactivated ECSs could be calculated by Equation (5):

$$EF^{\mathrm{D}}_{\mathrm{NO_X}_i}(v) = EF_{\mathrm{NO_X}_{\mathrm{COPERT}}}(v) + f_i^{\mathrm{M}}(v) \tag{5}$$

Where:

$EF^{\mathrm{D}}_{\mathrm{NO_X}_i}(v)$ = NO_X EF speed-dependent function for the case where the ECS of type *i* is deactivated (g/km),

$EF_{\mathrm{NO_X}_{\mathrm{COPERT}}}(v)$ = NO_X EF speed-dependent function from the COPERT database for the case where all ECSs are active (g/km),

$f_i^{\mathrm{M}}(v)$ = speed-dependent function of increased emissions due to manipulation of ECS of type *i* (g/km).

According to the data from Figure 12, the NO_X EFs of Euro 6 diesel cars with both EGR and DEF systems deactivated are even higher than those of Euro 0 diesel cars. Because newer vehicles have higher peak combustion temperatures in the engine cylinder, they produce more NO_X than older vehicles. When ECSs in newer vehicles are deactivated, they cause NO_X emissions that can be higher than those produced by Euro 0 vehicles. According to the results from the experimental tests — Figure 12, in the absence of valid $f_i^{\mathrm{M}}(v)$ functions for calculating the emissions of manipulated vehicles, lowering the Euro emission standard to Euro 0 can be applied. In that case, Equation (5) takes a simplified form — Equation (6):

$$EF^{\mathrm{D}}_{NO_{X\,i}}(v) = EF_{\mathrm{NO_X}\,\mathrm{COPERT;\,Euro\,0}}(v) \tag{6}$$

Where:

$EF_{\mathrm{NO_X}\,\mathrm{COPERT;\,Euro\,0}}(v)$= NO_X EF speed-dependent function from the COPERT database for a relevant Euro 0 vehicle (g/km).

Figure 16 provides a clearer view of the input data used by ARTEM. The input data used by the existing COPERT model are marked in red: vehicle mileage, vehicle database, meteorological data, and EF database. Additional input data with which the existing COPERT model was upgraded to ARTEM are marked in blue: OBD data, tailpipe test data, vehicle usage data, homologation data, and ECS manipulation data.

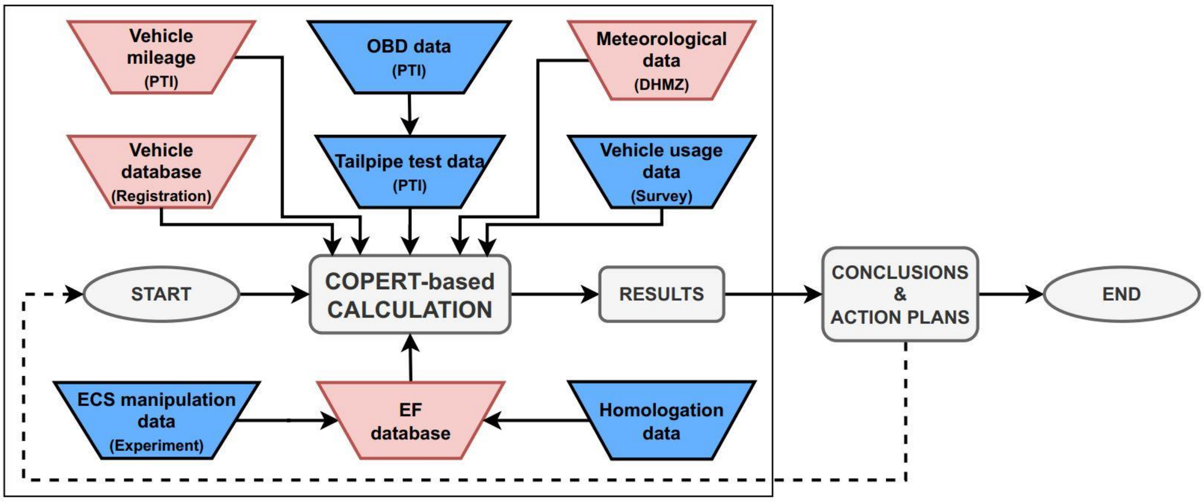


Figure 16. Diagrammatic representation of the ARTEM.

Figure 17 shows a flowchart that describes the proposed procedure and sequence of conducting the emission test during PTI, the criteria for selecting the appropriate emissions model and the formula for determining NO_X emissions according to the ARTEM. The upper part of the flowchart shows the sequence of actions that take place in the PTI station, which include an emission test — tailpipe or OBD test, and depending on the results of that test, the lower part of the flowchart shows which model needs to be applied — existing or advanced. The existing one (e.g. COPERT) would be used for vehicles that passed the emission test, while the ARTEM would be used to calculate the NO_X emissions of those vehicles that failed the emission test.

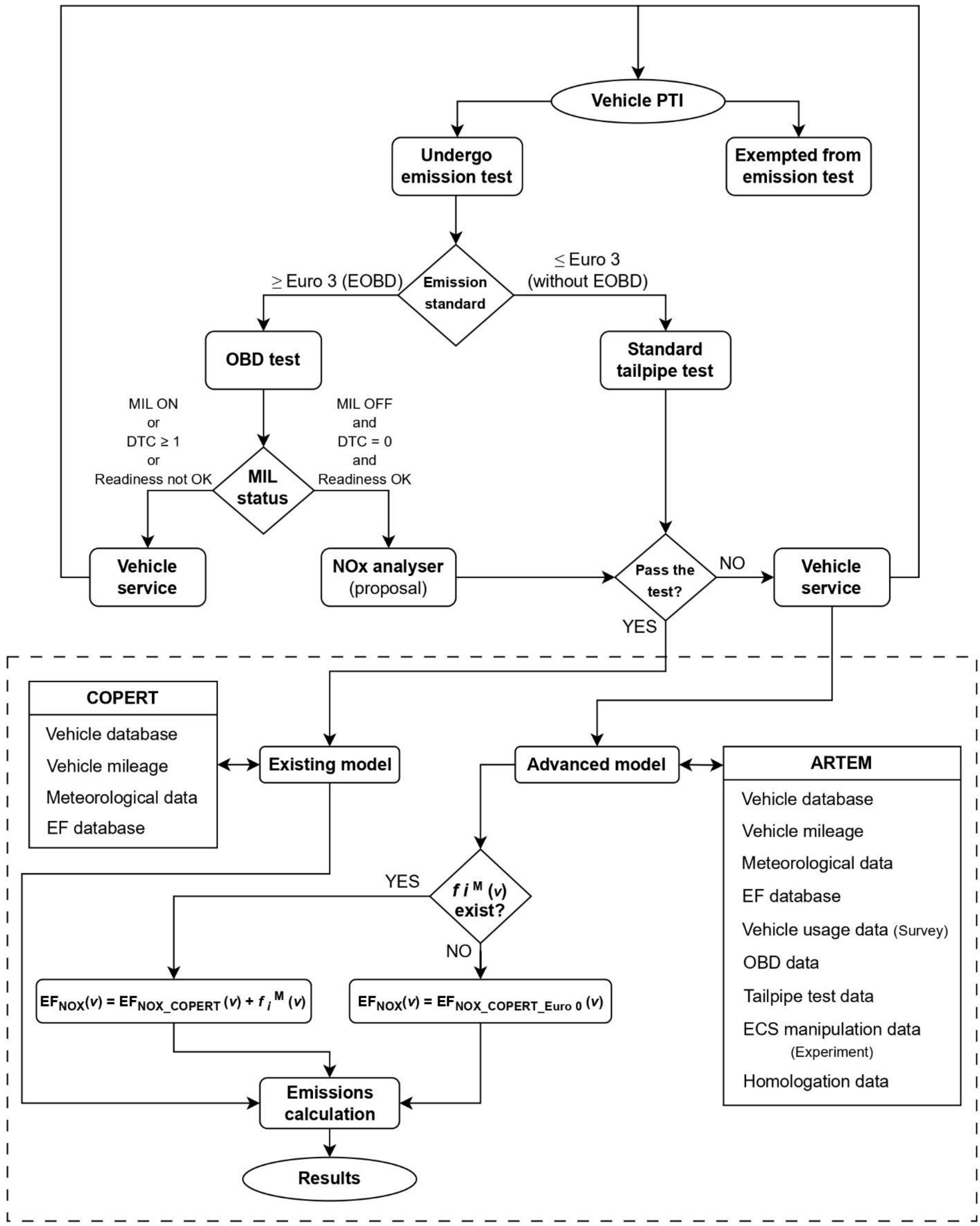


Figure 17. Proposal of the procedure and sequence of conducting the emission test during PTI, the criteria for selecting the appropriate emissions model and the formula for determining NO_X emissions according to the ARTEM.

Since existing emission calculation models do not include additional emissions generated by vehicles with manipulated ECSs, the presented approach allows a more accurate estimation of vehicle fleet emissions. Due to time limitations and limited resources, performing RDE measurements on more vehicles was impossible as part of the doctoral study. Therefore, new knowledge and scientific discoveries are applied only to the targeted part of the fleet — Euro 6 diesel cars, to calculate real NO_X emissions.

2.4 Calculation of NO_X emissions based on the findings of the ARTEM

Section 2.3.7 quantified the influences of individual parameters on the creation of NO_X emissions, and the results indicate that manipulations have by far the greatest influence. Therefore, the ARTEM is based solely on consistent scientific discoveries that include manipulations of ECSs of Euro 6 diesel cars, whose results and calculation methods can be validated. Since the database of registered vehicles does not record the information about which ECSs are implemented in an individual vehicle, three possible scenarios have been made to estimate the NO_X emissions of Euro 6 diesel cars. The calculation is limited to hot emissions in all scenarios because the experimental tests of cold-start emissions have not been considered. The following case scenarios are presented:

1) COPERT EF(v) — the best case,
2) HP and LP EGR OFF & DEF OFF — the worst case,
3) Lowering the fleet of manipulated Euro 6 diesel PCs to Euro 0.

The first scenario calculates NO_X emissions using COPERT EFs. It is the best scenario because it implies that all ECSs are active. In the second scenario — HP and LP EGR OFF & DEF OFF — the NO_X EFs from *JOURNAL PAPER III* were used. This scenario is the worst because it implies that all NO_X ECSs are deactivated. Without information on which ECSs are implemented in the vehicle, the third scenario is the only acceptable option. In this scenario, the NO_X EF is estimated by downgrading the vehicle's emission standard to Euro 0 level, providing a conservative estimate of NO_X emissions.

2.4.1 *Calculation of NO_X emissions for the COPERT EF(v) case scenario*

The COPERT was used to calculate NO_X emissions of Euro 6 diesel PCs — input data for Croatia in 2023, Table 14. All NO_X EF speed-dependent functions are according to the COPERT database. This scenario calculates the lowest emission values from the mentioned scenarios because it assumes no manipulated cars are in the vehicle fleet.

Table 14. Hot NO_X emissions of Euro 6 diesel PCs where all ECSs are active, according to COPERT calculation.

Case scenario 1	**Vehicle population (-)**		**Hot NO_X emissions (t)**	
Diesel PCs	Total	Manipulated	Total	Manipulated
Euro 6 a/b/c	206,681	0	2000	0
Euro 6 d-TEMP	51,204	0	68	0
Euro 6 d	38,018	0	41	0
All Euro 6	295,903	0	2109	0

2.4.2 *Calculation of NO_X emissions for the case scenario where HP EGR, LP EGR and the DEF are deactivated*

Assume that each Euro 6 diesel car — Euro 6 a/b/c, Euro 6d-TEMP and Euro 6d — with manipulated ECSs generates the same amount of NO_X emissions. In that case, NO_X emissions for case scenario two — HP EGR OFF, LP EGR OFF and DEF OFF — can be calculated by Equation (5). NO_X EF curve for case scenario two and official COPERT NO_X EF curves for diesel cars Euro 6 a/b/c, Euro 6d-TEMP and Euro 6d, are shown in Figure 18.

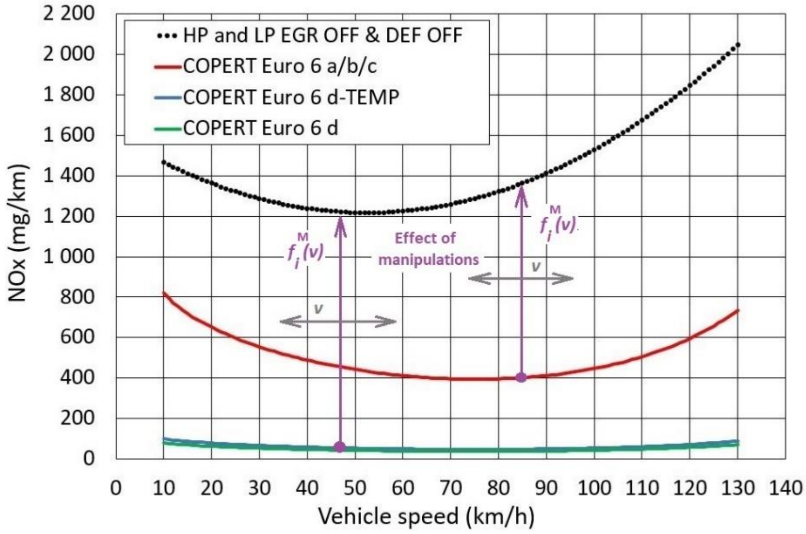


Figure 18. NO_X EF curve for case scenario two — HP EGR OFF, LP EGR OFF and DEF OFF — and official COPERT NO_X EF curves for diesel cars Euro 6 a/b/c, Euro 6d-TEMP and Euro 6d.

Applying Equation (1) and Equation (2) to the fleet segment of Euro 6 diesel cars with manipulated ECSs, Equation (7) can be formulated:

$$E^{\mathrm{D}}_{NOX_{i,r}}|_{v=\mathrm{const}} = EF^{\mathrm{D}}_{NOX_{i,r}}|_{v=\mathrm{const}} \times M_r \times N_{\mathrm{m}} \quad (7)$$

Where:

$E^{\mathrm{D}}_{NOX_{i,r}}|_{v=\mathrm{const}}$ = Hot NO_X emissions of vehicles with deactivated ECS of type i, driven on roads of type r (g),

$EF^{\mathrm{D}}_{NOX_{i,r}}|_{v=\mathrm{const}}$ = Hot NO_X EF of vehicles with deactivated ECS of type i, driven on roads of type r (g/km),

M_r = Mean annual mileage per vehicle driven on roads of type r (km),

N_{m} = Number of vehicles with manipulated ECS of type i in a year concerned.

Equation (7) calculates the hot NO_X emissions of manipulated vehicles and those of the total fleet of Euro 6 diesel PCs, Table 15.

Table 15. The hot NO_X emissions of Euro 6 diesel PCs with HP EGR, LP EGR and the DEF system deactivated.

Case scenario 2	**Vehicle population (-)**		**Hot NO_X emissions (t)**	
Diesel PCs	Total	Manipulated	Total	Manipulated
Euro 6 a/b/c	206,681	27,122	2402	664
Euro 6 d-TEMP	51,204	6719	264	205
Euro 6 d	38,018	4989	206	170
All Euro 6	295,903	38,830	2871	1039

In case scenario two, total NO_X emissions increased by approximately 36% compared to scenario one.

2.4.3 *Calculation of NO_X emissions for the case scenario where manipulated Euro 6 diesel PCs are downgraded to Euro 0*

In the absence of valid NO_X EFs of manipulated vehicles, lowering the Euro emission standard to Euro 0 according to Equation (6) can be applied to calculate their emissions. COPERT was used to calculate hot NO_X emissions, as shown in Table 16.

Table 16. Hot NO_X emissions of Euro 6 diesel PCs in a scenario where manipulated Euro 6 diesel cars are downgraded to the Euro 0 emission standard.

Case scenario 3	**Vehicle population (-)**		**Hot NO_X emissions (t)**	
Diesel PCs	Total	Manipulated	Total	Manipulated
Euro 6 a/b/c	206,681	27,122	2077	339
Euro 6 d-TEMP	51,204	6719	143	84
Euro 6 d	38,018	4989	99	63
All Euro 6	295,903	38,830	2319	486

In case scenario three, total NO_X emissions increased by approximately 10% compared to scenario one.

3 CONCLUSIONS

Existing models for estimating emissions from road transport are based on mean values of EFs and vehicle activities that cause emissions. The disadvantage of these models is that they usually use EFs obtained by measuring new and technically correct vehicles. In contrast, the EFs of used vehicles participating in traffic can significantly differ from the relevant COPERT EFs. In addition to EFs, annual distance travelled as a measure of vehicle activity varies significantly from vehicle to vehicle. Therefore, it is very important to know the actual annual distance travelled at the level of an individual vehicle.

The main objective of the research was to improve the model for calculating vehicle exhaust emissions from road transport by collecting, processing, and applying specific data, such as legislation data, results of periodic technical inspections of vehicles, OBD data, results of independent emissions measurements, vehicle user survey results, etc. Since the research began when the "Dieselgate" scandal and NO_X cheating were current, it focused on NO_X emissions of diesel PCs. Through quantitative and qualitative research and experimental tests, it was necessary to find parameters from real driving conditions that significantly affect the formation of NO_X emissions. For these purposes, the influence of individual parameters on the generation of emissions was analysed. Concerning the discoveries made as part of the conducted quantitative research and by conducting experimental tests in the laboratory and real driving conditions, new knowledge was gained about the influence of ECS manipulations on NO_X emissions. It has been scientifically proven that the effect of ECS manipulation on the formation of NO_X emissions is far greater than all other influential parameters investigated. Moreover, a new formula for calculating NO_X EFs of manipulated vehicles is set.

Considering the findings of the ARTEM, three scenarios were created to calculate the NO_X emissions of Euro 6 diesel cars. The first scenario represents emissions calculation according to the standard model using the existing COPERT EFs. In the remaining two scenarios — HP EGR, LP EGR and DEF deactivated, and Euro 6 diesel cars downgraded to Euro 0 — the ARTEM calculated NO_X emissions higher by 10% and 36%, respectively, compared to the standard COPERT model. In this way, the scientific contribution of the combined publications as a whole was realised — the initial hypotheses of the doctoral thesis were confirmed:

1. Collecting and processing data on vehicle use can contribute to creating more accurate models, and existing models for determining vehicle exhaust emissions from road transport could also be improved.

2. Using data from different sources and applying the ARTEM for calculating vehicle emissions from road transport makes it possible to estimate vehicle emissions in the observed area for a certain period with greater accuracy than existing models.

The doctoral thesis is based on three papers published in high-impact journals indexed in the Web of Science Core Collection database, four conference papers and one conference poster, all listed in the List of Publications and attached in the List of Appendices. The key results of individual papers and their partial scientific contribution are highlighted below.

JOURNAL PAPER I researched data on the vehicle population, vehicle age — Euro emission standard, roadworthiness, tailpipe test results, and changes in the structure of the Croatian road fleet during the period for which data is available. This article is important for achieving the research goal because, for the first time, the population of PCs in Croatia was calculated according to the Euro emission standard. Based on the internal method for determining the average annual mileage according to the COPERT nomenclature, *CONFERENCE PAPER I* presents data on the annual distance travelled by PCs. This article is important for achieving the research objective because it calculated the average annual mileage by PCs in Croatia at the individual vehicle level according to the Euro emission standard for the first time. Another important contribution of this article should be highlighted, which is the fulfilment of the prerequisites for using COPERT to calculate the annual emissions of PCs in Croatia. Thus, using PC population and mean annual mileage from the CVH database, as well as EFs and other predefined input data from the newer version of the COPERT 5 program, emissions of pollutants CO, NO_X, PM10, NH_3, VOC, NMVOC, greenhouse gas CO_2, as well as fuel consumption were calculated for the period from 2007 to 2016.

A study was conducted to detect high-polluting vehicles in the PC fleet, the results of which are presented in *CONFERENCE PAPER II*. This article's contribution to achieving the research objective is that it reduces the scope of the research and focuses on diesel cars. Data on the PC fleet that underwent PTI in January 2019 was gathered from the CVH database. Tailpipe and OBD test results were processed for petrol and diesel cars and shown in *CONFERENCE POSTER I*. The key results of this study indicate that the application of OBD tests can identify those Euro 3–Euro 6 vehicles in which the MIL is activated, which could cause excess pollution. The contribution of this article to the achievement of the research goal is that, for the first time, the possibilities of using OBD data to detect technically defective vehicles that cannot be detected by conventional test methods such as the tailpipe test have been investigated. The research results indicate that OBD tests can effectively replace conventional tailpipe emissions testing in Euro 6 vehicles.

After the initial research conducted in January 2019 on the possibilities of using OBD data during PTI, research on the wider application of OBD data followed. The OBD test results were collected and processed during the PTI of vehicles in Croatia 2020. The study included petrol and diesel cars that passed the tailpipe test, on which an OBD test was also performed, and the results are presented in the *CONFERENCE PAPER III*. The contribution of this article to the PTI of vehicles is that due to the significant number of vehicles with identified DTCs, a new and more efficient method for detecting potentially defective vehicles has been suggested. The introduction of the OBD test as mandatory for all vehicles equipped with an EOBD system is proposed. In addition to the existing OBD data, it is recommended that the number of DTCs be introduced as mandatory, and such data should be relevant for passing the roadworthiness test. The contribution of this article to the realisation of the research goal is that it was also concluded by applying OBD tests that diesel cars are more prone to malfunction and that they are justified candidates for further research on harmful emissions. The results presented in *CONFERENCE PAPER IV* indicate a significant number of vehicles on which certain modifications are performed, and the impact of such modifications on emissions has not yet been sufficiently investigated. Manipulations of ECSs of in-use vehicles are still a taboo subject that science and legislation do not address sufficiently. Therefore, the need to conduct experimental tests to measure the emissions of vehicles that have undergone certain modifications is justified.

The EGR is a known method of reducing NO_X, but the impact of its deactivation on emissions has not been quantified. Due to this, an evaluation of the effect of EGR valve manipulation on NO_X emissions in a Euro 5 diesel PC under stationary and transient engine operating conditions measuring emissions on a chassis dynamometer was performed. The results of this study are shown in *JOURNAL PAPER II*. An important contribution of this work to achieving the research goal is discovering a functional relationship between NO_X emissions of vehicles with an activated and deactivated EGR valve. The results point to the need for a correction of the NO_X EFs, which should include the factor of increased emissions due to manipulations. Although the number of studies investigating the effects of manipulation on vehicle ECSs has increased in recent years, the question of quantifying such vehicles on the road and modelling their emissions remains topical. Extensive research was conducted on a Euro 6 diesel car with a combination of manipulated ECSs to determine the influence of ECS manipulations on NO_X

emissions under real driving conditions. The research results are presented in *JOURNAL PAPER III*. The contribution of this study to accomplishing the research objective is that it has been proven that driving dynamics on the RDE route could significantly affect NO_X emissions in vehicles with deactivated ECSs. Given these results, the RDE data should be used instead of the constant-speed data to calculate emissions from manipulated vehicles. The results from *JOURNAL PAPER III* also contribute to a better understanding of how increasing vehicle mass has a negligible impact on NO_X emissions compared to the increase in emissions caused by manipulations of the ECSs. The significance of this study for the realisation of the research goal is that the emissions of vehicles with different combinations of deactivated ECSs were quantified in real driving conditions, and it was pointed out that such modifications can cause a multiple increase in NO_X emissions, even more than two orders of magnitude.

Comprehensive research results emerged while preparing the doctoral thesis, generating new scientific questions. According to the COPERT model, the vehicle's EF is the most important parameter, apart from the annual distance travelled. Since the annual distance covered by each vehicle is recorded during the PTI, it is reliable data that can be used at the individual vehicle level. However, experimental test results indicate that actual NO_X EFs can differ drastically from those listed in the COPERT database, especially if ECS manipulations are considered. The proposal is to implement quick NO_X measurements as part of PTI to detect vehicles with high NO_X pollution in the fleet. This way, high-polluting vehicles would be assigned an EF of increased value, enabling a more precise calculation of NO_X emissions at the individual vehicle level. The method for estimating NO_X emissions of manipulated Euro 6 diesel PCs presented in this PhD thesis can be applied to other vehicle categories, exhaust components and pollutants to obtain more accurate fleet emission values. An external evaluation, i.e., an inter-laboratory comparison of the results, is necessary to validate the presented method and ensure its official application.

Considering that the number of Euro 6 diesel vehicles will increase in the coming years, and the tendencies towards manipulations will continue, it can be concluded that the NO_X emissions of the vehicle fleet will also increase. Detecting such vehicles during PTI is far more important than the emissions calculation. Such an implementation would reduce the tendency to manipulations and encourage vehicle maintenance, and consequently significantly reduce actual emissions. In addition, vehicle users would be more inclined to buy vehicles that satisfy their needs and manner of use. For example, it has been proven that ECSs in diesel cars are prone to failure when the vehicle is used mainly in urban driving mode. Therefore, it is more appropriate to choose alternative solutions for urban driving. Although we are gradually moving from fossil fuel vehicles to EVs, this process is taking place too slowly, considering the requirements imposed by the legislation. In any case, vehicles powered by fossil fuels will be on the road for a long time. For this reason, it is necessary to conduct scientific research and apply their results in practice to reduce their harmful impact on the environment and human health as much as possible.

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BIOGRAPHY

Marko Rešetar was born on 19 November 1990 in Vinkovci, Croatia. He attended elementary school in Ljubešćica and the Secondary School for Electromechanical Engineering in Varaždin. After graduating from secondary school, he became a mechatronics technician. From 2009 to 2013, he completed undergraduate studies at the Faculty of Mechanical Engineering and Naval Architecture at the University of Zagreb. He graduated from the same faculty with a master's degree in mechanical engineering in 2015. Since 2015, he has been working as an expert employee in the Testing department of the CVH, where he deals with the testing and approval of vehicles and ADAS/AD testing. In the same year, he enrolled in doctoral studies at the abovementioned faculty. The field of research he dealt with during his doctoral studies is road transport emissions. During his doctoral studies, he participated in several international conferences and workshops. As the main author, he published eight scientific papers in journals and at international conferences. He is a member of the non-profit associations Croatian Metrology Society (HMD) and Croatian Society for Motors and Vehicles (HDMV). He speaks and writes in Croatian, English and German.

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LIST OF APPENDICES

JOURNAL PAPER I (Published journal article)

Changes and trends in the Croatian road vehicle fleet — Need for change of policy measures

JOURNAL PAPER II (Published journal article)

Increase in nitrogen oxides due to exhaust gas recirculation valve manipulation

JOURNAL PAPER III (Published journal article)

An estimate of the NO_X emissions of Euro 6 diesel passenger cars with manipulated emission control systems

CONFERENCE PAPER I

Road transport emissions of passenger cars in the Republic of Croatia

CONFERENCE PAPER II

The influence of passenger car population and their activities on NO_X and PM emissions (Data from Croatia)

CONFERENCE PAPER III

A new method for emission control system malfunction detection during the periodic technical inspection

CONFERENCE PAPER IV

Non-professional modifications of passenger cars

CONFERENCE POSTER I

Primary results of OBD tests collected during PTI of vehicles in Croatia

Article I (Published journal article)

Changes and trends in the Croatian road vehicle fleet — Need for change of policy measures

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Changes and trends in the Croatian road vehicle fleet – Need for change of policy measures

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ABSTRACT

Careful consideration was given to the impact of the structure of Croatian road vehicle fleet on traffic safety, as well as on the environment and human health. The 2008 economic crisis and the consequences of Croatia's accession to the EU in 2013 were studied as the factors leading to unfavourable trends and changes in vehicle structure. In accordance with the national policy measures, the highest levies have been imposed on new vehicles. With the age of the vehicle there is a reduction in taxes, while vehicles older than 10 years have been exempted from taxes. Combinations of such unfavourable aspects have resulted in an increase in technical defectiveness and ecological unfriendliness of vehicles. Increasing technical defectiveness of vehicles directly reduces traffic safety. The impact of changes in vehicle structure on traffic safety, as well as on the environment and human health, was analysed on the basis of processed data from the Centre for Vehicles of Croatia (CVH). The results of the study indicate the consequences of adverse changes in vehicle structure through emissions, technical roadworthiness of vehicles and the number of fatalities in road traffic. Comprehensible and decisive national policy measures are required in order to reverse the adverse trends.

1. Introduction

The data from technical inspections of vehicles were a prerequisite for studying the changes and trends of the road vehicle fleet in Croatia. The long tradition of technical inspections of vehicles on the territory of today's Republic of Croatia dates back to the 1950s, when the first controls of the vehicle's technical roadworthiness were performed on the roads. The first technical inspection stations began to open in the 1960s. The condition of the body and roadworthiness of basic vehicle assemblies were inspected in such stations. In 1968 there were 43 organisations authorised to carry out technical inspections of vehicles. The need for continuous monitoring of the development of vehicle products and technology of technical inspection implementation was recognised at the beginning of the 1970s. Consequently, Vehicle Roadworthiness Centre, a business association of vehicle inspection stations, was established in 1971. The system was integrated with the aim of organising and expertly monitoring the activities of vehicle inspection stations, conducting vehicle testing, conducting continuous training of technical roadworthiness supervisors and maintaining the testing equipment in the stations, in accordance with the regulations concerning road traffic safety. As a result, Croatia ranked among the few countries in Europe where organised periodic vehicle inspections were carried out at the time. It should be noted that, from its very beginning, the Vehicle Roadworthiness Centre was organised according to a similar model such as Technischer Überwachungs-Verein (TÜV), DEutscher KRAftfahrzeug-Überwachungsverein (DEKRA), Rijks Dienst Wegverkeer (RDW) and other European institutions dealing with vehicle roadworthiness. Moreover, the Vehicle Roadworthiness Centre was the only organisation in Croatia authorised to organise a unique system of vehicle inspections throughout the Croatian territory. On the other hand, certain countries have not managed to organise a unique system of technical inspections to this very day (Selim et al., 2011). In 1978, the Vehicle Roadworthiness Centre changed its name to Centre for Vehicles of Croatia (CVH) under which it still operates today.

The organisation of work improved with the unique vehicle inspection report coming into use in 1979, which contributed to the harmonisation of technical inspection process and enabled subsequent management of detailed statistics on the Croatian vehicle fleet. In the period of 15 years since the establishment of the Vehicle Roadworthiness Centre, great progress has been made in the area of vehicle inspections. The number of periodic technical inspections increased almost three-fold because of the sudden growth of the vehicle fleet. For these reasons, there was a need to open new technical inspection stations. From 1971 to 1986 the number of stations increased

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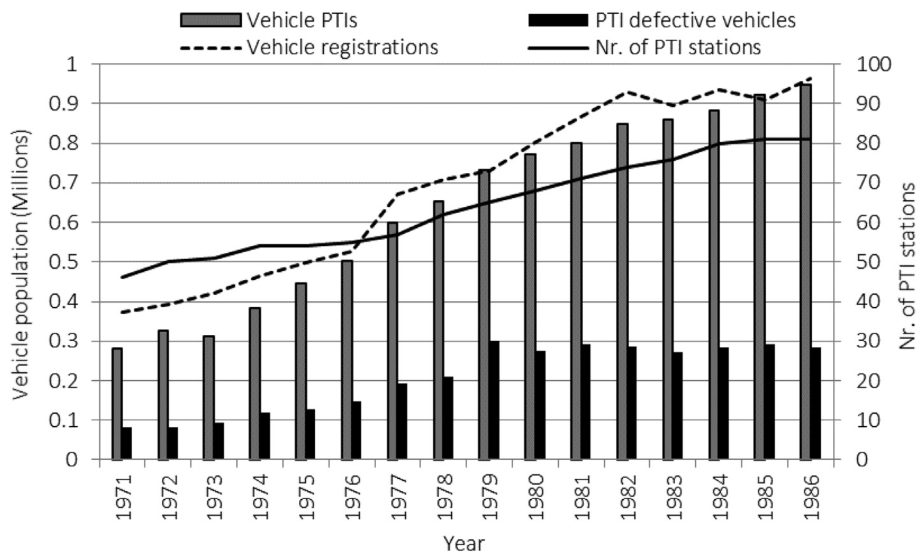

Fig. 1. The number of periodic technical inspections (PTIs), the number of defective vehicles in periodic technical inspections, the number of registered vehicles, and the number of technical inspection stations for the period 1971–1986.

from 46 to 81. Fig. 1 shows the number of conducted vehicle inspections, the number of technically defective vehicles, the number of registered vehicles, and the number of periodic technical inspection stations, for the period from 1971 to 1986.

Over one million of technical inspections were carried out in 1987. The data for the period from 1987 to 1995 are incomplete because a part of the data was permanently destroyed during the Croatian war of independence. However, it is a well-known fact that a decrease in the number of vehicle inspections was recorded in the period from 1990 to 1995 due to the war in Croatia, as well as a decrease in the number of technical inspection stations as they were damaged or destroyed in the war.

Since the end of the Croatian war of independence, that is, in the last 20 years there has been a continuous increase in the number of vehicles and vehicle inspections, as well as in the number of technical inspection stations, as can be seen in Fig. 2. The data on the number of registered vehicles are "sensitive" to legal changes related to vehicle registration and deregistration. Since 2011, the Ministry of Interior has systematically deregistered vehicles the registration certificates of which expired more than one year ago. Until then, this was not the case, which led to a significant difference between the number of technical inspections and the number of registered vehicles. Therefore, until 2012, the number of periodic technical inspections was significantly lower than the number of registered vehicles.

In order to facilitate a simpler storage of vehicle inspection data, in 1995 CVH initiated the process of introducing a unique information system for the electronic storage of data on vehicles and vehicle inspections. Consequently, since September 1997, CVH has had complete control over the data on the Croatian vehicle fleet. Modernisation of the established IT system was carried out in the period from 2005 to 2007. Today, this is a modern relational database that enables entry of all relevant data related to vehicle roadworthiness. On the other hand, after 10 years of making the latest version, the said database enables direct search and retrieval of data that are not immediately apparent. The latest version allows access to the raw data on vehicle fleet, the processing of which may bring about various studies, as is the case in the UK (Chatterton et al., 2015). Fig. 3 shows the timeline with highlighted key events and activities of CVH.

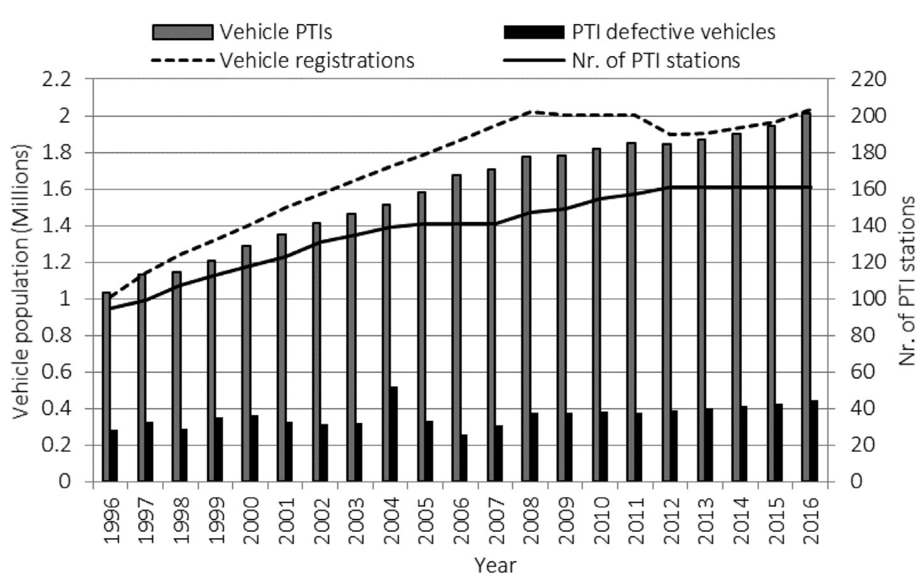

Fig. 2. The number of periodical technical inspections (PTIs), the number of defective vehicles in periodical technical inspections, the number of registered vehicles and the number of PTI stations for the period from 1996 to 2016.

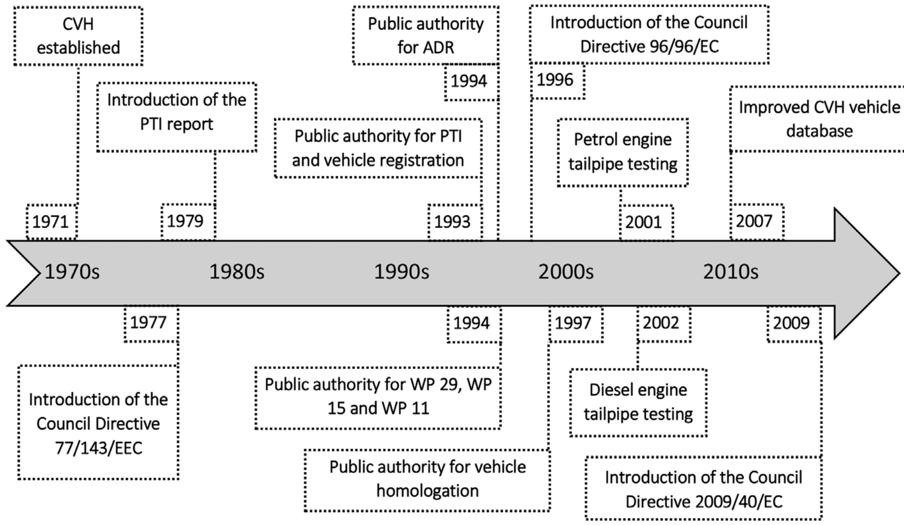

Fig. 3. CVH milestones from the 1970s to the 2010s.

From the very beginning, the development of the vehicle inspection system in Croatia was based on the experiences of the German model and similar models of other European countries (Sweden, Belgium, the Netherlands, etc.). For these reasons, the technical inspection system did not undergo significant changes after Croatia's accession to the European Union (the EU), as opposed to the systems of some other EU member states.

Vehicle inspections in Croatia, aimed at checking technical roadworthiness and ecological compliance of vehicles, are entirely regulated by law and bylaws, which are in line with the relevant EU Directives. Technical inspections are carried out on vehicles of all categories (L, M, N, O, T), except for work machineries. During a technical inspection, it is determined whether a vehicle has the required devices and equipment, whether such devices and equipment are functioning and whether they meet the defined conditions for participation in road traffic.

Technical inspections of L-, M-, N-, T-category motor vehicles and O2-, O3- and O4-category trailers in Croatia are carried out once a year. Despite the raised question concerning the cost-effectiveness of conducting technical inspections once a year, some studies point to the advantages that could be gained if a technical inspection was performed even more frequently (Keall and Newstead, 2013). On the other hand, in Norway cars should undergo an inspection every second year, starting the fourth year after the car was first registered (Christensen and Elvik, 2007). In Croatia, new vehicles undergo periodic technical inspection after two years following the first technical inspection and then once a year. Exceptions are M2-, M3-, N2-, N3-category vehicles, as well as medical emergency vehicles and taxis, which are subject to periodic technical inspection each year. In addition, periodic technical inspection of O1-category trailers is performed every three years after the first technical inspection. Work machineries are not subject to technical inspections.

CVH provides professional and logistic support to all vehicle inspection stations in the Republic of Croatia, continuously issues expert instructions on conducting vehicle inspections and related activities, maintains and calibrates test equipment in the stations, provides adequate IT and technical support for the implementation of activities in the stations, conducts training of the existing and future employees and introduces new technologies to the vehicle inspection procedure and related activities.

Today, the technical inspection system in Croatia is comparable to the system of any EU member country and is fully in line with the existing European legislation. The system comprises 159 stations for periodic technical inspection and 9 stations for preventive technical inspection, with over 1600 employees and two professional organisations, Centre for Vehicles of Croatia (CVH) and the Croatian Auto Club (HAK) which supervises the operation of technical inspection stations.

2. Methodology and data sources

During the first periodic vehicle inspection, the set of data from the certificate of conformity (CoC), manufacturer's certificate of origin or vehicle technical specification is entered in the internal (electronic) vehicle database. The system for data downloading by vehicle dealership is fully automated through web service to avoid the possibility of errors in copying. After each technical inspection performed, the measurement data and the identified deficiencies are entered in the internal (electronic) database of technical inspections. If a vehicle has been modified in the course of its utilisation, as compared to the condition recorded in the previous technical inspection, such vehicle is subject to testing. After the testing, the modifications are recorded and entered in the vehicle database. This method allows monitoring of the vehicle's condition and technical characteristics throughout the life-cycle of the vehicle. Fig. 4 shows the data collection scheme used for vehicle inspections.

Each vehicle is defined by a unique Vehicle Identification Number (VIN) and a corresponding identifier which can interconnect the data from the vehicle database and the data from the technical inspection database. Thus, when applying for a technical inspection, first the data on the relevant vehicle is copied from the vehicle database, and after the technical inspection is performed, the results are entered in the technical inspection database. Some of the data contained in the vehicle

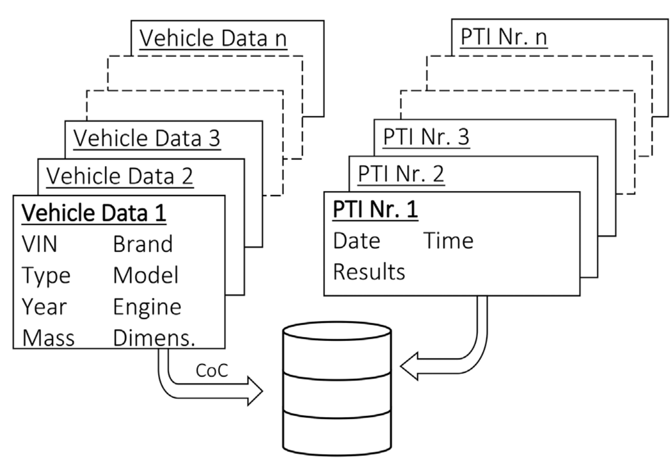

Fig. 4. Scheme of CVH database system with vehicle and PTI data.

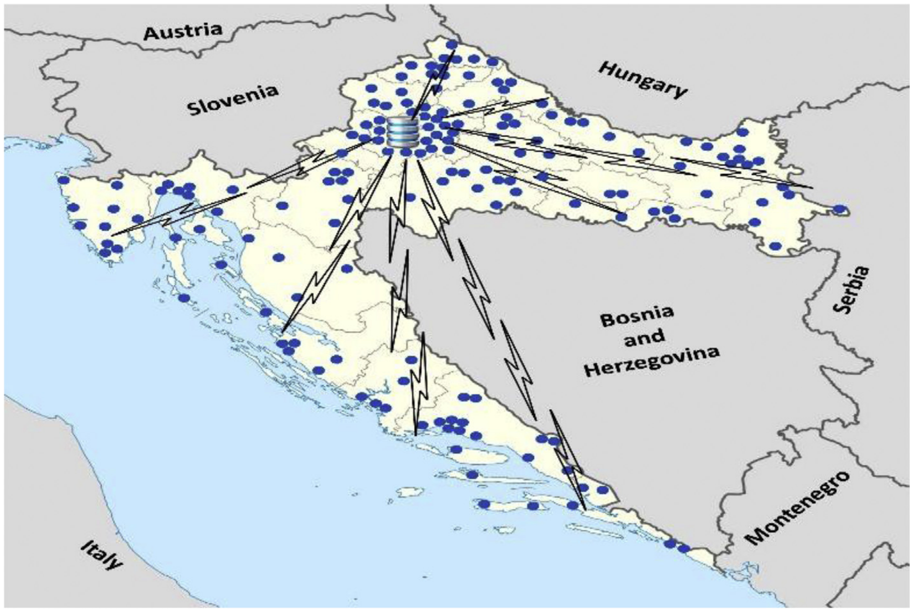

Fig. 5. PTI station locations and central data collection within an internal IT system.

database are the following: ID, VIN, registration plate, vehicle category, brand, type, model, year of production/first registration in Croatia, mass and dimension, engine, top speed, etc. Some of the data to be entered in the technical inspection database are the following: ID, type of PTI, PTI station location ID, PTI date and time, mileage, tailpipe test results, brake test results, brake fluid's boiling point, test results for shock absorbers, and all detected faults.

The data on vehicles and technical inspection results are collected in each technical inspection station. Use of a unique IT system enables data input in electronic form, and all data are stored on the central server, Fig. 5.

Therefore, systematic data collection during vehicle inspections has provided the prerequisites for the analysis of the structure of the Croatian vehicle fleet.

3. Results and comparison data

3.1. Changes and trends of road vehicle fleet structure and vehicle aging

The following types of vehicles for a period of 20 years, i.e. from 1996 to 2016, were analysed: mopeds and motorcycles (L), passenger cars (M1), buses (M2, M3), trucks and vans (N), tractors (T) and trailers and semi-trailers (O). Fig. 6 shows the structure of vehicles according to vehicle categories. In this paper are used standard ECE (Economic Commission for Europe) categories of vehicles (L, M, N, T and O), and due to its practical use instead of the M1 category, the title "Passenger Cars or abbrev. PCs" is used. There is an evident proportion between the numbers of vehicles by categories, as well as an almost constant increase in the number of vehicles in each vehicle category, PCs in particular. However, the impact of the global economic crisis which affected Croatia is evident in the period from 2008 to 2013 in which the number of vehicles did not change significantly.

Average age of all road vehicles in Croatia in 2016 was 13.76 years. Passenger cars are slightly younger, with average age of 12.76 years. A significant discrepancy is observed in comparison with the EU where PCs were on average 9.73 (Statista, 2017) or 10.7 (ACEA, 2016) years old in 2015. Such a big difference in average age between the Statista and ACEA data for years 2013, 2014 and 2015 is because ACEA uses revised data which also taken into account import of used PCs in

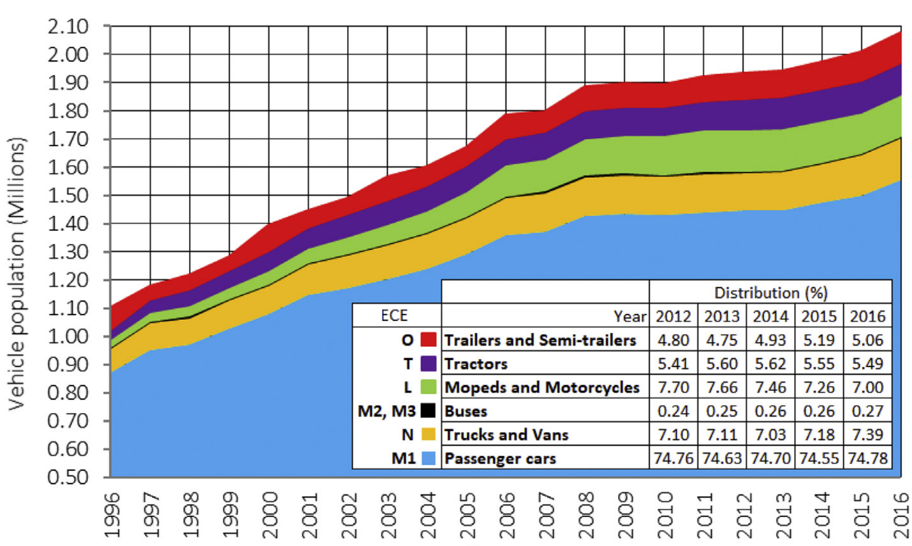

Fig. 6. Vehicle fleet in Croatia according to vehicle categories – PTI data.

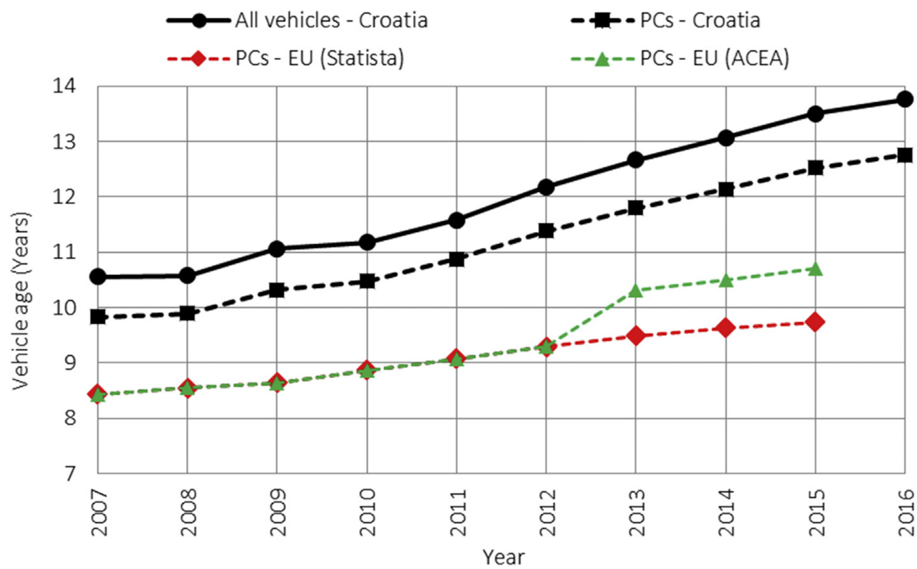

Fig. 7. Comparison of average vehicle age between Croatia and the EU.

eastern European countries. It is evident in Fig. 7 that the vehicle age in Croatia has constantly been increasing since 2010 and there have been increasing discrepancies in relation to the EU average because of the consequence of the 2008 economic crisis. When Croatia joined the EU in 2013, that trend continued because of imports of older used vehicles. The reason for the sudden increase in imports of older used vehicles from the EU was a provision that had been in force until the accession to the EU. In accordance with the said provision, import of vehicles that did not meet at least the Euro 3 ecological standard was banned. Upon the accession to the EU, subject to the requirement for the free movement of people and goods, the said provision was abolished, thus allowing imports of cheaper but also very old vehicles which meet only the lower emission standards.

3.2. Changes and trends of PC fleet

A change in the vehicle fleet structure of M1 category was analysed based on the data on the number of newly registered PCs. Column chart in Fig. 8 shows both the number of newly registered petrol and diesel PCs and their mutual relationship. The unfavourable trend of changing the vehicle fleet structure has been observed since 2008 (when the global economic crisis occurred), and this trend has continued in Croatia to this very day. Thus, the reduced sale of new vehicles over the past 7 years has had a tremendous impact on the increase in vehicle age in Croatia. It is evident in Fig. 8 that 2009 saw a drop in the number of newly registered cars by almost 50% compared to 2008. Also, it can be observed that after 2012 and the long-lasting dominance of petrol cars, the number of newly registered diesel cars exceeded the number of newly registered petrol cars, and this trend continued. The reason for this change lies in the lower price of diesel fuel compared to petrol, as well as in the technological level with which new diesel engines significantly reduce fuel consumption. Some countries even prompted the improvement of on-road fuel efficiency. For example, the Spanish Government issued a dieselization policy for the period from 1998 to 2006 to reduce CO_2 emissions (Clerides and Zachariadis, 2008; Fontaras and Samaras, 2007). For that reason, the effect of dieselization

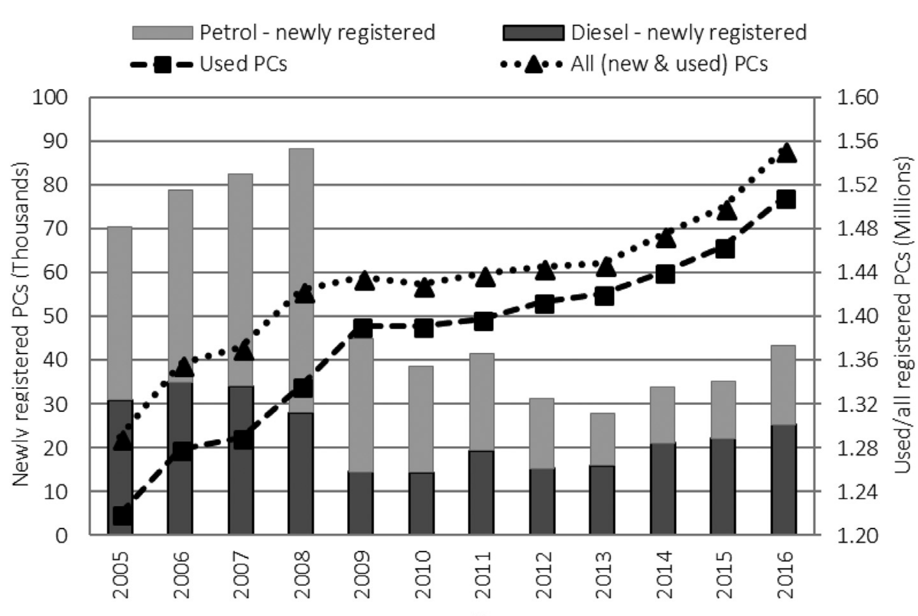

Fig. 8. The number of newly registered petrol and diesel PCs, the number of used PCs and the total number of PCs (newly registered + used).

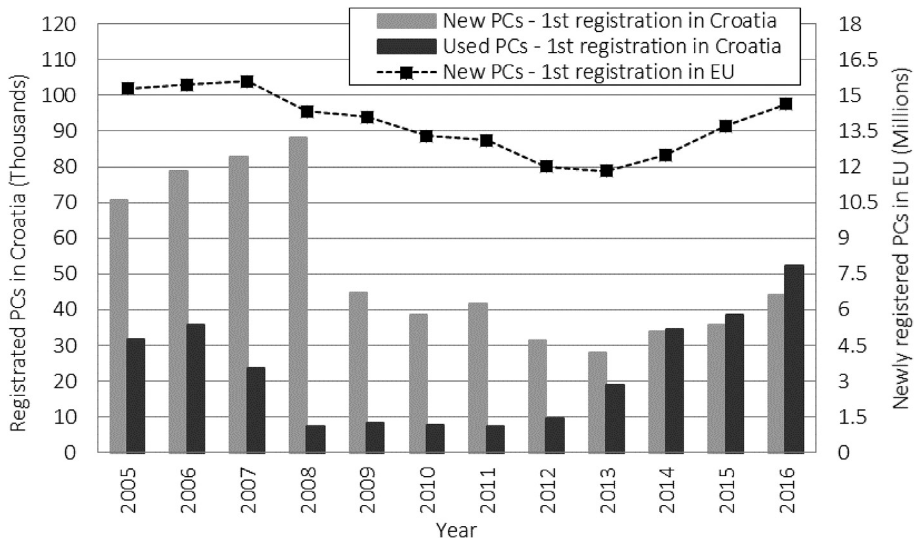

Fig. 9. The number of new and used PCs with the first registration in Croatia and the number of new PCs with the first registration in the EU.

on emissions in Spanish PC fleet was investigated (González and Marrero, 2012). Moreover, Zervas determined the CO_2 benefit from the increasing percentage of diesel PCs in Ireland (Zervas, 2006). However, in the past few years measurements of emissions from actual driving conditions have revealed the disadvantages of diesel PCs in terms of NO_x emissions (O'Driscoll et al., 2016; Weiss et al., 2012). Consequently, there is an ever increasing pressure on diesel-fuelled PCs and new studies focus on alternative energy sources (Datta and Mandal, 2016; Ugurlu and Oztuna, 2015; Windecker and Ruder, 2013). On the other hand, some of the studies point to the under-taxation of diesel vehicles considering air pollution, congestion, accidents, noise and climate change (Santos, 2017). Santos case study indicates that most of the marginal external cost of transport comes from congestion and accidents. Neither of these externalities is included in a road fuel taxation in the Republic of Croatia.

Fig. 8 also shows the number of all (newly registered + used) PCs and used cars, as well as the ratio between them. There is evident trend of an increase in the number of used cars until 2009. In the next five years, there was no significant change in the number of vehicles, until 2013 when Croatia became a full member of the EU. An increased import of older used cars followed, which further increased the age of the vehicle fleet, and this trend has continued to this day.

By 2008, the purchase of new cars maintained a significant difference in relation to the number of used PCs and all PCs. However, in 2009 this difference was almost halved and until today it has not changed significantly. If attention is paid to the number of newly registered cars in the period from 2005 to 2008, as well as in the period from 2008 until today, the above-stated reasons for the unfavourable trend and the adverse changes in vehicle structure are clearly visible.

Fig. 9 shows the number of new and used PCs with the first registration in Croatia, as well as the ratio between them. Based on their ratio alone, it can be concluded that in 2008 the number of new cars was almost 12 times higher than the number of used cars. However, in just a few years, the number of used cars surpassed the number of new cars, and the trend is still unfavourable. The reason for this is the consequence of Croatia's accession to the EU, which enabled an intensive import of old used vehicles from the EU.

Fig. 9 also shows the number of new PCs with the first registration in the EU (ICCT, 2016). It is evident that the impact of the 2008 economic crisis was stronger in Croatia than in the EU. The number of new cars with the first registration in Croatia in 2009 was about 50% lower than in 2008, while in the EU this ratio was far lower.

The parameter by which it is possible to influence a changes and trends of the PC fleet is special ecological fee according to CO_2

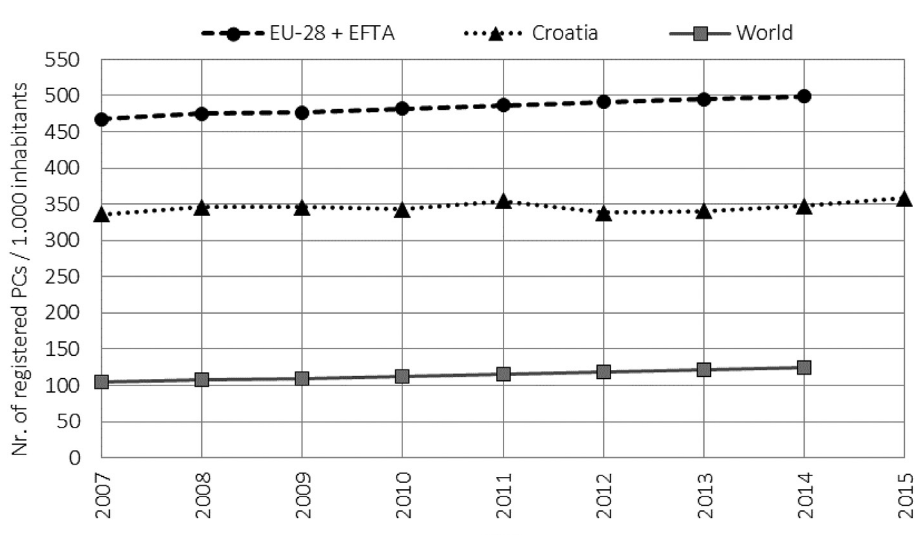

Fig. 10. Comparison of registered PCs per 1000 inhabitants for EU-28 + EFTA member countries, Croatia and the world.

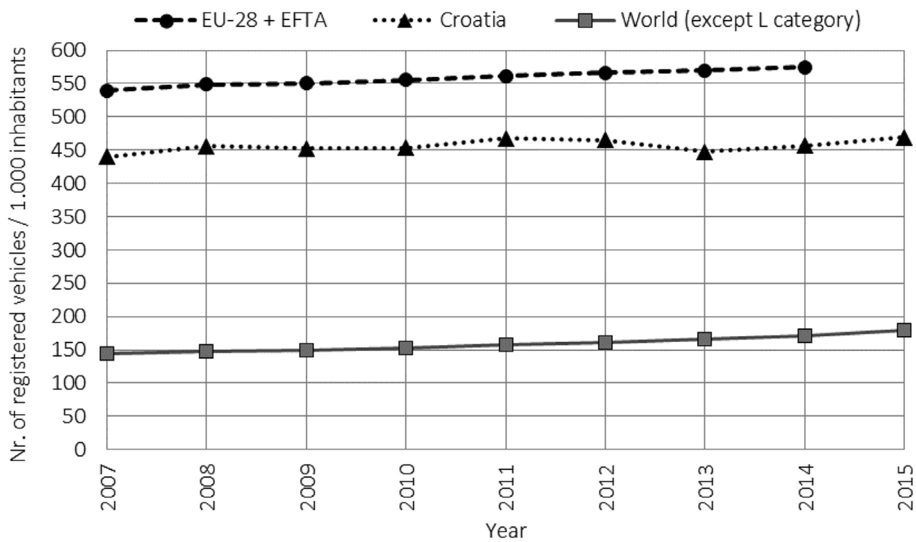

Fig. 11. Comparison of all registered vehicles per 1000 inhabitants for EU-28 + EFTA member countries, Croatia and the world.

emission. Unfortunately, the special ecological fee is set by Ministry of environmental protection, and it is relatively cheap (even for Croatia). This small fee is not expansive enough to be the driving force for vehicles owners to change their minds. Namely, if the fee for three or four years makes significant amount the owners could calculate that it is more economical to have “more ecological” vehicles and pay less for the fees. Currently, the price range for the special ecological fee is from around 5.00 EUR to almost 100.00 EUR. So, even paying a highest ecological fee for a few years won't make an impact that it will be cheaper to buy a more ecological vehicle.

3.3. Predictions of change in vehicle fleet structure over the next few years

Based on the data on the number of newly registered PCs in 2016 and the comparison with the number of newly registered PCs in 2015, a significant increase in both is evident. In 2016, the number of PC registrations increased by as much as 23.5% compared to 2015. If this trend continues, the number of newly registered PCs should increase in the coming years. This is also evidenced by the results of previous studies (Pukšec et al., 2013). However, at the same time, the change in the number of used vehicles that are first registered in Croatia should be monitored as well. These two data reflect the general condition of the vehicle fleet structure, which can be observed in Fig. 9. The number of used PCs in 2013 increased by nearly 100% compared to 2012. By 2014, the number of used PCs with the first registration in Croatia exceeded the number of newly registered PCs. Given that the average age of PCs has grown steadily for years, it is clear that the vehicle fleet is not, in principle, renewed with newer vehicles, but quite the contrary. It is evident that, if the prices of imported used vehicles continue to fall, the age of the Croatian vehicle fleet will increase in the coming years. It is, therefore, necessary to introduce certain financial measures that discourage the import of older used vehicles but stimulate the purchase of new vehicles with low emissions.

3.4. Ratio between the number of vehicles and the number of inhabitants (vehicle ownership density)

The number of vehicles per capita is one of the indicators of a country's development. It is, therefore, interesting to consider the ratio between the number of vehicles and the number of inhabitants in Croatia and to compare it with the EU-28 member countries and EFTA[1] member countries and the world.

The number of registered vehicles per 1000 inhabitants for the aforementioned member countries was calculated by using the data on the population of EU-28 member countries (Eurostat, 2016) and EFTA member countries (Switzerland, Norway, Iceland and Liechtenstein) (The World Bank, 2016), as well as the data on the number of registered vehicles for EU-28 member countries and EFTA member countries (OICA, 2016). Moreover, the number of registered vehicles per 1000 inhabitants of the world was calculated by using the data on the total world population (The World Bank, 2016) and the data on the number of registered vehicles worldwide (OICA, 2016). In addition, the number of registered vehicles per 1000 inhabitants in Croatia was calculated by using the data on the population of Croatia (The World Bank, 2016) and the data on the number of registered vehicles in Croatia (Croatian Bureau of Statistics, 2016).

Fig. 10 shows a comparison of the number of registered PCs per 1000 inhabitants for the aforementioned member countries, Croatia and the world.

It is evident in Fig. 10 that the number of registered PCs per 1000 inhabitants in Croatia in about three-fold compared to the world average. However, compared to the average state of the EU-28 + EFTA member countries, Croatia has about 150 PCs per 1000 inhabitants fewer, and thus is significantly below the average.

Fig. 11 shows a comparison of the number of all registered vehicles per 1000 inhabitants for the aforementioned EU-28 + EFTA member countries, Croatia and the world.

The current trends in the Republic of Croatia are a decrease in the number of inhabitants and aging of the population due to youth emigration. In the near future, this could have a significant impact on reducing the number of registered vehicles per 1000 inhabitants as well as on increasing the age of vehicles. In fact, similar demographic trends are also present in other countries, such as in Japan (Yagi and Managi, 2016).

3.5. Correlation between the number of vehicles and GDP

It has been proven that there is an evident correlation between the number of vehicles and GDP. In most countries, increase in the number

[1] The European Free Trade Association (EFTA) is an intergovernmental organisation set up for the promotion of free trade and economic integration to the benefit of its four Member States: Norway, Switzerland, Iceland and Liechtenstein.

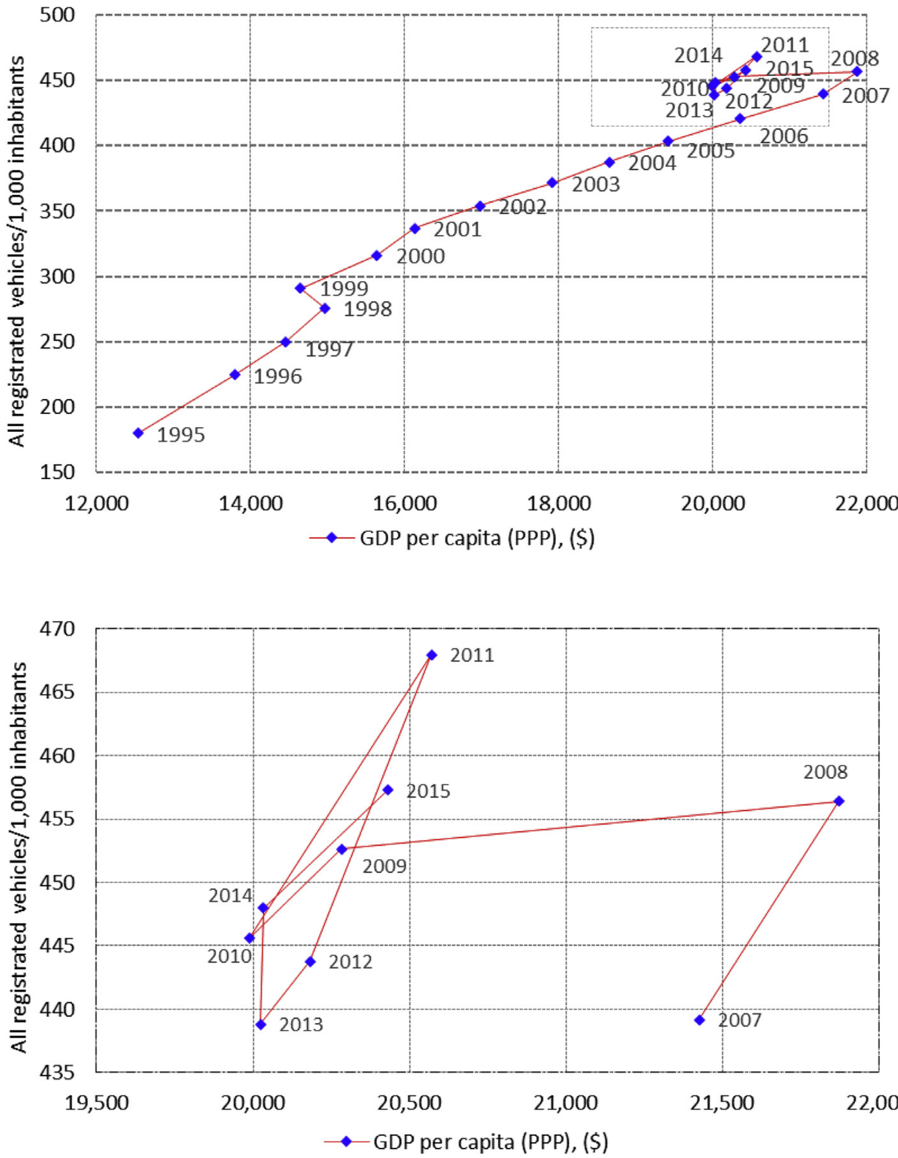

Fig. 12. Relation between vehicle fleet per capita and GDP per capita in Croatia for the period 1995–2015 (top chart) and separately for the period 2007–2015 (bottom chart).

of vehicles is proportional to the GDP growth, theoretically according to the Gompertz curve (Wu et al., 2014). However, in order to demonstrate the above-mentioned correlation, it is necessary to observe a longer period of time. Reliable data on the number of inhabitants, the number of registered vehicles and GDP per capita in Croatia is available only for the period since 1995 (Croatian Bureau of Statistics, 2016; The World Bank, 2016). Thus, Fig. 12 shows relation between the number of all registered vehicles per 1,000 inhabitants and GDP per capita in the period from 1995 to 2015. For the mentioned period a strong positive correlation between GDP per capita and number of registered vehicles per 1,000 inhabitants was determined. Although it seems that there are two significantly different periods from 1995 to 2008 and from 2009 to 2015. The analysis shows that correlation coefficient r does not change much for those two periods as well as for whole period. ($r_{1995-2008} = 0.9763$; $r_{2009-2015} = 0.9077$; $r_{1995-2008} = 0.9776$).

The reason for deviation in the period from 2008 to 2015 is the impact of the economic crisis that hit Europe in 2008 (Crescenzi et al., 2016) and took a heavy toll on Croatia.

Data for several EU member countries was collected and processed for the purpose of demonstrating relation of the number of vehicles with GDP and making a comparison with Croatia. Fig. 13 shows relation of the number of PCs per 1,000 inhabitants with GDP per capita in the period 2007–2014.

It is evident that in most of the listed countries there was a corresponding relation of the number of PCs per 1000 inhabitants with GDP per capita and that the number of vehicles increased with the GDP growth. However, in some countries (Hungary, Croatia) there is no apparent relation in the period from 2007 to 2014 as can be seen in Fig. 13. As regards Croatia, the reason for this is a significant long-term recovery from the economic crisis. Most EU countries overcame the crisis in 2–3 years, which was not the case in Croatia.

A qualitative relation between the relative change in the number of newly registered PCs and the relative change of GDP in Croatia in the period 2008–2016 is noticeable upon their concurrent analysis, as shown in Fig. 14. There is a significant and positive correlation between the annual GDP growth rate and relative change of newly registered PCs. The statistical analysis shows that the correlation coefficient r for those two variables $r = 0.8841$ and that correlation is significant. Thus, the change in GDP has a significant impact on the change in the number of newly registered vehicles.

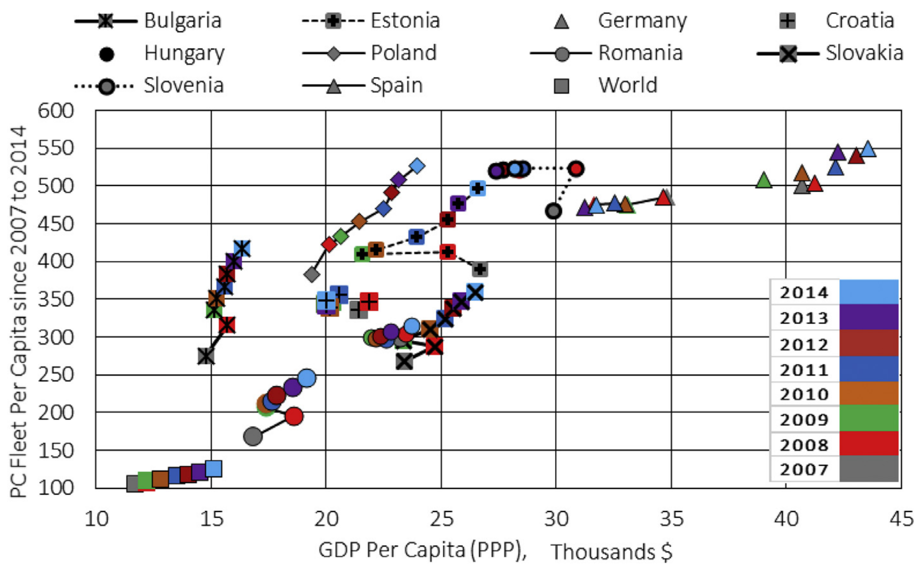

Fig. 13. Relation between PCs per capita and GDP per capita (2007–2014).

Fig. 14. Relative change in the number of newly registered PCs and in GDP in Croatia for the period from 2008 to 2016.

3.6. *Impact of vehicle age on technical roadworthiness*

An important indicator of the vehicle fleet condition is the average vehicle age. Every vehicle to be registered has to be technically roadworthy. The vehicle's technical roadworthiness is checked for parts, devices and assemblies such as the steering device, braking device, lighting and light-signalling device, engine, exhaust gas aftertreatment systems, chassis, suspension parts, gearbox, vehicle equipment, etc. When checking technical roadworthiness, all observed deficiencies are noted. Some of the deficiencies are tolerated, but for the majority there is no tolerance and the vehicle is declared technically defective, and the user is referred to the service centre (garage) in order to repair founded deficiencies.

More than three decades ago, DEKRA's results indicated the impact of vehicle age on the number of traffic accidents (Grandel, 1985). Potential link between the average vehicle age and the percentage of technically defective vehicles was studied in view of the constant increase in the average vehicle age in Croatia which has been recorded in the last decade. Since CVH has been keeping the statistics of vehicle inspection results for many years, these data were used to show the correlation of vehicle age on technical defectiveness. The study showed a qualitative link between the stated two values, as presented in Fig. 15.

For the period from 2006 to 2016 the average age of the vehicle fleet in Croatia steadily increases. Similar can be seen with the percentage of technically defective vehicles during PTI. It is notable that in the last eight years the growth rate for technically defective vehicles is not so strong as a growth od average vehicle age. In the other hand, the statistical analysis shows that correlation coefficient r for those two variables $r = 0.6682$ what is above the critical value of 0.6021 for a significance level of 0.05, so it can be concluded that correlation is significant.

In technical inspections in 2016, technical defectiveness was recorded in 22.00% of vehicles. There were 23.1% of technically defective PCs, which means that almost every fourth PC was technically defective. The majority of deficiencies were observed on the parts of the lighting equipment, braking devices, wheels and suspension, as well as during the tailpipe test, etc. The expected relation which indicated that the increase in the number of technically defective vehicles was proportional to the increase in vehicle age was determined by observing the technical defectiveness of PCs compared to vehicle age, as shown in

Fig. 16. The technical defectiveness of vehicles on the PTI shows stable, almost linear growth with average age of the vehicle. This conclusion is confirmed with correlation coefficient $r = 0.9927$.

3.7. Impact of technical defectiveness of vehicles on the number of traffic accidents with fatalities

In order to follow the trend of the number of fatalities in traffic accidents, the number of fatalities per 100,000 inhabitants is shown. Data for several EU member countries were considered and a comparison of the results for the period from 2004 to 2013 was made. The said results are shown in Fig. 17 (WHO, 2015).

It is obvious that Croatia is one of the EU member countries with the highest mortality rate in road traffic. If the results for other member countries were presented as well, the data for Croatia would show even more significant deviation. According to the data for 2014 and 2015, there was a repeated increase of mortality rate in Croatia in 2015. In the same year, there were 8.3 deaths per 100,000 inhabitants, indicating Croatia's significant deviation from the EU average. If the data on the number of injured in traffic accidents were included, the results would be even more devastating.

A project for checking technical roadworthiness of vehicles involved in traffic accidents with fatalities was carried out in Croatia from 2012 to 2015, as part of the National Road Traffic Safety Programme. During the study, technical defectiveness was found in 70 out of 166 inspected vehicles. The average age of the inspected vehicles was 14.54 years, indicating that old vehicles aged above the average were involved in such traffic accidents. During periodic technical inspections of vehicles in 2015, 21.94% of defective vehicles were found, while as much as 42.17% of defective vehicles participated in traffic accidents within the project. These results point to the fact that in traffic accidents with fatalities there is a significantly higher percentage of technically defective vehicles than the one established during a periodic technical inspection.

3.8. Impact of vehicle structure on tailpipe emissions

In accordance with the foregoing, exhaust gas aftertreatment systems are one of the devices the operation of which is checked during a vehicle inspection. Data on the number of PCs, manufactured in 1984 and later, which took the tailpipe test in 2014 are shown in Fig. 18.

The ratio between the number of petrol cars and diesel PCs that did

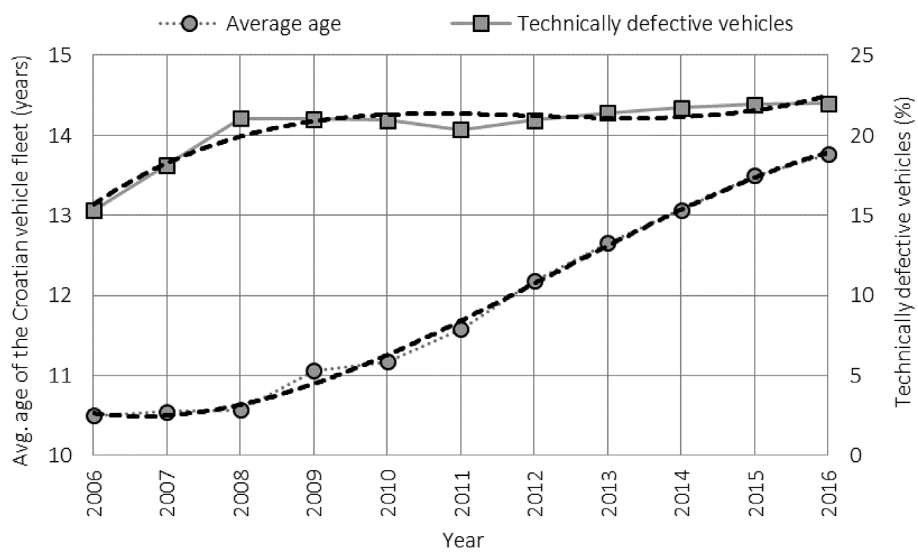

Fig. 15. Average age of the Croatian road vehicle fleet and percentage of technically defective vehicles in Croatia from 2006 to 2016.

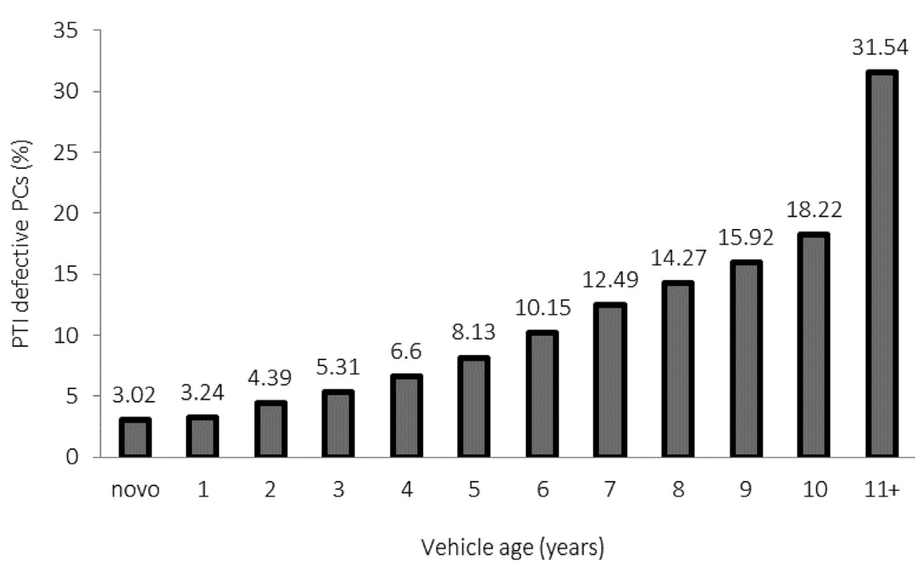

Fig. 16. Percentage of PTI defective PCs in 2015, in relation to vehicle age.

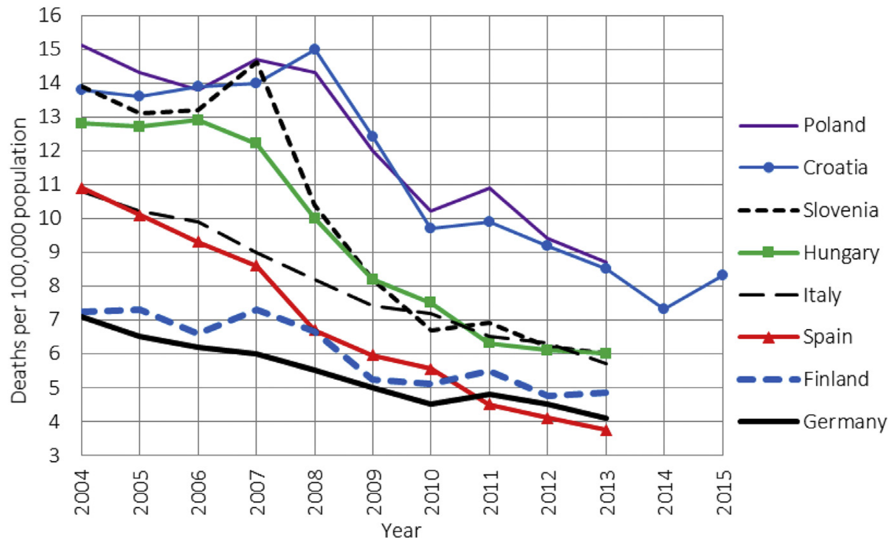

Fig. 17. Road traffic deaths in some EU countries.

not pass the tailpipe test is also shown. Older petrol cars record much more deficiencies in exhaust gas aftertreatment systems compared to older diesel cars. However, the testing results for newer petrol cars are considerably better than the results for newer diesel cars.

Very interesting are the curves in the upper part of the diagram in Fig. 18. They are a true indication that newer cars (up to about 10 years old), in principle, do not show almost any signs of defectiveness on exhaust gas aftertreatment systems, but this is not the case with older vehicles, particularly petrol cars.

Testing results from technical inspections indicate that older vehicles are insufficiently maintained and pose a potential danger to road traffic safety. Furthermore, they are becoming ecologically unfriendly.

Since it has been pointed out that PCs are by far the most numerous category which contributes greatly to air and environmental pollution caused by tailpipe emissions, the said category has been used to review the vehicle structure with respect to emission standards.

Emission standards are divided into groups ranging from Euro 0 to Euro 6, where Euro 0 covers all emission standards that precede Euro 1. Fig. 19 shows a change in vehicle structure from 2007 to 2016 according to emission standards.

Fig. 19 shows the structure of vehicles that meet a certain emission standard and it is easy to conclude that the majority of the PC fleet is in line with Euro 2, Euro 3 and Euro 4 emission standards. According to the 2016 data, vehicles that met Euro 0 and Euro 1 emission standards accounted for 10% of all cars, Euro 2, Euro 3 and Euro 4 vehicles accounted for 71% of all PCs, while Euro 5 and Euro 6 cars accounted for 19% of all cars. In other words, 10% of PCs were older than 22, 71% were between 8 and 22, and only 19% were up to 8 years old. The number of cars that met the Euro 0 emission standard in 2016 was about four times lower than in 2007. The number of cars that meet the Euro 1 emission standard has also been falling, but the fall is significantly slower compared to Euro 0 vehicles. The problem are cars that meet the Euro 2, Euro 3 and Euro 4 emission standards as their number has not changed considerably for several years. The reason for this is the increased import of such used vehicles. There is a tendency to reduce the number of used vehicles, and to increase considerably the number of newer vehicles which meet the Euro 5 and Euro 6 emission standards, as well as the number of electric vehicles. However, the results are not yet satisfactory. It has been demonstrated that the impact of vehicle mass is one of the key parameters for estimating emissions (Fontaras and Dilara, 2012). Therefore, the promotion of smaller newer vehicles, i.e. newer vehicles of lower mass, can significantly reduce

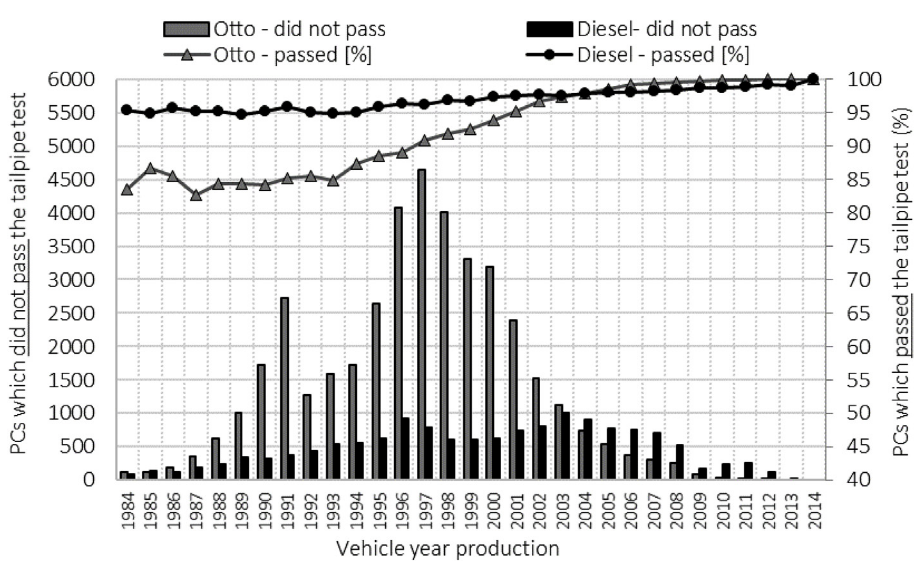

Fig. 18. Number of PCs which did not pass the tailpipe test, and percentage of PCs which passed the tailpipe test – data from Croatia in 2014.

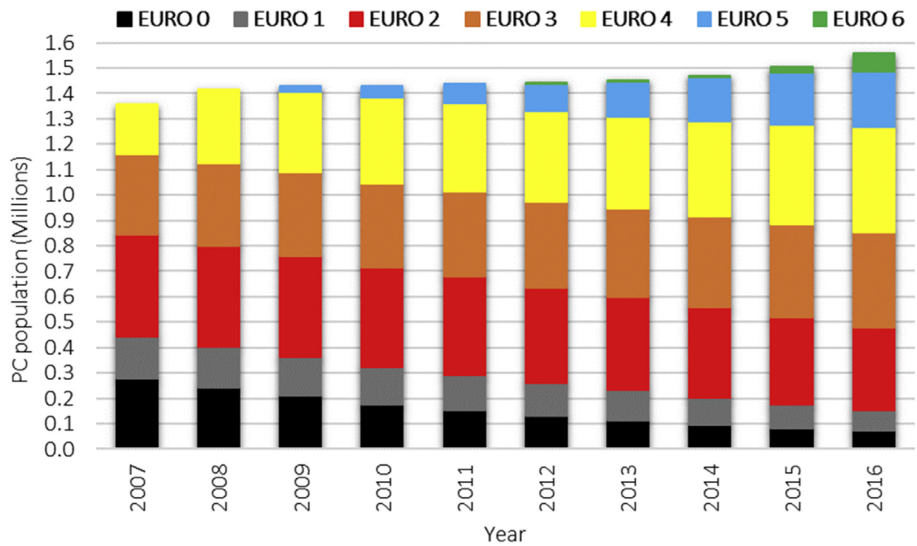

Fig. 19. PCs in Croatia according to EURO emission standard, in the period from 2007 to 2016.

emissions (Fontaras and Samaras, 2010).

Vehicle age is directly related to the amount of emissions which vehicles generate into the atmosphere. Older vehicles are of lower Euro standards, that is, they generate more emissions per kilometre of distance travelled, compared to newer vehicles. In order to determine the approximate status of generated emissions, it is necessary to establish the utilisation conditions of the vehicle fleet. In most countries the average annual distance travelled reduces with the increase in vehicle age (Caserini et al., 2013). In other words, newer vehicles are utilised significantly more than older vehicles. Therefore, it is necessary to determine the values of the average annual distance travelled for vehicles of particular categories and emission standards. Determination of this data will enable the calculation of annual generated emissions. Comparison of the calculated emissions would point to the part of the vehicle fleet that contributes to air and environmental pollution to the largest extent. Also, if part of the vehicle fleet was replaced in accordance with the corresponding legislative or other measures, the annual reduction in the generated emissions of the renewed vehicle fleet could be presented. Currently, such calculation models are being prepared and will be published soon.

3.9. Calculation of the number of vehicles leaving the fleet (end-of-life vehicles and exported vehicles)

Data on the number of vehicles leaving the fleet is necessary to determine measures to change the vehicle structure trend. The model for the assessment of the number of end-of-life vehicles in Belgium was used by Inghels (Inghels et al., 2016). Simplified calculation of the annual number of vehicles leaving the fleet can be described by the following equation:

$$n_{out_i} = n_{i-1} + (n_{new_i} + n_{used_i}) - n_i \tag{1}$$

n_{out_i} – number of registered vehicles leaving fleet (scrapped and country's exported vehicles),
n_{i-1} – number of registered vehicles from the previous year,
n_{new_i} – number of new vehicles with 1st registration in the current year,

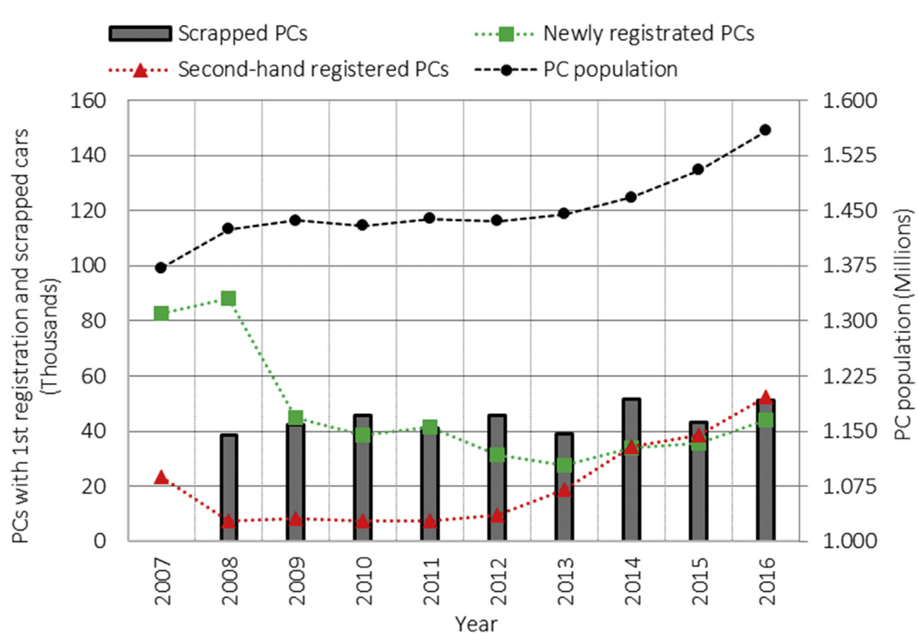

Fig. 20. Trends and changes of PC fleet in Croatia from 2007 to 2016.

n_{used_i} – number of used vehicles with 1st registration in the current year,
n_i – number of registered vehicles in the current year.

For the sake of their great amount, i.e. their significance, only the category of PCs was considered and Fig. 20 shows trends and changes in the structure of PCs in Croatia from 2007 to 2016.

The unfavourable trends of decreasing the number of newly registered vehicles and increasing the number of used vehicles with the first registration in Croatia are shown in Fig. 20 trend lines. Since 2014, however, there has been a slight increase in the number of newly registered vehicles. Nevertheless, since 2014, or one year after Croatia's accession to the EU, there has been a greater number of used vehicles with 1st registration in Croatia than of the new ones. This trend is adversely affecting the average age of vehicles that are by far above the EU average. What is even more important is the increase in technical defectiveness of vehicles, and consequently the reduction of traffic safety. In addition, tailpipe emissions from road traffic continue to grow due to increased imports of older used vehicles, as well as due to adverse change in the number of scrapped vehicles. In order to renew the vehicle fleet, strict national policy measures are needed, based on which subsidies and tax reliefs would, on the one hand, encourage the removal of old, technically defective and ecologically unfriendly vehicles from the traffic, and, on the other hand, encourage the purchase of new vehicles. Similar measures are in place in Russia and China, which have been facing a significant increase in the number of vehicles for two decades (Kholod and Evans, 2016; Wu et al., 2017). Purchase of used cars in Croatia is discouraged by excise duties on imports of such vehicles, but such excise duties should also be introduced later in the course of technical inspection and registration. It is necessary to create a sustainable model of taxation based on models of developed European countries, such as Sweden (Besser Hugosson et al., 2016).

4. Conclusion

A number of important features have been identified by studying the database of vehicle inspections in Croatia. The consequences of unfavourable economic opportunities in the country have been causing an increase in the average vehicle age for a number of years. Consequently, the purchase of new vehicles, as well as the maintenance of used vehicles, has been reduced. National tax measures impose the highest levies on new vehicles. With the age of the vehicle there is a reduction in taxes, while vehicles older than 10 years have been exempted from taxes. The result of such unfavourable conditions is the increase in technical defectiveness and ecological unfriendliness of vehicles. In road accidents in 2015, 348 people lost their lives and 15,024 were injured. As a result, the costs to insurance companies for the consequences of deaths, as well as the costs to the country for the treatment of victims and persons suffering from illnesses caused by exposure to increased concentrations of harmful tailpipe emissions are constantly increasing. Trends are unfavourable and changes are needed undeniably as soon as possible. The number of vehicles in Croatia is expected to increase significantly in the forthcoming period. The type of vehicles to achieve this growth with is, therefore, important. The aim is to achieve the said growth with new vehicles that are technically roadworthy, environmentally friendly and that will both directly and indirectly affect the reduction in the number of traffic accidents and the reduction in the number of people affected by the harmful tailpipe emissions from road traffic.

One of the main problems of the Croatian road vehicle fleet is a relatively high average age which is constantly growing for last ten years. To change this negative trend, policy measures could be aimed in the direction of the fiscal policy of the Republic of Croatia.

The vehicle owners in the Republic of Croatia during the ownership of the vehicle are facing three taxes. The first one is at the moment of the vehicle purchase (new or used one), the second one is annual vehicle tax (up to vehicle's age of ten years), and the third one is an annual special ecological fee.

The first and second taxes are based on the wrong model because they are practically in favour of old vehicles instead promoting the purchase and use of newer vehicles.

The tax at the moment of vehicle purchase is divided into two parts – VAT and a special tax for both new and used vehicles which consist of price part and ecological fee. For new vehicles, the ecological fee is set too high, while used vehicles ecological fee is decreasing with vehicle age, what is directly the opposite of desirable goal.

Annual tax for vehicles up to the vehicle's age of ten years is also set wrong. Namely, the annual tax decreases with the vehicle's age, and after the age of ten, there is no more tax. Again, such taxation model is in favour of older vehicles.

Furthermore, once the vehicles are in use, the owners pay a special ecological fee every year. The current model for vehicles grouping is adequate, but levels of fees should be increased. This increase in fees should be five- and even ten-fold, to change consumer habits. Namely, the maximum fee is about the same as the cost of one tank of fuel, which is not high enough to influence an owner's readiness to invest in newer and eco-friendly vehicle. Of course, such a decision is politically very unpopular measure, but to relax it, the incentives model for the purchase of new vehicles should be introduced. Through incentives, the main goal should be removing old vehicles from the roads and replacing them with new vehicles with low emissions.

The additional problem is that collected fees are not mainly reinvested in road transport sector, as they are used for covering other government expenses.

It is possible to define new taxation models which will bring the same amount of tax but in the way that old vehicles and high polluters are not favoured. With such rebalancing, it is possible to slow down, stop or even reduce the average age of a vehicle, to achieve better roadworthiness of the vehicles, to reduce emissions, to act preventively in order to reduce the number of traffic accidents and the deaths in traffic.

To adopt scientifically based political and tax measures, it was necessary to study the structure of the vehicle fleet. Aspects which adversely affect the change of the vehicle fleet, and consequently traffic safety, human health and environmental pollution were pointed out. Based on the results presented, it is necessary to create models that will allow the assessment of the effect of a particular proposal of measures.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.tranpol.2018.08.005.

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Article II (Published journal article)

Increase in nitrogen oxides due to exhaust gas recirculation valve manipulation

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Increase in nitrogen oxides due to exhaust gas recirculation valve manipulation

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ABSTRACT

Exhaust gas recirculation (EGR) is a known method of reducing nitrogen oxides (NO_X), but the impact of its deactivation on emissions has not been quantified. This paper, therefore, considers the impact of deactivating the EGR valve on NO_X emissions in a diesel Euro 5 vehicle. The measurements were performed during nine driving cycles and in all cases, a significant increase in NO_X emissions was found when the EGR valve was deactivated. NO_X emissions increased between 176% and 407%, depending on the cycle driven. Measurement results indicate the origin of significant amounts of NO_X emissions. Recommendations are to inform regulatory authorities about the effects of such manipulations in order to adopt more stringent measures and introduce them during periodic technical inspection of vehicles with the view to preventing such interventions.

1. Introduction

Type-approval emissions tests are conducted on vehicles to check their emissions. Although the test requirements were generally not difficult to meet according to the outdated New European Driving Cycle (NEDC), the question arose whether such tests were in fact realistic. Recent investigations have shown that under real driving conditions nitrogen oxide (NO_X) emissions significantly exceed the levels achieved during vehicle type-approval procedures (Cha et al., 2019; Murena et al., 2019; O'Driscoll et al., 2018). Moreover, some manufacturers also used the so-called "defeat devices" to deliberately cheat the type-approval procedure (Hooftman et al., 2018). An example of such use was the Dieselgate scandal (Ayala, 2018; Wang et al., 2016), which revealed that Volkswagen's fraudulent emission data was associated with 45,000 disability-adjusted life years (Oldenkamp et al., 2016). Although emissions in real-world driving are generally higher than in type-approval tests, these emissions are further increased by the use of "defeat devices". Although manufacturers have the obligation to meet very strict requirements for new vehicles, the question arises of what happens with emissions during a vehicle's lifecycle.

New insights into failures of diesel emission control systems have prompted member states to launch campaigns in order to identify

Abbreviations: COPERT, computer programme to calculate emissions from road transport; CVH, Centre for Vehicles of Croatia (Cro. Centar za vozila Hrvatske); DEF, diesel exhaust fluid; DPF, diesel particulate filter; ECE, Economic Commission for Europe; EEA, European Economic Area; EF, emission factor; EGR, exhaust gas recirculation; EMEP, European Monitoring and Evaluation Programme; EUDC, extra-urban driving cycle; FAP, particle filter (Fr. filtre à particule); HDDV, heavy-duty diesel vehicle; NEDC, New European driving cycle; NO_X, nitrogen oxides; OBD, on-board diagnostics; PTI, periodic technical inspection; RPM, revolution per minute; SCR, selective catalytic reduction.

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in-use vehicle emissions levels (Ntziachristos et al., 2016). Age-based analysis conducted in California on gasoline light-duty vehicles using remote sensing devices indicated that 1994–2003 model-year vehicles, which had been up to 20 years old when sampled, deteriorated approximately linearly with age for carbon monoxide, hydrocarbons and nitric oxide (Zhan et al., 2020). Studies generally indicate that vehicle emissions increase with vehicle age and total distance travelled (Borken-Kleefeld and Chen, 2015; Chen and Borken-Kleefeld, 2016; Lozhkina and Lozhkin, 2016).

Since 2014, the population of passenger cars in Croatia has been constantly growing, which has, in turn, led to increased emissions (Rešetar et al., 2017b). In-use vehicle emissions increase significantly due to engine malfunction caused by wear-and-tear and improper maintenance (Hao et al., 2020). Subsequent manipulations on the exhaust system components could cause NO_X emissions to exceed type-approval values many times over. A study conducted in the Republic of Korea on four Euro 4 diesel light-duty vehicles manufactured between 2008 and 2010 has shown that a faulty exhaust gas recirculation (EGR) valve contributed to the increase of NO_X emission factors (EFs) between 2.47 and 2.93 in laboratory conditions. The same test performed on the road showed the increase of NO_X EFs between 1.14 and 1.27, leading to the conclusion that the impact of EGR valve failure is more pronounced in laboratory conditions than on the road (Lee et al., 2019).

Manipulations are common not only in passenger cars but also in heavy-duty diesel vehicles (HDDVs) (He et al., 2020). In one malfunction simulation on a Scania G280 manual transmission truck, the diesel particulate filter (DPF) pressure sensor was disconnected. In these conditions, regeneration was affected and particles were accumulated within the DPF. As a result, DPF became excessively clogged, causing nitric oxide emissions to increase by more than 1600% (Huang et al., 2019). Although DPF is a technology that primarily reduces particulate matter (PM) emissions, it is evident that its malfunction can significantly affect NO_X emissions. Heavy-duty diesel vehicles are far more exploited than passenger cars and are more prone to selective catalytic reduction (SCR) system manipulations due to a higher diesel exhaust fluid (DEF) consumption. SCR temperature sensors can be tampered with by keeping the inlet sensors slightly away from their original position in the engine exhaust. This way, vehicle owners save on the cost of DEF (He et al., 2020). A study carried out in China evaluated the accuracy of on-board sensing devices based on portable emission measurement system data. As a part of the study, HDDVs were operated under normal conditions and conditions simulating a tampered vehicle with no DEF for the SCR system. During the tampered SCR simulation, the average vehicle NO_X emissions increased from 22 g/kg_{fuel} to 48 g/kg_{fuel}, with both the portable emission measurement system and on-board sensing quantified consistent trends (Cheng et al., 2019). With the increase in the number of Euro 6 passenger cars with a built-in DEF system, the number of manipulations is also expected to increase.

This research was preceded by our previous relevant studies. In Croatia, NO_X emissions in passenger cars have been on the increase since 2014 (Rešetar et al., 2017b). In the 2017 study, NO_X emissions and implied EFs were calculated using the COPERT 5 computer program and it was found that all passenger cars from Euro 3 to Euro 6 exceeded the NO_X limit values (Rešetar et al., 2017a). In terms of policy framework, the highest levies are imposed on new vehicles and they decrease with vehicle age, so those older than 10 years are exempted from taxes altogether (Rešetar et al., 2018). Such policy measures have led to an increase in vehicles average age, which impairs vehicle technical roadworthiness.

Given that repairs and replacements of exhaust system components, such as DPFs, EGR valves, NO_X sensors, SCR catalysts and DEF systems are relatively expensive, vehicle owners often choose the tampering method. In Croatia, on-board diagnostic (OBD) testing methods as a part of the obligatory periodic technical inspection (PTI) have been implemented since 2019 (Rešetar et al., 2019). The use of the OBD test has greatly reduced the amount of unprofessional tampering as all the necessary information is gathered from the engine control unit, regardless of the malfunction indicator lamp status on the dashboard. Unfortunately, OBD tests are not mandatory, but only an alternative to tailpipe tests for Euro 6 vehicles. The results of a study conducted in 2020 in Croatia on a passenger car fleet indicated there was a significant number of vehicles that had passed the emission test but had active diagnostic trouble codes. Therefore, a new method is proposed to detect emission control system malfunction during the PTI (Rešetar et al., 2021).

A study based on OBD data was conducted on HDDVs. Forty-five vehicles equipped with the SCR system with malfunction indicator lamp status activated were identified and their emissions were measured before and after the repairs. In the post-repair phase, with malfunction indicator lamp status deactivated, NO_X reductions greater than 80% were recorded in more than 45% of tested vehicles (Jiang et al., 2021). However, numerous service workshops today use the methods of remapping the engine control unit as well as EGR, DPF and other exhaust after-treatment systems. In these circumstances, OBD tests cannot detect faults.

The motivation behind conducting this study stem from the results of technical inspections of passenger cars in the Republic of Croatia. Every year, a significant number of vehicles in which the EGR valve has either been removed or physically blocked are identified during a periodic technical inspection. These are usually older vehicles with a pneumatically activated EGR valve. It can be assumed that the situation is similar with newer vehicles. However, in newer vehicles, such manipulations are quite difficult or nearly impossible to detect without the use of special equipment. In some cases, visual inspections or vehicle diagnostics cannot determine the manipulations of the emission control system, so the most reliable method for detecting potential tampering is the exhaust emissions measurement. There is a lack of knowledge regarding the significance of the emissions-related system malfunctions for vehicle performance. Therefore, this study was carried out to evaluate the effect of EGR valve manipulation on NO_X emissions in a Euro 5 diesel passenger car under stationary and transient engine operating conditions on a chassis dynamometer. The measurement of road motor vehicles NO_X emissions allows for the identification of EGR system manipulations. The aim of the present study was also to investigate whether there is a functional relationship between NO_X emissions of the vehicle with activated and deactivated EGR valve. The results point to the need for a correction of the NO_X EFs, which should include the factor of increased emissions due to manipulations.

Table 1
Technical data of MAHA devices.

Device	Model	Specifications	
Chassis dynamometer	LPS 3000	Roller set: R100/1	Max. wheel power: 260 kW
		Roller diameter: 318 mm	Max. tractive force: 6 kN
		Min. wheel diameter: 305 mm	Max. RPM: 10.000
		Wheel track: 800–2300 mm	Max. axle load: 2500 kg
		Max. test speed: 250 km/h	
Emission tester	MET 6.3	Measuring principle – Infrared spectrometry: carbon monoxide (% vol.), carbon dioxide (% vol.), hydrocarbons (ppm)	
		Measuring principle – Electrochemical detection: oxygen (% vol.), nitric oxide (ppm), nitrogen dioxide (ppm)	
		nitric oxide and nitrogen dioxide resolution 1 ppm vol.	
		Measuring principle – absorbance measurement: Opacity (%)	
		Calculable values: λ (-), Opacity coefficient K (m^{-1}),Soot mass concentration (mg/m^3)	
		Connection type: LAN, Wi-Fi	
OBD module	VCI	Supported communications protocols:	
		ISO-TP through CAN (ISO 15765)	
		WWH-OBD (ISO 27145)	
		SAE J1939	
		KWP 2000 (ISO 14230)	
		CARB (ISO 9141)	
		Connection type: Wi-Fi	

Table 2
Tested vehicle technical data.

Make	Peugeot
Commercial name	308 SW I
Homologation type/variant/version	4E9HD8/1SCU
Year of production	2014
Mileage	180.000 km
Mass in running order	1475 kg
Drive	Front wheel drive
Engine designation	1.6 HDI SOHC 1560 cm^3 4-cylinder turbocharged
Engine power	84 kW
Emission standard	Euro 5b
Emission control	diesel oxidation catalyst + DPF + EGR
NO_X type-approval value	161.3 mg/km
Tire size	195/65 R 15

2. Materials and methods

2.1. Measurement equipment and test vehicle

Measurements were performed using the equipment in the Centre for Vehicles of Croatia (CVH) testing lab. Test equipment included MAHA LPS 3000 chassis dynamometer, MAHA MET 6.3 emission tester, MAHA VCI OBD module, CVH OBD tool, a personal computer and a smartphone with FAP application. The specifications of MAHA devices used are shown in Table 1.

The chassis dynamometer load simulation is carried out with an eddy-current brake. LPS 3000 simulates air resistance, tire rolling, flexing resistance and inertia resistance, which correspond to driving resistances of a forward-moving road vehicle. The measurements were carried out on a car with well-known technical data, PTI results, regular maintenance activities and operating regimes (business travel routes). The vehicle technical data relevant for the measurement of NO_X emissions are given in Table 2.

2.2. Measurement sequence

NO_X emissions were measured in two cycles. In the first cycle, tests were performed with an activated EGR valve (EGR ON), after which the vehicle was taken to an authorized Peugeot service workshop, where the EGR valve was disconnected. This enabled the EGR valve to remain closed at all times, which prevented EGR. In the second cycle, NO_X emissions were measured with a deactivated EGR valve (EGR OFF).

Table 3
EGR valve position, depending on the gear selected and vehicle speed.

Gear	RPM	Vehicle speed (km/h)	Tractive force (kN)	EGR valve position (%)	Accelerator pedal position (%)
N	815 – 825	0	0	vary (0 – 25)	0
I	1205	10	0.170	25	9
II	1265	20	1.224	26	10
	3160	50	1.870	0	31
III	2105	50	1.888	35	21
	2515	60	2.215	26	25
IV	1490	50	1.877	26	12
	1800	60	2.215	29	15
	2370	80	2.975	32	21
	2970	100	3.946	10	25
V	1320	60	2.190	21	10
	1760	80	2.972	26	17
	2210	100	4.005	28	23
	2630	120	5.241	23	25
VI	1475	80	2.974	21	14
	1835	100	3.974	21	20
	2190	120	5.159	22	24

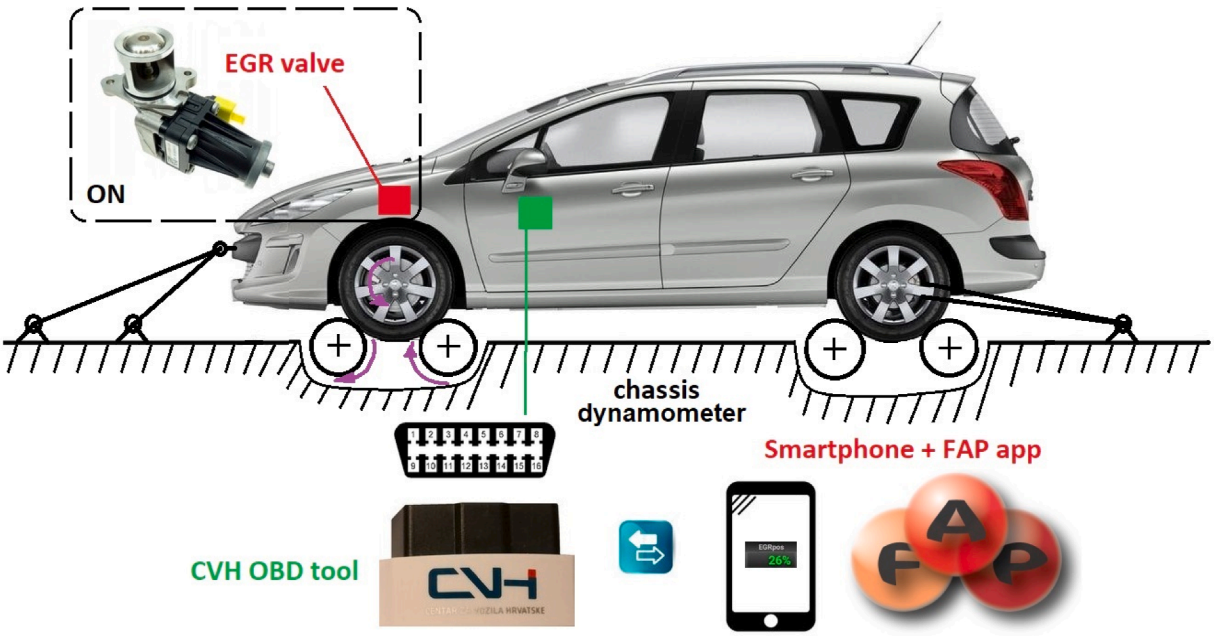

Fig. 1. The method of measuring EGR valve position on a chassis dynamometer.

2.3. Measurement procedures

Before starting the measurements, preparatory activities were undertaken pursuant to the instructions of the MAHA chassis dynamometer manufacturer. First, the test vehicle was put on a chassis dynamometer, and after a 15-minute test run, the engine and the exhaust system components were warmed up to a normal operating temperature (coolant temperature ≈ 80 °C). All measurements were performed at an ambient temperature in the range of 20 to 25 °C to minimize the impact of this parameter. One of the goals was to determine the relative changes in emissions with the EGR valve activated and deactivated under approximately the same test conditions. Therefore, strict type-approval emission test conditions were not necessary since emissions were not considered in absolute values. The measuring of the EGR valve position also took into account the period of value stabilization of up to 20 s.

Before measuring NO_X emissions, the EGR valve position was recorded while driving at different constant speeds and gear ratios on the chassis dynamometer (referred to in Table 3 in Results and Discussion). For this purpose, the CVH OBD tool and a smartphone with the FAP application were used, Fig. 1.

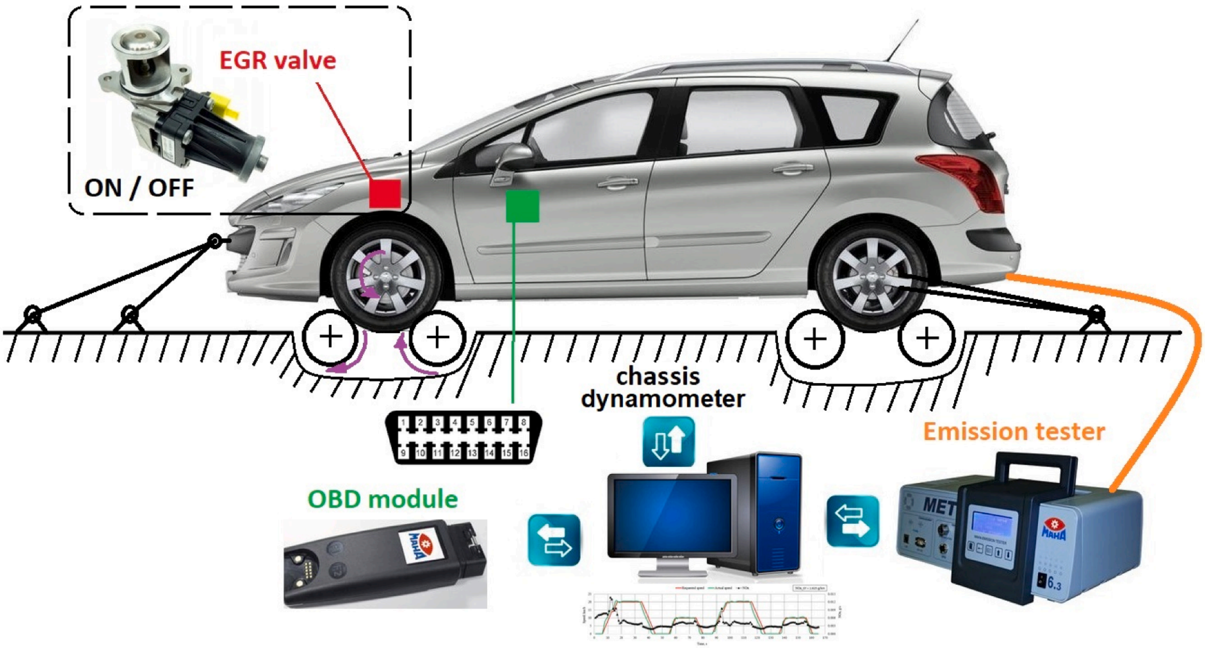

Fig. 2. The method of measuring NO_X emissions on a chassis dynamometer.

Although the FAP application is primarily used for checking DPF conditions and additive levels, it also provides a number of other options. The parameters used for the research include the following OBD data: engine RPM, selected gear, derived vehicle speed, and current EGR valve position. After completing the measurement of the EGR valve position, the CVH OBD tool was disconnected from the vehicle's OBD connector, and the MAHA VCI OBD module was connected. Its purpose is to collect and forward all the necessary data from the vehicle to the computer which manages the processes. The chassis dynamometer and emissions tester were also connected to the computer. Calibration, leakage check and zero adjustments were performed in line with the instructions of the MAHA emissions tester. Then, an emissions tester probe was installed into the vehicle's exhaust pipe. After all the required parameters were set in the dynamometer and the emission tester software, the measuring system was ready for emissions measurement, Fig. 2.

The vehicle's total distance travelled was calculated based on the rollers' total revolutions and diameter, with the assumption that there was no relative slip between the vehicle's drive wheels and rollers, as shown in Eq. (1) below.

$$distance = (d_{\mathrm{rol}} \times \pi \times n_{\mathrm{rol}})/1000 \tag{1}$$

where:
distance = vehicle's total distance travelled on the rollers, per driving cycle (km);
d_{rol} = rollers diameter (m), $d_{\mathrm{rol}} = 0.318$ m;
n_{rol} = total revolutions of the rollers, per driving cycle (-).

NO_X emissions were measured in volume fractions with the measurement resolution of 1 ppm (vol) using the electrochemical measurement principle. By using the OBD and emissions tester data, as well as manufacturer-specific data, it is possible to calculate NO_X mass flow. Given that mathematical formulas for calculating NO_X mass flow (mg/s) have not been made public by the manufacturer, these data are not shown here. With NO_X mass flow measured, and vehicle's total distance travelled according to Eq. (1), NO_X EF was calculated as shown in Eq. (2) below.

$$EF_{NOX} = \frac{\int_0^t f(E_{NO_X}(t))dt}{distance} = \frac{\mathrm{AVG}(E_{NO_X}) \times t}{distance} \tag{2}$$

where:
EF_{NOX} = NO_X EF, referring to the cycle driven (mg/km);
E_{NO_X} = NO_X mass flow (mg/s);
$\mathrm{AVG}(E_{NO_X})$ = mean value of the NO_X mass flow, per driving cycle (mg/s);
t = driving cycle time (s).

2.4. Driving cycles – Standard and non-standard

In order to consider different driving modes and driver behaviours, in addition to three standard driving cycles, six arbitrary driving cycles were created. For each driving cycle, five consecutive measurements were performed, and the displayed results represent the

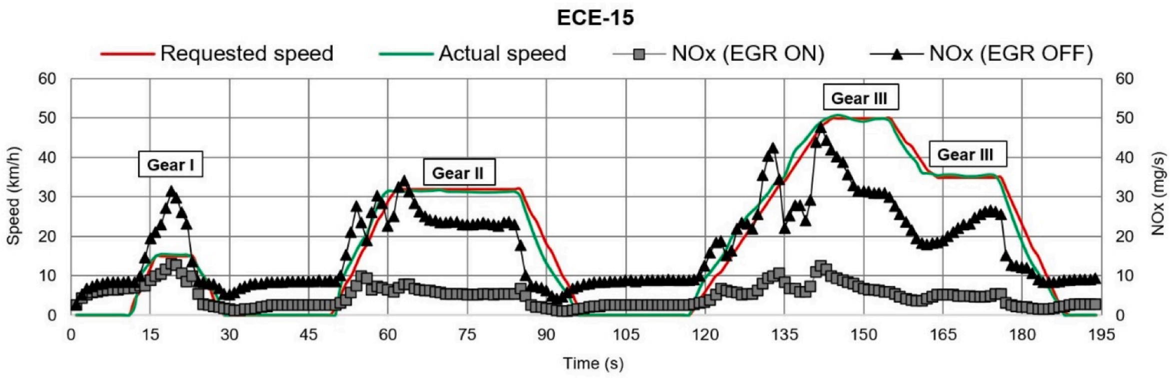

Fig. 3. Measurement results according to ECE-15 cycle.

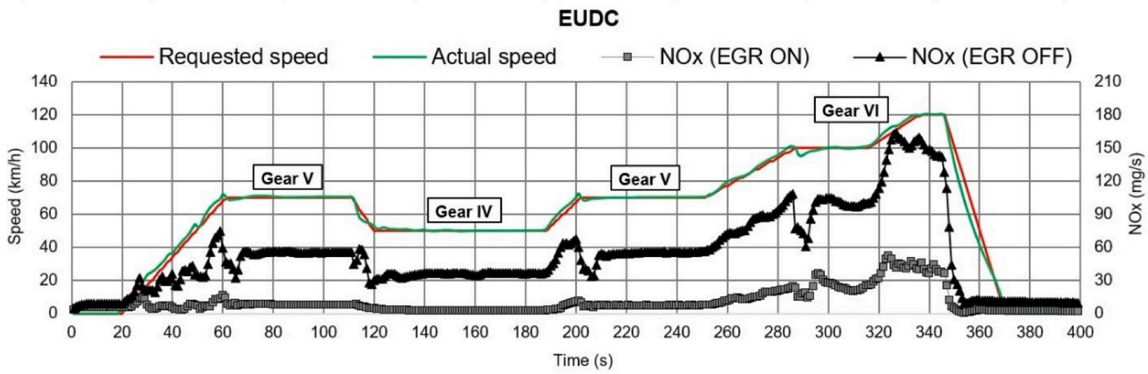

Fig. 4. Measurement results according to EUDC cycle.

mean values in each second of the cycle. All measurements were performed with the start-stop system switched off.

2.4.1. Standard driving cycles

ECE-15 and EUDC were used as standard driving cycles, and NEDC was derived as their combination. ECE-15 is an urban driving cycle, devised to represent driving conditions in a city, and in this case first and second gear in the transmission were used. EUDC is an extra-urban driving cycle, reflecting driving on city bypasses, and in this test, after the initial acceleration phase, fourth, fifth and sixth gear in transmission were used. NEDC was used for EU type-approval testing of emissions and fuel consumption from light-duty vehicles and is based on the existing ECE-15 and EUDC cycles.

2.4.2. Non-standard driving cycles

Gear N indicates a cycle when the engine is idling and runs between 815 RPM and 825 RPM. Gear I-II cycle simulates traffic congestion during urban rush-hour driving and consists of two repeating sub-cycles. The first sub-cycle was driven in the second gear at 20 km/h, while the second sub-cycle was driven in the first gear at 10 km/h. The next Gear II-III-IV cycle simulates driving on a road with a 50 km/h speed limit. This cycle consists of three sub-cycles with a driving speed of 50 km/h. The first sub-cycle was driven in second gear, the second one in third gear, and the third one in fourth gear. In this case, the impact of driver behaviour on emissions can be observed. Gear IV-V-VI cycle follows, stimulating free-flow driving on inter-city roads. This cycle consists of three sub-cycles with a driving speed of 80 km/h and 100 km/h. The first sub-cycle was driven in fourth gear, the second one in fifth gear, and the third in sixth gear. Finally, the Gear V-VI cycle simulates free-flow driving on a highway. The cycle consists of two sub-cycles with a driving speed of 120 km/h. The first sub-cycle was driven in fifth gear and the second one in sixth gear.

3. Results and discussion

3.1. EGR valve position

The results obtained by measuring the EGR valve position, while driving at a constant speed in a selected gear, are shown in Table 3. Tractive force as a function of driving speed represents the sum of all driving resistances. Each measurement was performed over 60 s, and the results represent mean values in the given period.

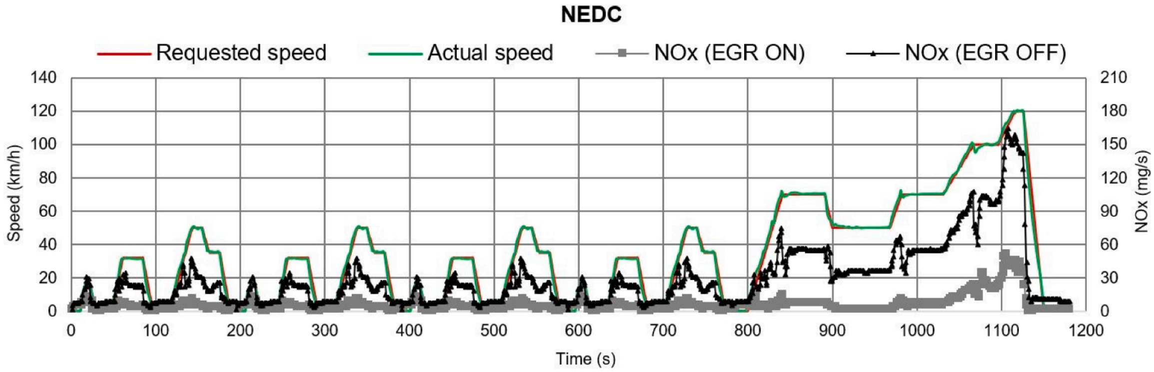

Fig. 5. Measurement results according to derived NEDC cycle.

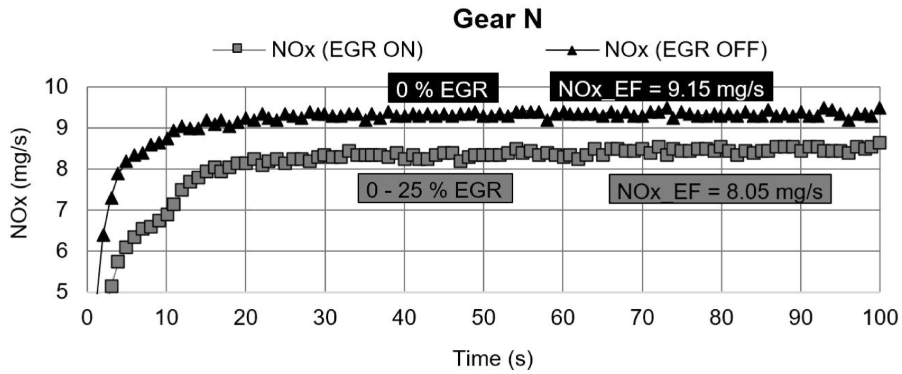

Fig. 6. Measurement results during Gear N cycle.

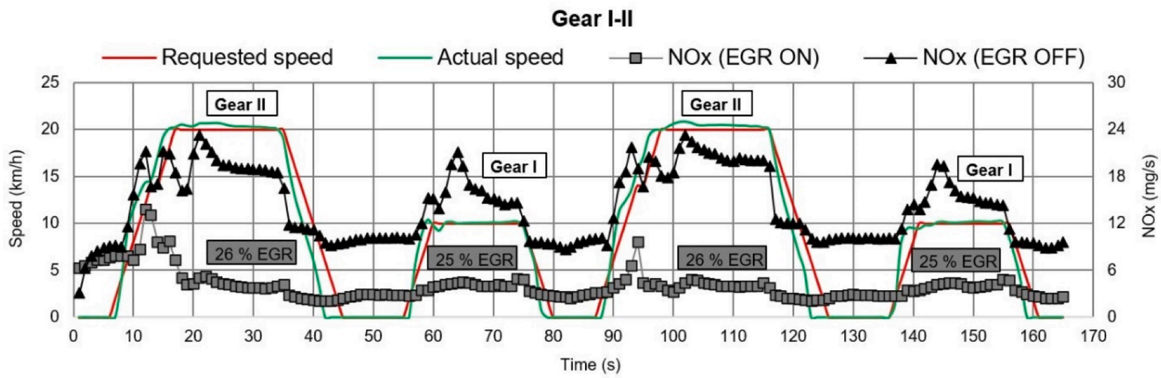

Fig. 7. Measurement results according to Gear I-II cycle.

Generally, a driving cycle is defined by a driving speed profile (km/h). Emission calculation tools, such as COPERT, use EFs as functions of an average driving speed (km/h). For that reason, the vehicle speed is used to interpret the results instead of engine RPM.

3.2. NO_X emissions before and after the EGR valve deactivation

The results of NO_X emission measurements before and after EGR valve manipulation are shown below. To facilitate interpretation, both results are shown on the same graph, along with the EGR valve position for non-standard driving cycles. After manipulation, the EGR valve position was at 0% at all times (indicated as EGR OFF in the graph – no EGR).

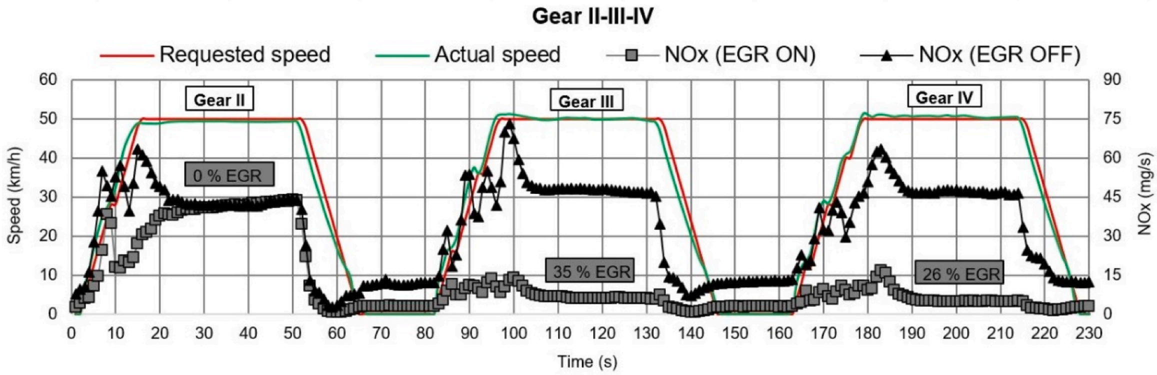

Fig. 8. Measurement results according to Gear II-III-IV cycle.

Table 4
Comparison of NO_X emissions by driving at 50 km/h in second, third and fourth gear with EGR valve ON and OFF, respectively.

Vehicle speed = 50 km/h	NO_X (mg/km) at EGR valve position (%)		
	Gear II	Gear III	Gear IV
EGR ON	3142 at 0	492 at 35	384 at 26
EGR OFF	3188 at 0	3534 at 0	3464 at 0
NO_X increase (%)	1	618	802

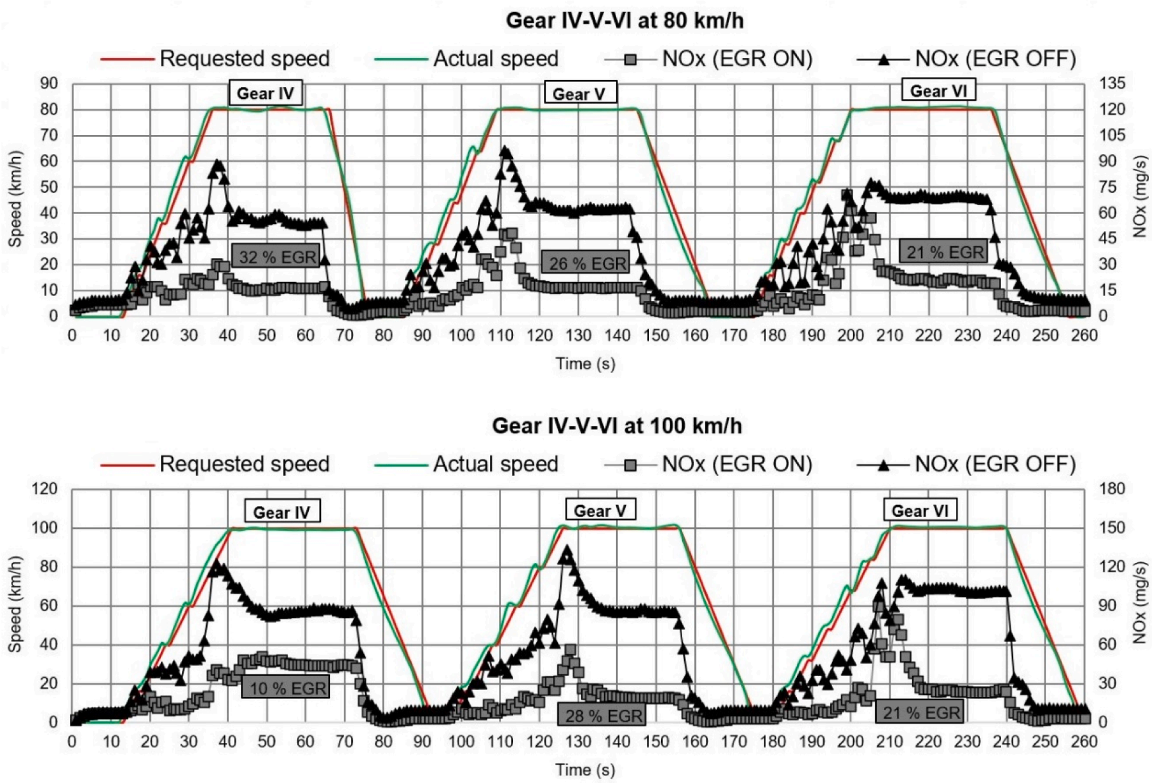

Fig. 9. Measurement results according to Gear IV-V-VI cycle at 80 and 100 km/h.

Table 5
Comparison of NO_X emissions at 80 and 100 km/h in fourth, fifth and sixth gear with activated and deactivated EGR valve.

Vehicle speed (km/h)		NO_X (mg/km) at EGR valve position (%)		
		Gear IV	Gear V	Gear VI
80	EGR ON	753 at 32	786 at 26	975 at 21
	EGR OFF	2637 at 0	2926 at 0	3211 at 0
	NO_X increase (%)	250	272	229
100	EGR ON	1647 at 10	722 at 28	917 at 21
	EGR OFF	3210 at 0	3267 at 0	3865 at 0
	NO_X increase (%)	95	352	321

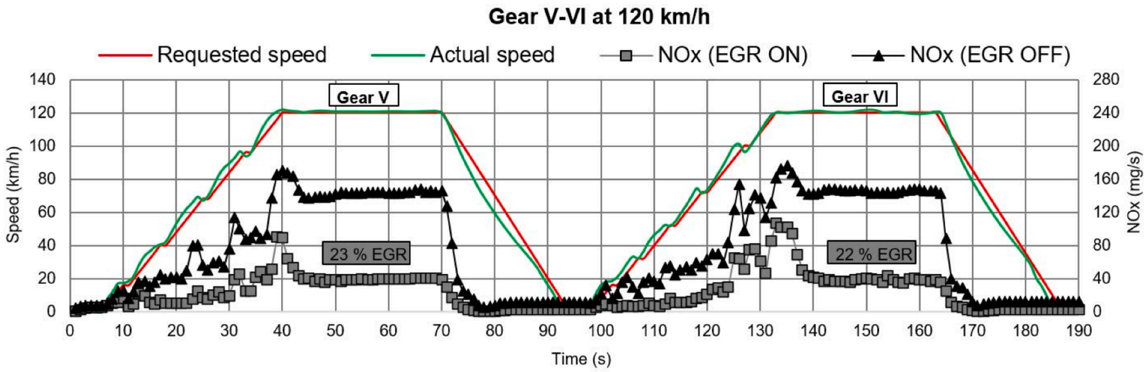

Fig. 10. Measurement results according to Gear V-VI cycle at 120 km/h.

3.2.1. *Standard driving cycles*

Fig. 3 shows NO_X mass flow with activated EGR (EGR ON) and deactivated EGR (EGR OFF) during the ECE-15 cycle. When the EGR valve was activated, NO_X EF was 941 mg/km and when it was deactivated, EF was 3378 mg/km. Therefore, in the case of ECE-15, EGR valve deactivation caused an increase in NO_X emissions by 259%.

Fig. 4 shows NO_X mass flow with activated and deactivated EGR during the EUDC cycle. When the EGR valve was activated, NO_X EF was 630 mg/km, while during its deactivation EF was 3195 mg/km. In this case, therefore, EGR valve deactivation caused an increase in NO_X emissions of 407%.

Fig. 5 shows NO_X mass flow with activated and deactivated EGR during the NEDC cycle. When the EGR valve was activated, NO_X EF was 748 mg/km; when it was deactivated, EF was 3267 mg/km. In conclusion, in the case of NEDC, EGR valve deactivation caused an increase in NO_X emissions of 337%.

3.2.2. *Non-standard driving cycles*

Fig. 6 shows NO_X mass flow with activated and deactivated EGR during a Gear N cycle. The values shown refer to the period of 100 s immediately after the engine has been started. Approximately 20 s are required for the stabilization of values. With an activated EGR valve, NO_X mass flow was 8.05 mg/s, and when deactivated, NO_X mass flow was 9.15 mg/s. Therefore, the deactivated EGR valve contributed to an increase in NO_X emissions of 13.7%.

Fig. 7 shows NO_X mass flow with activated and deactivated EGR during Gear I-II. NO_X EF was 1625 mg/km with the valve activated, and 5564 mg/km with the valve deactivated. EGR valve deactivation caused an increase in NO_X emissions of 242%.

Fig. 8 shows NO_X mass flow with activated and deactivated EGR during Gear II-III-IV cycle. NO_X EF was 1300 mg/km when the EGR valve activated, and 3646 mg/km when it was deactivated. Therefore, EGR valve deactivation caused an increase in NO_X emissions of 180%. When driven in second gear at 50 km/h, the EGR valve remained closed (0%). This action is a consequence of the natural calibration of the engine and depends on the respective operating point of the engine (more on this in subsection 3.2.3). In this case, NO_X mass flow was approximately equal in both cases, i.e., with the EGR valve both activated and deactivated.

Driving in third and fourth gear with activated EGR resulted in significantly lower emissions. In the third gear, the EGR valve was opened 35%, while in the fourth gear it was opened 26%. Table 4 shows the comparison of NO_X emissions at a constant speed of 50 km/h, with the EGR valve activated and deactivated, respectively. The calculated NO_X increase factor indicates the importance of the EGR valve functionality.

Fig. 9 shows NO_X mass flow with activated and deactivated EGR during the Gear IV-V-VI cycle. In the cycle, at the maximum driving speed of 80 km/h, NO_X EF was 1022 mg/km with an activated EGR valve and 2822 mg/km with a deactivated valve. EGR valve deactivation caused an increase in NO_X emissions of 176%. In the cycle, at the maximum driving speed of 100 km/h, NO_X EF was 1072 mg/km with an activated valve and 3060 mg/s when the valve was deactivated. The deactivated EGR valve increased NO_X emissions by 185%. When driven at a constant speed of 80 km/h and 100 km/h with deactivated EGR, significantly higher NO_X emissions were

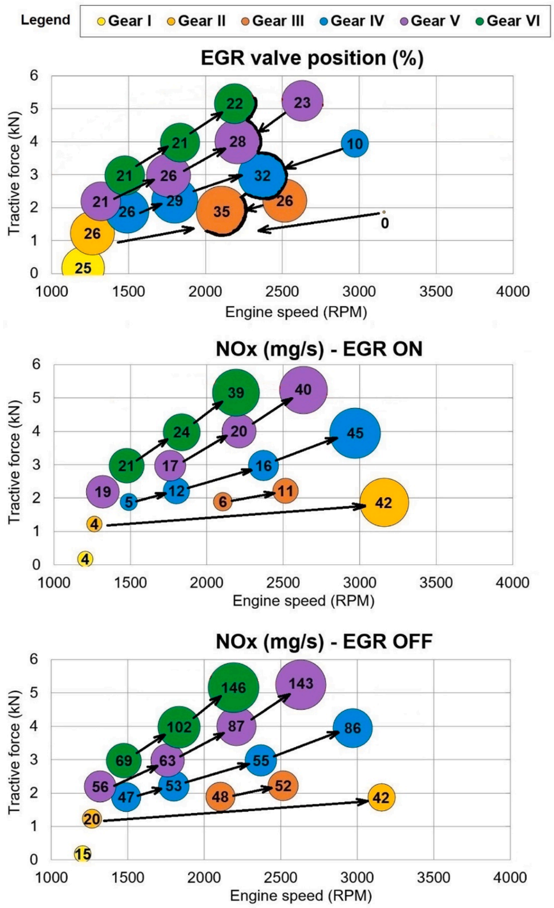

Fig. 11. EGR valve position and NO_X emissions with the EGR valve ON/OFF in the engine operating field.

always achieved, compared to driving with the activated valve, Fig. 9.

The higher the driving speed is, the higher are NO_X emissions with deactivated EGR, Table 5.

Fig. 10 shows NO_X mass flow with activated and deactivated EGR valve during Gear V-VI cycle. NO_X EF was 1197 mg/km when the valve was activated, and 3673 mg/km when it was deactivated. EGR valve deactivation caused an increase in NO_X emissions of 207%. When driven at a constant speed of 120 km/h with a deactivated valve, significantly higher NO_X emissions were achieved compared to driving with an activated EGR valve.

3.2.3. EGR valve position and NO_X emissions in the operating range of the engine

The tractive force on the driven wheels at constant driving speed on the chassis dynamometer corresponds to the driving resistances. Since gradient and acceleration resistances are not present here, the total driving resistances are obtained by applying Eq. (3).

$$F_R = (0.5 \times \rho \times c_w \times A_{front} \times v^2) + (m \times g \times \mu_f) + (m \times g \times \mu_r) \quad (3)$$

where:
F_R = driving resistances (N);
ρ = air density (kg/m^3);
c_w = air resistance coefficient (-);
A_{front} = vehicle frontal area (m^2);
v = driving speed (m/s);
m = vehicle mass (kg);
g = gravitation constant (m/s^2);
μ_f = tire flexing resistance coefficient (-);
μ_r = tire rolling resistance coefficient (-).

The MAHA test setup records the tractive force measured at the drive wheels during the measurement. The tractive force on the drive wheels in the selected gear is directly proportional (~) to the engine load. For this reason, the tractive force was used instead of

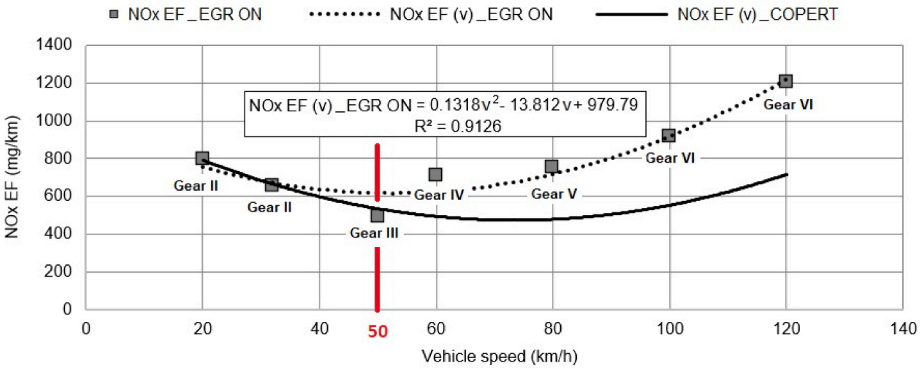

Fig. 12. Comparison of NO_X EF speed-dependent function with the COPERT curve.

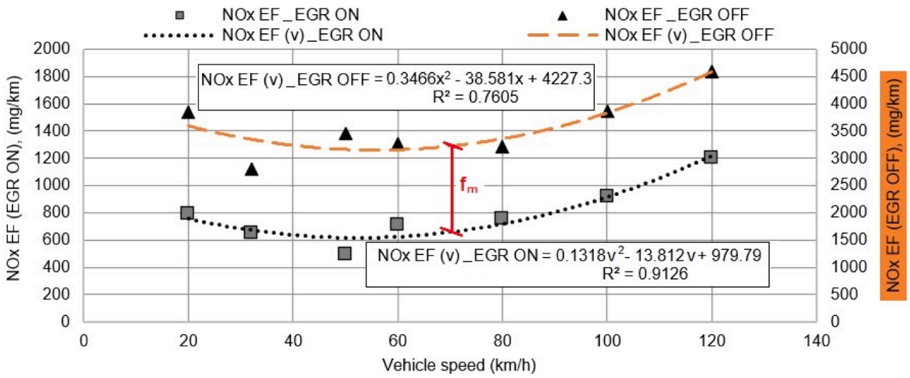

Fig. 13. Comparison of NO_X EFs and their speed-dependent functions, with activated and deactivated EGR valve, respectively.

the engine torque in the following graphs, Fig. 11. Although the operating range of the engine under load is from about 1000 to 4000 RPM, the EGR valve position graph shows that the EGR valve operates in the low to medium speed range. As engine load and speed increase, the EGR valve position also increases. However, above an engine speed of 2200–2400 RPM the EGR valve position decreases. For example, in fourth gear at 2970 RPM the position of the EGR valve was significantly reduced to 10% and in second gear at 3160 RPM the EGR valve was completely closed (0%).

The graphs NO_X (mg/s) - EGR ON and NO_X (mg/s) - EGR OFF show that with increasing engine load and speed, the NO_X emissions generally increase, regardless of the position of the EGR valve. With the EGR valve activated, NO_X emissions remained below 25 g/s in the range of low to medium loads and speeds. At higher loads and speeds, the position of the EGR valve is reduced, increasing emissions up to 45 g/s. This action is a result of the engine's natural calibration and depends on each individual engine operating point. When the EGR valve is deactivated, emissions increase significantly over the entire engine operating range - up to 146 g/s, Fig. 11.

3.3. *Verification of NO_X EFs as speed-dependent functions*

Engine calibration takes into account numerous parameters that lead to deviations in particular emissions. As mentioned earlier, emissions vary even at the same speed depending on the gear used, due to changes in engine operating conditions. However, there are some emission inventory calculating methods that describe emissions in a simplified form, without many influencing parameters. According to the Tier 3 approach, the NO_X hot EFs are speed-dependent and the methodology described in the EMEP/EEA guidebook is implemented in COPERT (EEA, 2019). For the test vehicle, which conforms to the Diesel/Medium/Euro 5/DPF configuration according to COPERT nomenclature, Eq. (4) was used to calculate *NO_X EF*.

$$EF_{NO_X}(v) = \frac{\left[0.0000667136 \bullet v^2 - 0.011381467 \bullet v + 0.945951727 + \left(\frac{1.923608149}{v}\right)\right]}{-0.0000515046 \bullet v^2 + 0.004264272 \bullet v + 1} \quad (4)$$

where:
$EF_{NO_X}(v)$ = COPERT NO_X EF speed-dependent function (g/km);
v = vehicle speed (km/h).

Since the emissions are measured at different constant driving speeds, it is possible to write an equation for the set of measurement points, i.e., a second-degree polynomial, similar to the one defined in the EMEP/EEA guidebook. The motivation for verification of

Table 6
NO_X emissions and relative increase in NO_X emissions with deactivated EGR, according to the cycle driven.

Cycle	NO_X (mg/km)		NO_X increase (%)
	EGR ON	EGR OFF	
ECE-15	941	3377	259
EUDC	630	3196	407
NEDC	748	3267	337
Gear I-II	1625	5564	242
Gear II-III-IV	1300	3646	180
Gear IV-V-VI (80 km/h)	1022	2822	176
Gear IV-V-VI (100 km/h)	1072	3060	185
Gear V-VI	1197	3673	207

NO_X EFs as speed-dependent functions arose from the question of whether the measurement results correspond to the data in COPERT. For the measured NO_X EFs at different constant driving speeds and gear ratios, a second-degree polynomial was created and compared with the COPERT curve, Fig. 12.

It can be concluded that the measured results fit well in the COPERT data in the low-speed area, ranging from 20 km/h to 50 km/h. However, for driving speeds above 50 km/h, a significant deviation was observed. That is, the higher the driving speed, the greater the deviation in NO_X EFs. The data in COPERT are based on experimental measurements of a number of vehicles in a real traffic scenario, whereas the results of this study refer to a vehicle tested in the laboratory. As the test conditions differ from those in COPERT, the application of this verification is limited.

However, the measurements with activated and deactivated EGR valve were performed under the same test conditions. Therefore, the speed-dependent methodology can be applied to the results of this study before and after manipulation of the EGR valve. A similar functional dependence of NO_X EFs on driving speed was also found in the case of measurements with deactivated EGR, Fig. 13. An important finding is that the NO_X EF function with deactivated EGR valve is significantly higher than the NO_X EF function with activated valve.

With activated EGR valve, NO_X EF function based on quadratic regression model fits the measured data with a coefficient of determination $R^2 = 0.91$. A slightly lower data matching was obtained in the case of the deactivated valve ($R^2 = 0.76$). From the graph in Fig. 13. one can visually conclude that both polynomials are qualitatively very similar. This leads to the following hypothesis: The emission factor of a vehicle with deactivated EGR valve can be determined relatively accurately if the EF of a vehicle with activated EGR valve is known.

For a test vehicle with the EGR valve deactivated, NO_X EF can be calculated by applying Eq. (5):

$$EF_{NO_{X_d}}(v) = EF_{NO_{X_a}}(v) + f_m(v) \tag{5}$$

where:
$EF_{NO_{X_d}}(v)$ = NO_X EF speed-dependent function for EGR OFF case (g/km);
$EF_{NO_{X_a}}(v)$ = NO_X EF speed-dependent function for EGR ON case (g/km);
$f_m(v)$ = speed-dependent factor of increased emissions due to manipulation (g/km).

For the test vehicle, the factor of increased emissions due to the manipulation was between 2533 and 3368 g/km. This finding, if applied to a wider range of vehicles, could be implemented in existing emission calculation models such as COPERT.

Regarding the functional dependence between NO_X EFs and driving speed, the comparison of the measured results with the data from the EMEP/EEA guidebook indicated significant differences at driving speeds higher than 50 km/h. Most NO_X emissions are generated at higher engine RPMs and loads (García and Monsalve-Serrano, 2019; Nuesch et al., 2014; Oglieve et al., 2017). To reduce NO_X emissions, the share of EGR needs to be increased (Agarwal et al., 2011). However, with an EGR share of more than 30%, there is a significant increase in particulate matter emissions (Wang et al., 2017). Therefore, the application of the EGR system is limited to low and moderate engine RPMs and loads (CITA, 2019). Consequently, newer Euro 6 diesel cars should along with EGR also use one of the after-treatment technologies, such as lean NO_X trap (LNT) or SCR to reduce NO_X emissions (Myung et al., 2017; Söderena et al., 2020). Since the test vehicle had only an EGR system to control NO_X emissions, the fact that EFs are significantly higher at higher driving speeds compared to the COPERT data is not surprising. However, the average values of NO_X emissions with activated EGR valve do not deviate significantly from the results of related studies (Cha et al., 2019; O'Driscoll et al., 2016).

3.4. Discussion

According to the data from Table 3, which shows EGR valve position depending on vehicle gear and speed, it can be concluded that the valve position largely depends on driving conditions, and ranges from 0% to 35%. When the engine was idling, the EGR valve position varied between 0% and 25%, and the percentage greatly depended on the previous engine operating mode. Due to a larger number of records in the fourth and fifth gear, it is evident that the position of the EGR valve rises with the increase of the driving speed up to a certain limit. After crossing that limit, the position of the EGR valve decreases. By further increasing the driving speed, the EGR valve closes completely, as was the case when driving in second gear at a speed of 50 km/h. When manufacturers' calibration measures for these operating conditions are taken into account, the performances are within the normal values for this type of engine.

Table 7
NO_X emissions and relative increase in NO_X emissions with deactivated EGR at different constant driving speeds.

Gear	Vehicle speed (km/h)	EGR valve position (%)	NO_X (mg/km)		NO_X increase (%)
			EGR ON	EGR OFF	
I	10	25	1583	6049	282
II	20	26	797	3852	383
	50	0	3142	3188	1
III	50	35	492	3534	618
	60	26	812	3265	302
IV	50	26	384	3464	802
	60	29	710	3320	368
	80	32	753	2637	250
	100	10	1647	3210	95
V	60	21	1096	3518	221
	80	26	786	2926	272
	100	28	722	3267	352
	120	23	1225	4514	268
VI	80	21	975	3211	229
	100	21	917	3865	321
	120	22	1206	4587	280

According to the Gear N cycle, EGR valve deactivation caused NO_X emissions to increase by 13.7%. As the Gear N cycle represented a test without a load, an increase in NO_X emissions was the smallest compared to other cycles driven. An increase in NO_X emissions was determined in all loaded tests with deactivated EGR valve, Table 6. The rise in NO_X emissions is significant and ranges from 176% to 407%, depending on the cycle driven. Comparing the Gear IV-V-VI cycle at 80 km/h and 100 km/h, the following conclusion can be drawn: the higher the driving speed, the higher the NO_X emissions with deactivated EGR valve.

In the case of deactivated EGR, the driving speed increases from 80 km/h to 100 km/h in the same gear, and an increase in NO_X emission was observed. Emissions increased by 21.7% in fourth gear, 11.7% in fifth gear, and 20.4% in sixth gear. However, at a driving speed of 120 km/h in fifth and sixth gear, no significant differences either in EGR valve position or in NO_X emissions were observed.

An increase in NO_X emissions at any of the constant driving speeds was detected with deactivated EGR, Table 7. It ranges from 95% to 802%, except in the second gear at 50 km/h, with EGR deactivated at all times. The highest NO_X emission by far was recorded in first gear at 10 km/h with deactivated EGR, which is a driving regime that occurs during urban rush-hour driving. Extremely high NO_X emissions with deactivated EGR were achieved at higher driving speeds and higher loads, during extra-urban driving, where the value reached 4514 mg/km in fifth gear at 120 km/h, and 4587 mg/km in sixth gear.

Given the findings and conclusions from this research, it would be scientifically beneficial to continue the research of fault detection techniques on the EGR or any other emission reduction system built in vehicles.

4. Conclusions

The purpose of this study was to define the impact of deactivating the EGR valve in a diesel Euro 5 car on NO_X emissions. It was carried out by measuring car emissions on a chassis dynamometer at nine driving cycles with activated and deactivated EGR valve, respectively. In all observed tests, a significant increase in NO_X emissions was found with deactivated EGR. Since the Gear N cycle represented a test without load, an increase in NO_X emissions was the smallest compared to loaded cycles driven. NO_X emissions increased between 176% and 407%, depending on the loaded cycle driven. During NEDC, deactivated EGR contributed to NO_X increase of 337%. Although gear selection at the same driving speed considerably affects NO_X emissions with activated EGR, this is not the case when the EGR valve is deactivated. Finally, the following conclusion was drawn: the higher the driving speed in a selected gear is, the higher are NO_X emissions with deactivated EGR.

The results of this study indicate that EGR valve manipulations cause a significant increase in NO_X emissions. Regulatory authorities need to be informed about the effects of such manipulations in order to adopt more stringent measures with the view to preventing such interventions. As a deterrent to such activities, introducing penalties in the case of identified manipulations on exhaust system components should also be considered. Depending on new insight in relevant areas, CVH may plan to develop an EGR system failure detection method that could be applied during periodic technical inspections. This would make it possible to contribute to a significant reduction in NO_X emissions in road transport, which would in turn result in a positive impact on both the environment and human health.

The limitation of the proposed method is that it was applied to the test vehicle under laboratory conditions on a chassis dynamometer. Therefore, in the research that will follow a test vehicle with a PEMS device in a real traffic scenario will be used. This method can also be applied to other emission control systems, such as SCR catalytic converters, NO_X traps, urea dosing systems and others that are also susceptible to tampering. For vehicles with such non-functioning systems, the vehicle's NO_X EF could also be determined. In addition, the DPF system is also very susceptible to manipulation. Therefore, the effects of manipulations on the DPF system on other harmful exhaust substances such as particulate matter (PM) can also be considered.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Article III (Published journal article)

An estimate of the NO_X emissions of Euro 6 diesel passenger cars with manipulated emission control systems

sustainability

Article

An Estimate of the NO_X Emissions of Euro 6 Diesel Passenger Cars with Manipulated Emission Control Systems

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Abstract: The motivation for conducting this research stems from the increasingly applied manipulations of emission control systems (ECSs), especially those in diesel passenger cars (PCs). The study aimed to investigate the influence of manipulations of exhaust gas recirculation (EGR) valves and a diesel exhaust fluid (DEF)-dosing system on the nitrogen oxide (NO_X) emissions of a Euro 6 diesel vehicle and, through the quantification of vehicles with manipulated ECSs, estimate the emissions of Euro 6 diesel PCs. Portable emissions measurement system (PEMS) measurements were performed on a Euro 6 diesel vehicle at a constant speed and on real driving emission (RDE) routes. The speed-dependent functions of the NO_X hot emission factor (EF) were calculated for seven different scenarios. The results showed that the NO_X EFs for the worst-case scenarios were more than two orders of magnitude higher than those where all ECSs were active. Applying the calculated EFs and the survey answers on the percentage of manipulated PCs to the Croatian Euro 6 diesel PC fleet, the results showed that the emission levels were up to 46.3% higher than the emissions calculated by the official computer program COPERT v5.6.5, with a tendency towards significantly higher values. The main conclusion is that vehicle manufacturers, policymakers, and the general public need to be informed about the enormous damage that in-use vehicles with manipulated ECSs cause to the environment and human health, in order to prevent such actions.

Keywords: nitrogen oxides (NO_X); emission factors (EFs); emission control systems (ECSs); exhaust gas recirculation (EGR); diesel exhaust fluid (DEF); portable emissions measurement system (PEMS)

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1. Introduction

With the entry into force of Directives 91/441/EEC and 93/59/EEC on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emissions from motor vehicles, the era of limiting emissions of nitrogen oxides (NO_X) from passenger cars (PCs) has begun in the European Union (EU). One widely accepted technique to reduce NO_X emissions in diesel engines is exhaust gas recirculation (EGR) [1]. The application of non-cooled EGR started in some Euro 1 light-duty vehicles (LDVs), becoming the primary NO_X reduction strategy in nearly all Euro 2 LDVs. Cooled EGR was implemented in some Euro 3 larger-engine LDVs, becoming the standard in Euro 4 and later diesel vehicles. Since 2014, the Euro 6 emission standard has been in force. The installation of two EGR loops, high-pressure (HP) and low-pressure (LP), has become the standard in Euro 6 diesel vehicles. HP EGR is used at lower engine speeds and loads, while at higher engine loads and speeds, LP EGR is applied. Another NO_X reduction technique applied to a wide range of Euro 6 diesel LDVs is the lean NO_X trap (LNT), also known as the NO_X adsorber [2]. A more recent technique for reducing NO_X emissions that is applied to Euro 6 larger-size engine vehicles is selective catalytic reduction (SCR) with urea, also known as diesel exhaust fluid (DEF) [3]. Combining 10–20% EGR with the SCR system gives the best results in NO_X reduction [4]. This way, vehicles equipped with EGR and

SCR can meet even the strictest requirements of the NO_X emission limit values of the Euro 6 emission standard.

Despite all the mentioned NO_X reduction techniques, some manufacturers have cheated on emission tests at type approval by installing illegal software, also known as a "defeat device", that could detect when the vehicle was being tested, changing its performance accordingly to improve its NO_X emission values [5]. Not long after the "Dieselgate" scandal was published, the requirements for measuring emissions at type approval became stricter. Since September 2017, for measurements of emissions at type approval, the longer-lasting and more dynamic Worldwide Light-duty Test Procedure (WLTP) has begun replacing the New European Driving Cycle (NEDC), which was used for many years until then [6–8]. In addition to laboratory measurements, measurements of particle number (PN) and NO_X emissions in real driving conditions, the so-called real driving emissions (RDE), were introduced [9,10]. Such measurements are performed with a portable emissions measurement system (PEMS) [11,12].

In principle, two approaches are used to estimate emissions from road transport: top–down and bottom–up. While the bottom–up approach begins from the local data or the specific emission source, the top–down approach starts from values of annual emissions assessed at a national level [13,14]. Official emission models used by European countries are COPERT, HBEFA, VERSIT+, EMV, and Liipasto. COPERT (Computer program to calculate emissions from road transport) is the EU standard vehicle emissions calculator, which is also globally adopted. It uses vehicle population, mileage, speed, and other data such as ambient conditions and calculates the emissions and energy consumption for a specific country or region [15–19]. Research on newer Euro 6 PCs conducted in the 2014–2016 period shows that NO_X emission factors (EFs) were twice the EFs used in emission models [20]. Because of those mentioned above, existing models for estimating emissions from road transport are constantly being upgraded, which is why they relatively well estimate the emissions from newer vehicles [21]. However, such models are mostly upgraded due to the entry of new vehicles on the market and the new technologies applied to such vehicles. In contrast, the models are not updated as a rule for older vehicles. The trend of increasing the age of vehicles in Europe has been ongoing since 2007, and it is known that vehicle emissions worsen with vehicle age [22,23].

In addition to older vehicles, newer vehicles are also subject to the deterioration and failure of emission control systems (ECSs) [24,25]. Diesel vehicles are more prone to breakdowns, especially if they are mainly used in urban traffic. Due to their high maintenance and replacement costs, such systems are often subject to illegal activities, i.e., tampering, such as physical removal or disruption, software deactivation, etc. [26,27]. The most common manipulations in diesel PCs and LCVs are on the EGR valve, diesel particulate filter (DPF), NO_X sensor, SCR, and DEF dosing system, etc. [28,29]. Previous studies have shown that tampering with ECSs significantly increases pollutant emissions, especially for NO_X and PN [30–32]. It is well known that the emissions mentioned above are very harmful to human health and the environment [33–36]. Because of that, harmful emissions are limited by legislation.

Manipulations of the ECSs of in-use vehicles are still a taboo subject that has not been sufficiently addressed by science and legislation. The motivation for conducting this research stems from the increasing number of services offered by car repair shops through online advertisements, including ECU remap, chip tuning, EGR OFF, DPF OFF, and DEF OFF, etc. Due to limited technical capabilities, the existing emission analysers in periodic technical inspection (PTI) stations cannot be used to detect tampering with the ECSs during the tailpipe emission test [37]. Even with the help of onboard diagnostics (OBD), it is difficult to determine whether ECSs have been tampered with [38]. In this way, many manipulated vehicles pass the emissions test without the disclosure of significant technical defects. Although the number of studies investigating the effects of manipulation on vehicle ECSs has increased in recent years, the question of quantifying such vehicles on the road and modelling their emissions remains topical. The contribution of manipulated vehicles to emissions at the fleet level remains unknown. The lack of such studies opens up space for new research. By measuring the emissions of manipulated vehicles under real driving conditions on the road, it is possible to create models that offer a more accurate assessment of the emissions of such vehicles. This work aimed to investigate the influence of manipulations of the EGR valve and DEF dosing system on the NO_X emissions of Euro 6 diesel PCs and, based on the PEMS measurements, to estimate the emissions of manipulated vehicles. However, to apply the emission results to the targeted part of the vehicle fleet, it is first necessary to know the structure of the vehicle fleet, which, for the Republic of Croatia, has been monitored in detail at the individual vehicle level since 2008 [39].

Furthermore, questions arise of how high the share of manipulated vehicles in the targeted vehicle fleet is and how much these vehicles contribute to the fleet's emissions increase. As ECS manipulations are not legal, there are no available data on the number of vehicles with manipulated ECSs at the level of an individual country. To estimate emissions inventories, some studies, among other sources, use the results of surveys conducted on respondents who are directly involved in creating harmful emissions [40,41]. This study aimed to estimate the share of manipulated vehicles in the vehicle fleet as accurately as possible so the calculation of NO_X emissions can be as realistic as possible. For this purpose, an anonymous survey was conducted among PC owners. The survey's main objective was to quantify car users' habits and preferences towards ECS manipulations. In a sample of 2000 respondents—owners of a PC with an internal combustion engine (ICE)—209 (or 10.45%) had carried out certain manipulations on the ECSs.

This paper proposes a novel approach to estimate the real driving emissions of vehicles with manipulated ECSs. This study is based on the Tier 3 methodology, where EFs depend on the average vehicle driving speed, as described in the EMEP/EEA air pollutant emission inventory guidebook [42]. Using the NO_X EFs determined in this study and applying the bottom–up approach, the emissions of Euro 6 diesel PCs were estimated. These values were then compared with the official computer program COPERT 5 results. The main conclusions are that the emissions of the test vehicle with both the EGR and DEF systems manipulated exceeded the typical values by more than two orders of magnitude compared to the case where all ECSs were active. Applying the survey results and extending them to the targeted fleet, the NO_X emissions of Euro 6 diesel PCs were calculated. The results showed that the hot emissions were up to 46.3% higher than those calculated by the official computer program COPERT 5, with a tendency towards significantly higher values. The innovation of this article is the quantification of the real NO_X emissions of the targeted vehicle fleet, primarily considering the impact of high-polluting vehicles—those with manipulated ECSs. This research was necessary to show where significant amounts of "hidden" NO_X emissions from road transport come from and to encourage policymakers to develop methods to prevent such manipulations. The results of this study are of great importance for vehicle manufacturers and policymakers, but also for the general public, to raise awareness and stimulate action to prevent the tremendous damage that vehicles with manipulated ECSs cause to the environment and human health. Based on additional measurements, it is planned to create a model for calculating the emissions of manipulated vehicles.

2. Materials and Methods

2.1. Measurement Equipment and Test Vehicle

The measurements were carried out with the equipment owned by the National Reference Laboratory for Emissions from Internal Combustion Engines for Non-Road Mobile Machinery from the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb. The technical data of the measuring equipment used are listed in Table 1.

Table 1. Technical data of the measuring equipment.

Device	Manufacturer and Model	Specifications	
PEMS	AVL M.O.V.E GAS PEMS iS+	Exhaust concentrations: CO, CO_2, NO, NO_2, O_2	Power supply: 22–28.8 V DC (max. 28 A)
		Measurement principle: NDIR, NDUV, O_2 sensor	Power consumption: <300 W
		Engine parameters: OBD	Dimensions: 495 × 334 × 377 mm
		Vehicle speed and position: GPS (GARMIN)	Mass: 30 kg (without accessories)
		Exhaust mass flow and temperature: EFM 495	Noise load: <70 dB(A)
		Update recording frequency: Up to 5 Hz for gaseous components	Operation sea level: <3000 m
		Ambient parameters: pressure, temperature, relative humidity	Relative air humidity: ≤95%, non-condensing

The measurements were carried out on a company minivan with known technical data, PTI results, and regular maintenance activities. The technical data of the vehicle can be found in Table 2.

Table 2. Technical data of the test vehicle.

General Features	Specifications
Make	Volkswagen Wolfsburg, Germany
Commercial name	Caddy (IV)
Homologation type	2KN
Year of production	2020
Mileage	55,000 km
Mass in running order	1794 kg
Drive	All-wheel drive (4motion)
Gearbox	Manual (6-speed)
Tyre size; load index and speed rating	205/55 R 16; 94H
Tyre pressure	Without load: 2.7 bar With load: 2.9 bar (front)/3.2 bar (rear)
Engine designation	2.0 TDI 1968 cm^3 Four-cylinder turbocharged
Engine power	90 kW (2750–4250 min^{-1})
Emission standard	Euro 6 d-TEMP-EVAP-ISC
Emission control	DOC, DPF, HP EGR, LP EGR, SCR + DEF, ASC
NO_X type-approval value	WLTP: 47.7 mg/km
	Max. RDE: 220.5 mg/km

For safety reasons, the test vehicle had a yellow warning system on the roof and an additional bracket for the rear registration plate and lighting equipment. The test vehicle with installed measuring equipment is shown in Figure 1.

Figure 1. Test vehicle with installed measuring equipment.

2.2. Measurement Procedure

Before the NO_X emission measurement started, preparatory measures were carried out according to the instructions of the test equipment manufacturer, including a pre-test procedure following Commission Regulation (EU) 2018/1832 to improve the emission type approval tests and procedures for light passenger and commercial vehicles, including those for in-service conformity and real-driving emissions. Immediately, the engine and exhaust system components were warmed to normal operating temperature (coolant temperature ≈ 90 °C). After that followed the main test—constant speed and then RDE. During the RDE run, all driving requirements met the Commission Regulation (EU) 2018/1832 criteria. After each measurement, a post-test activity was also carried out following the abovementioned regulation.

Cold-start emissions are excluded from all measurements, and only hot emissions are observed to simplify and speed up the test procedures. Therefore, the measurement results are not comparable with the type approval values, as they include the cold-start phase. Tests in which the DPF regeneration was identified were not considered. All measurements were carried out in the second half of September and the first half of October 2022 at an ambient temperature between 10 and 25 °C to minimise the effects of this parameter. All tests were conducted during calm weather conditions to prevent extra wind resistance to the test vehicle. The appearance of additional rolling resistance was prevented so that tyres were inflated depending on the vehicle's load to the pressure prescribed by the manufacturer. During the RDE measurements, slope resistances through an elevation change were kept far below the limits of Commission Regulation (EU) 2018/1832.

NO_X concentration was measured by non-dispersive ultraviolet spectroscopy (NDUV) and reported in parts per million (ppm). The NO and NO_2 emission analyser display resolution was 0.1 ppm. The accuracy of the analyser was ±0.2% of full scale or ±2% rel. The mass flow rate of the exhaust gases was measured with a flow meter and is expressed in kilograms per hour (kg/h). The accuracy of the exhaust gas flow meter was ±2.0% of a reading or ±0.5% of full scale, whichever was greater. Vehicle speed (v) was measured with the Garmin GPS device and is expressed in kilometres per hour (km/h). With the above-known data—NO_X concentration, NO_X mass flow rate, and vehicle speed—the averaged NO_X EFs were calculated, as shown in Equation (1) below.

$$EF_{NOx} = \frac{\int_0^t f(E_{NOx}(t))dt}{d} = \frac{AVG(E_{NOx}) \times t}{d} = \frac{AVG(C_{NOx} \times EMF) \times t}{d} \quad (1)$$

where:

EF_{NOx} = NO_X EF, related to the driving cycle (mg/km);
E_{NOx} = NO_X mass flow rate (mg/s);
$AVG(E_{NOx})$ = mean value of the NO_X mass flow rate per driving cycle (mg/s);
C_{NOx} = NO_X concentration (ppm);
EMF = exhaust mass flow rate (mg/s);
t = run time (s);
d = distance of the driving cycle (km).

2.3. Measurement Sequence

The first set of NO_X emission measurements was carried out on a vehicle with its ECSs activated, corresponding to the condition in which the vehicle was type-approved by the manufacturer. Before each further measurement, the vehicle was taken to an authorised Volkswagen workshop, where the individual ECSs were deactivated. Before the second series of measurements was carried out, the HP EGR was deactivated. For the third series of measurements, the LP EGR was deactivated. During the fourth series of measurements, the DEF injector was deactivated. The fifth set of measurements was performed on a vehicle with the HP EGR and the DEF injector deactivated. The sixth set of measurements was performed on a vehicle with the LP EGR OFF and DEF OFF. The seventh set of measurements was carried out on a vehicle with the HP EGR OFF, LP EGR OFF, and DEF OFF. The flowchart of the experiment is shown in Figure 2.

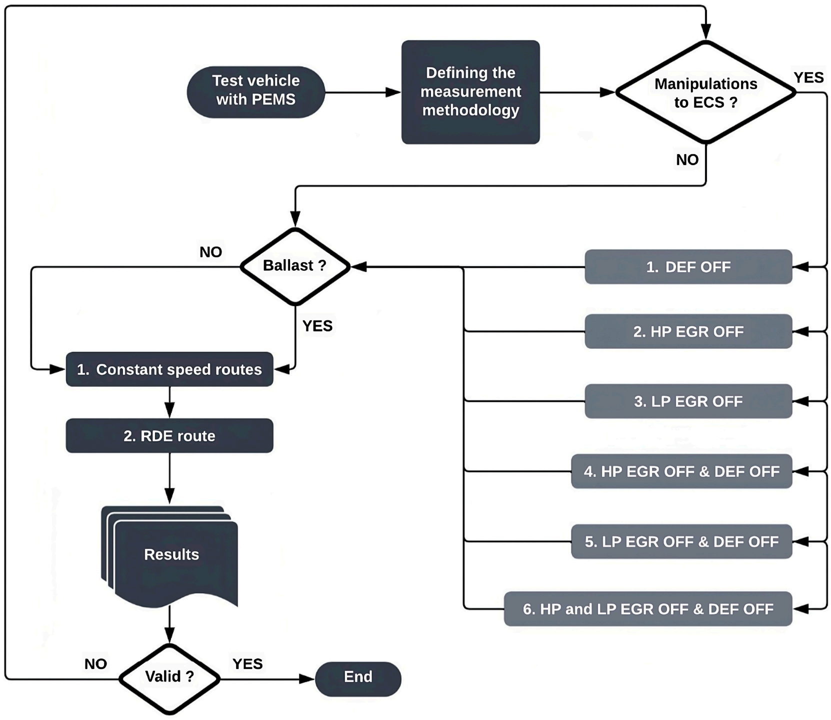


Figure 2. The flowchart of the experiment.

Each set of NO_X emission measurements included runs at constant speeds from 10 km/h to 140 km/h with a 10 km/h step under approximately steady-state engine operating conditions and runs under transient engine operating conditions, each with the vehicle mass in running order (MIRO) increased by the weight of the driver, an additional passenger, and the measurement equipment. The ballast was additionally used in two measurement series to determine the influence of the vehicle mass on emissions. The ballast increased the vehicle mass to the gross vehicle weight rating (GVWR).

2.3.1. Constant-Speed Runs

The runs in different selected gears, at constant speeds of 10 to 80 km/h, lasted 60 s and were carried out on a 2 km test track, while the runs at constant speeds of 90 to 140 km/h lasted 120 s and were carried out on a not frequently used motorway section with moderate gradients. The gear ratios and engine speeds for various constant driving speeds are given in Table 3.

Table 3. Engine and transmission data of the vehicle, relevant for different constant driving speeds.

<table>
<tr><th>Vehicle Speed (km/h)</th><th>Gear</th><th>Overall Gear Ratio (-)</th><th>Engine Speed (RPM)</th></tr>
<tr><td>10</td><td>1</td><td>15.962</td><td>1382</td></tr>
<tr><td>20</td><td>2</td><td>8.292</td><td>1436</td></tr>
<tr><td>30</td><td>3</td><td>5.323</td><td>1383</td></tr>
<tr><td>40</td><td>4</td><td>3.684</td><td>1276</td></tr>
<tr><td>50</td><td>5</td><td rowspan="3">2.805</td><td>1215</td></tr>
<tr><td>60</td><td>5</td><td>1457</td></tr>
<tr><td>70</td><td>5</td><td>1700</td></tr>
<tr><td>80</td><td>6</td><td rowspan="7">2.347</td><td>1626</td></tr>
<tr><td>90</td><td>6</td><td>1829</td></tr>
<tr><td>100</td><td>6</td><td>2032</td></tr>
<tr><td>110</td><td>6</td><td>2236</td></tr>
<tr><td>120</td><td>6</td><td>2439</td></tr>
<tr><td>130</td><td>6</td><td>2642</td></tr>
<tr><td>140</td><td>6</td><td>2845</td></tr>
</table>

2.3.2. RDE Trip

The transient engine operating conditions were fulfilled on the RDE route, which included the city of Zagreb and the surrounding area. The route length was 86 km, and the average travel time was 108 min. The RDE trips were divided into urban (U), rural (R), and motorway (M) segments. Accordingly, the average driving speeds and emission factors were calculated for each RDE driving segment.

2.4. Calculation Method Proposal

The Tier 3 methodology, where EFs depend on the average vehicle driving speed, as described in the EMEP/EEA air pollutant emission inventory guidebook, was used to estimate the real driving emissions of vehicles with manipulated ECSs. Since all measurements were taken when the engine and exhaust aftertreatment devices were heated to normal operating temperature, only the hot emissions were measured and included in this calculation.

A proposal for a general formula for determining the NO_X EFs of vehicles with deactivated ECS is shown below, Equation (2).

$$EF^{D}_{\mathrm{NOx}\_i}(v) = EF^{A}_{\mathrm{NOx}}(v) + f^{M}_{i}(v) \tag{2}$$

where:

$EF^{D}_{\mathrm{NOx}\_i}(v)$ = NO_X EF speed-dependent function for a vehicle with deactivated ECSs of type i (mg/km);

$EF^{A}_{\mathrm{NOx}}(v)$ = NO_X EF speed-dependent function for a vehicle with activated ECSs (mg/km);

$f^{M}_{i}(v)$ = speed-dependent function of increased emissions due to manipulation of ECS of type i (mg/km).

3. Results

This section contains the results of the emission measurements for seven different working regimes of the ECSs, as described in the measurement sequence section and shown in Figure 2. Based on the processed measurement results in Sections 3.1–3.7, the relevant Euro emission standard for the test vehicle was determined following the COPERT nomenclature in Section 3.8, and the NO_X emissions calculation for Euro 6 diesel vehicles with manipulated ECSs was proposed in Section 3.9. Based on an anonymous survey conducted among vehicle owners, the proportion of manipulated PCs in the Republic of Croatia was determined in Section 3.10. Considering the emission measurement results and the survey results, the NO_X emission inventory of the Euro 6 diesel PC fleet was assessed in six scenarios in Section 3.11.

3.1. Measurements with All ECSs Activated

The NO_X emissions of the test vehicle with activated ECSs had to be determined first. The vehicle emissions were considered for the case of MIRO and GVWR for driving at a constant speed and RDE driving, as shown in Figure 3.

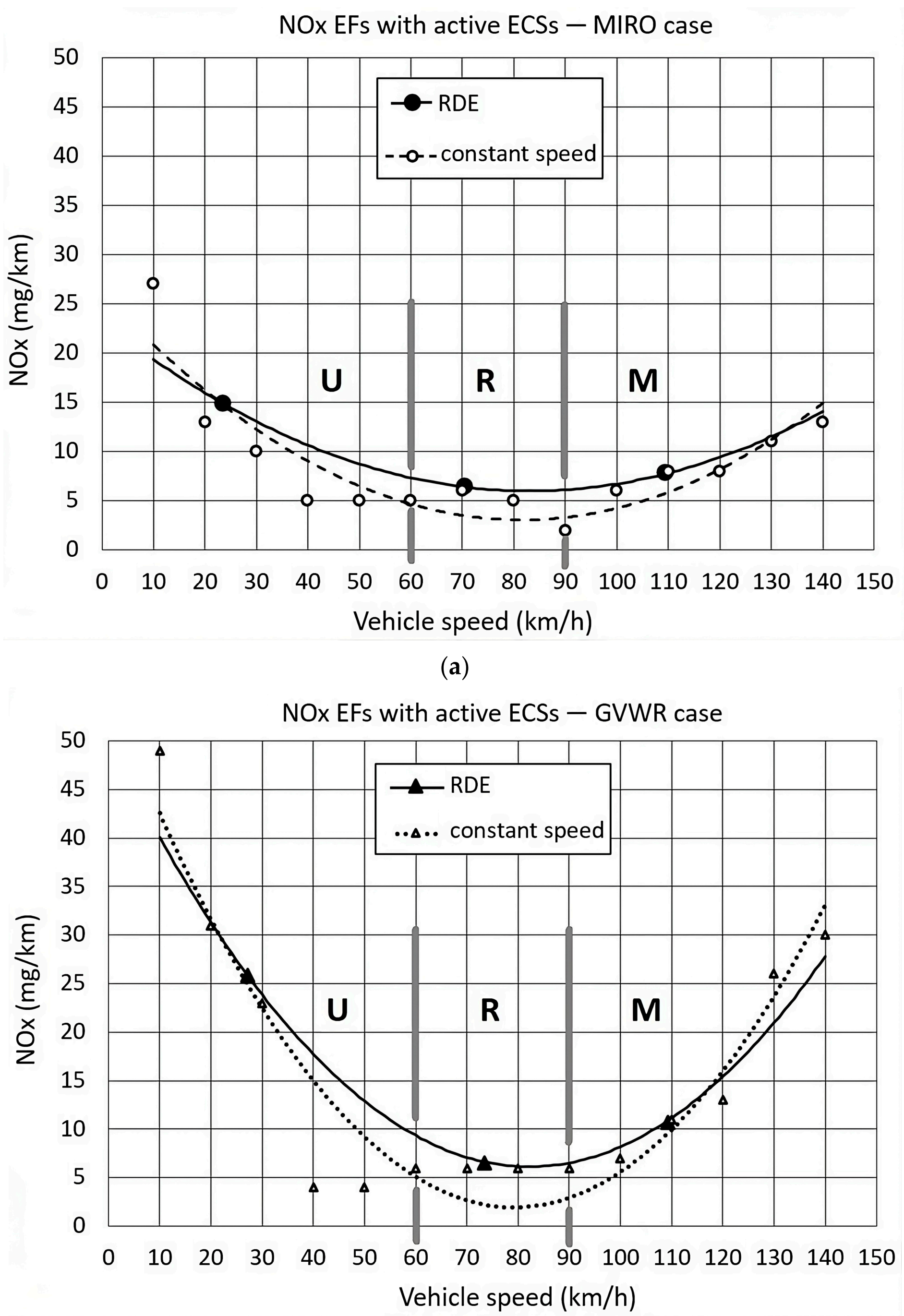


Figure 3. NO_X EFs with active ECSs for the case of MIRO (**a**) and GVWR (**b**).

For the case of MIRO at a constant speed, when all ECSs were activated, the function NO_X EF fits the measured data based on a quadratic regression model with a coefficient of determination R^2 = 0.81. A slightly higher data agreement was achieved in the case of GVWR at a constant speed (R^2 = 0.90). For the RDE trips, all measurement results where the driving speed was below 60 km/h were assigned to the urban part (U), those between 60 and 90 km/h to the rural part (R), and those above 90 km/h to the motorway part (M). Essential data such as trip distance, trip duration, average vehicle speed, and NO_X EFs were calculated for the U/R/M sections and are shown in Table 4.

Table 4. RDE trip results for the case where all ECSs were activated.

All ECSs Activated		**Mass of the Test Vehicle**		**Relative Increase (%)**
		MIRO 2050 kg	**GVWR 2350 kg**	
Trip distance (km)	Total trip	84.4	86.38	
	U	31.5	30.70	
	R	26.8	27.79	
	M	26.1	27.89	
Trip duration (min)	Total trip	117.1	105.75	
	U	80.0	67.73	
	R	22.8	22.70	
	M	14.3	15.32	
Average vehicle speed (km/h)	Total trip	43.2	49.01	
	U	23.6	27.19	
	R	70.5	73.45	
	M	109.4	109.25	
NO_X EF (mg/km)	Total trip	10.0	14.7	+47
	U	14.9	25.8	+73
	R	6.5	6.5	0
	M	7.9	10.7	+35

According to the results of the RDE test, an increase in vehicle mass of 300 kg led to an increase in emissions of 47% (total trip). The increase in emissions due to the increase in vehicle mass in the U/R/M section was 73%/0%/35%.

3.2. Measurements with the DEF System Deactivated

After unplugging the DEF module, a "Check Engine" light appeared on the dashboard with a warning message that the vehicle's range was limited to 1000 km and the engine could not be started after that. The emissions of the test vehicle when the DEF system was deactivated are shown in Figure 4.

For the case of MIRO at a constant speed, when the DEF system was deactivated, the function NO_X EF fits the measured data based on a quadratic regression model with a coefficient of determination R^2 = 0.88.

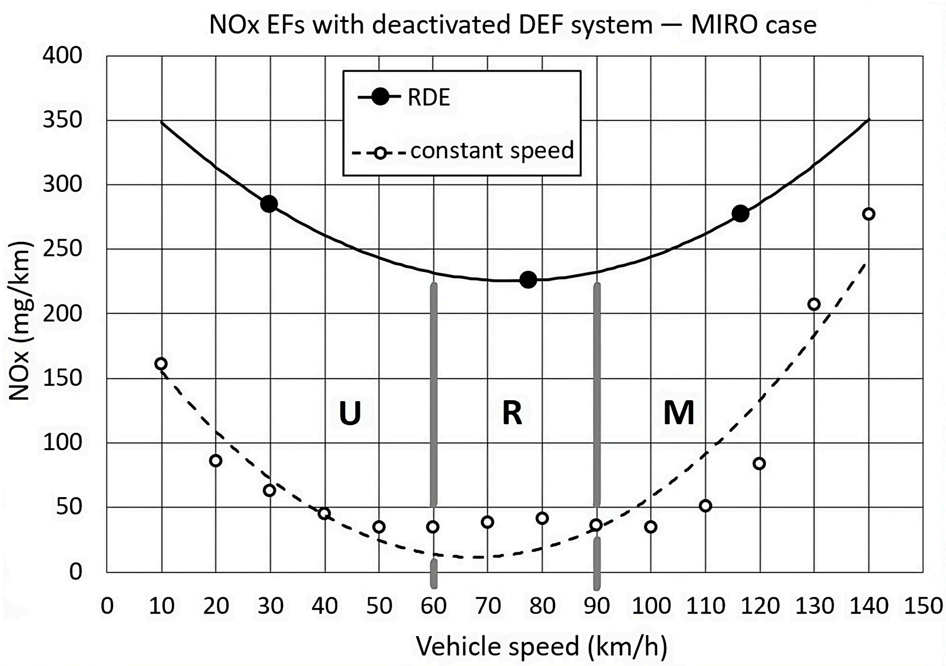


Figure 4. NO_X EFs with deactivated DEF system.

3.3. Measurements with the HP EGR Valve Deactivated

The HP EGR valve was deactivated by disconnecting the HP EGR valve connector, after which, a "Check Engine" light appeared on the dashboard. The emissions of the test vehicle after the deactivation of the HP EGR valve are shown in Figure 5.

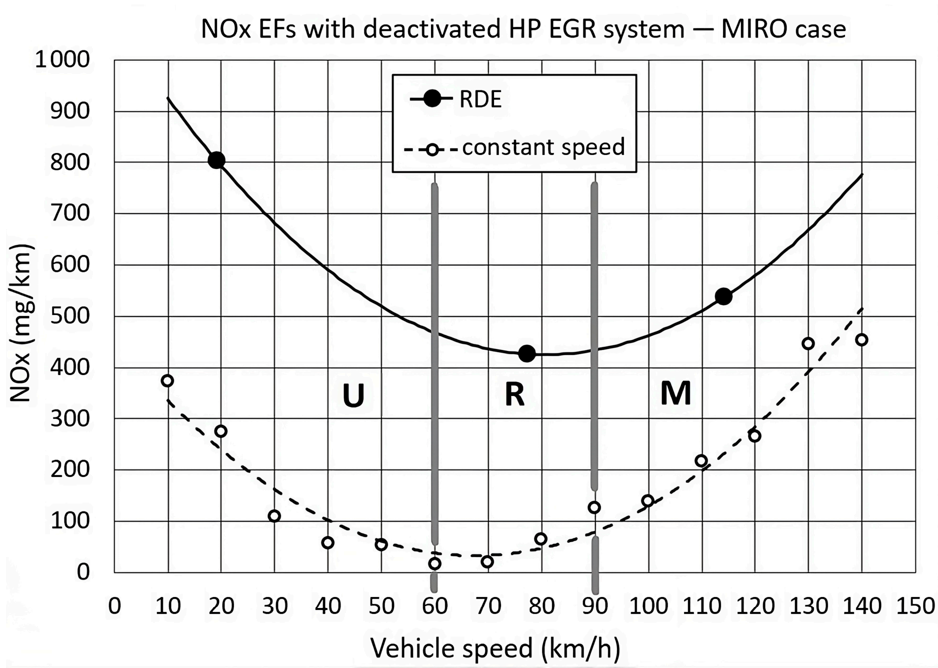


Figure 5. NO_X EFs with deactivated HP EGR valve.

For the case of MIRO at a constant speed, when the HP EGR valve was deactivated, the function NO_X EF fits the measured data with a coefficient of determination $R^2 = 0.94$.

3.4. Measurements with the LP EGR Valve Deactivated

Since the LP EGR valve is located in a hard-to-reach place on the vehicle, the LP EGR valve was deactivated by disconnecting the wires of the LP EGR valve from the engine control module. A "Check Engine" light then appeared on the dashboard. Diagnostic trouble codes relevant only to the LP EGR were found when the diagnostic tool check was performed. In other words, the other ECSs were functioning properly. The emissions of the test vehicle after turning off the LP EGR valve are shown in Figure 6.

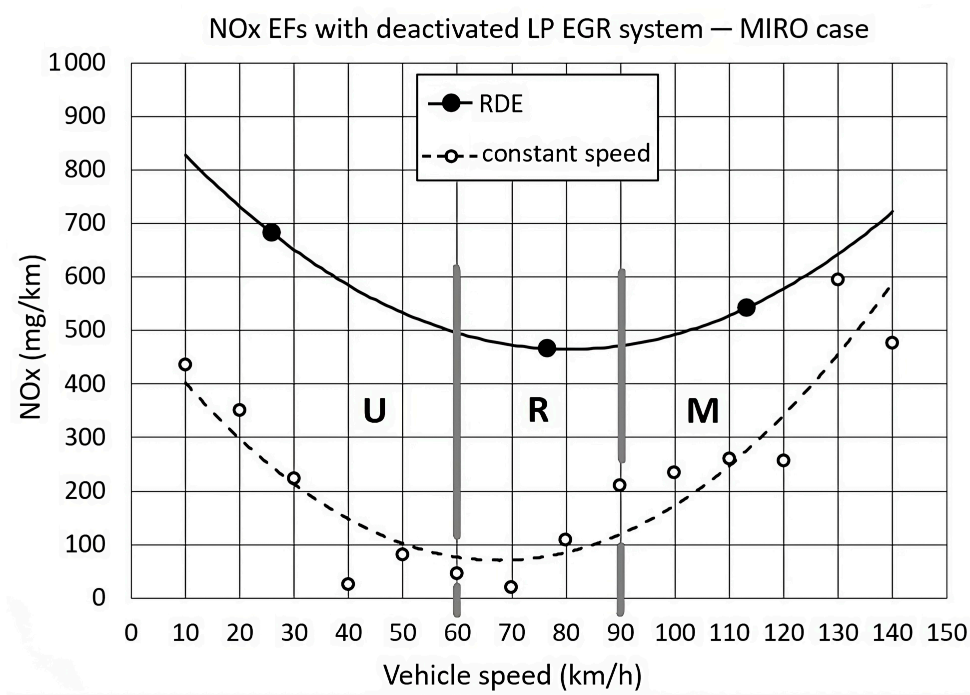


Figure 6. NO_X EFs with deactivated LP EGR valve.

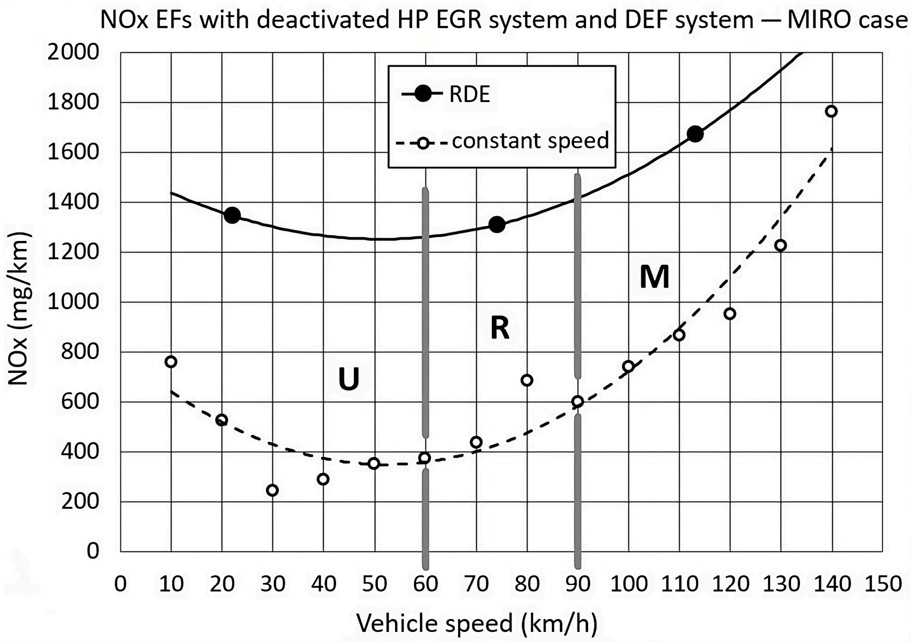
For the case of MIRO at a constant speed, when the LP EGR valve was deactivated, the function NO_X EF fits the measured data with a coefficient of determination $R^2 = 0.82$.

3.5. Measurements with Deactivated HP EGR Valve and DEF System

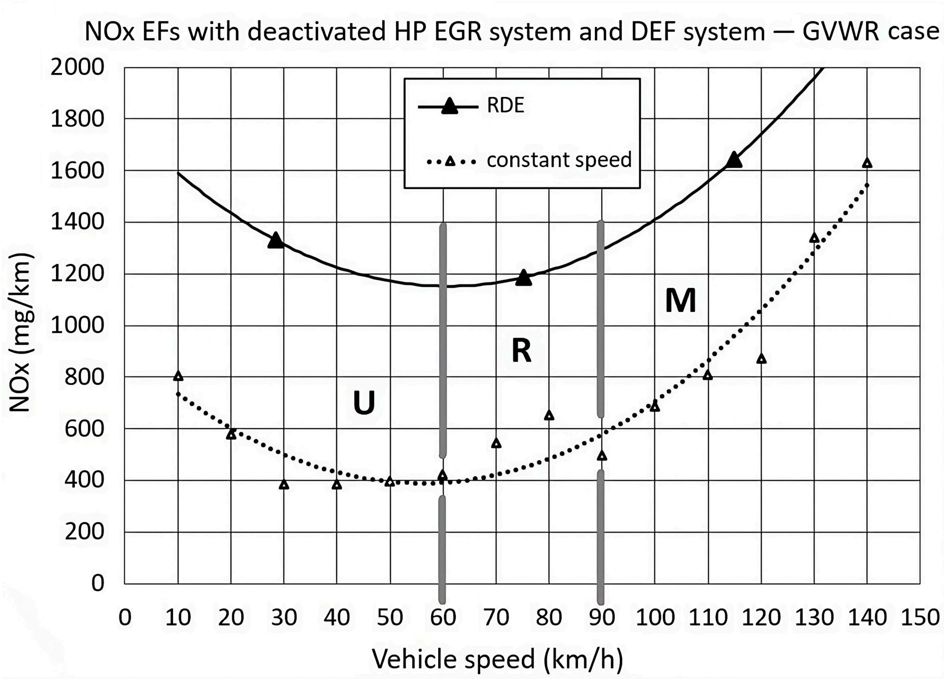
To determine the impact of manipulations on emissions when several ECSs were deactivated, a combination of deactivated HP EGR and DEF was first considered and tested, as shown in Figure 7.

For the case of both MIRO and GVWR at a constant speed, when the HP EGR valve and DEF system were deactivated, the function NO_X EF fits the measured data with a coefficient of determination $R^2 = 0.93$. For the RDE trips, relevant data such as trip distance, trip duration, average vehicle speed, and NO_X EFs were calculated for the U/R/M sections and are shown in Table 5.

According to the results of the RDE test with the HP EGR valve and the DEF system deactivated, increasing the vehicle mass by 300 kg did not affect emissions. Furthermore, emissions decreased by 3.6% on the overall route, while they decreased by 1.1%/9.5%/0.5% in the U/R/M sections. The main cause for this could be relatively lighter traffic conditions in the urban part of the RDE with GVWR.



(**a**)



(**b**)

Figure 7. NO_X EFs with deactivated HP EGR valve and DEF system for the case of MIRO (**a**) and GVWR (**b**).

Table 5. RDE trip results for the case where the HP EGR valve and DEF system were deactivated.

HP EGR OFF and DEF OFF		Mass of the Test Vehicle		Relative Increase (%)
		MIRO 2050 kg	GVWR 2350 kg	
Trip distance (km)	Total trip	86.1	85.6	
	U	29.3	29.0	
	R	29.3	28.5	
	M	27.5	28.2	
Trip duration (min)	Total trip	117.9	98.5	
	U	79.6	61.1	
	R	23.7	22.7	
	M	14.6	14.7	
Average vehicle speed (km/h)	Total trip	43.8	52.2	
	U	22.01	28.4	
	R	74.3	75.3	
	M	113.2	114.9	
NO_X EF (mg/km)	Total trip	1439	1387	−4
	U	1346	1331	−1
	R	1311	1187	−9
	M	1673	1664	−1

3.6. Measurements with Deactivated LP EGR Valve and DEF System

The influence of the simultaneous deactivation of the LP EGR valve and the DEF system on NO_X emissions is considered in this subsection, as shown in Figure 8.

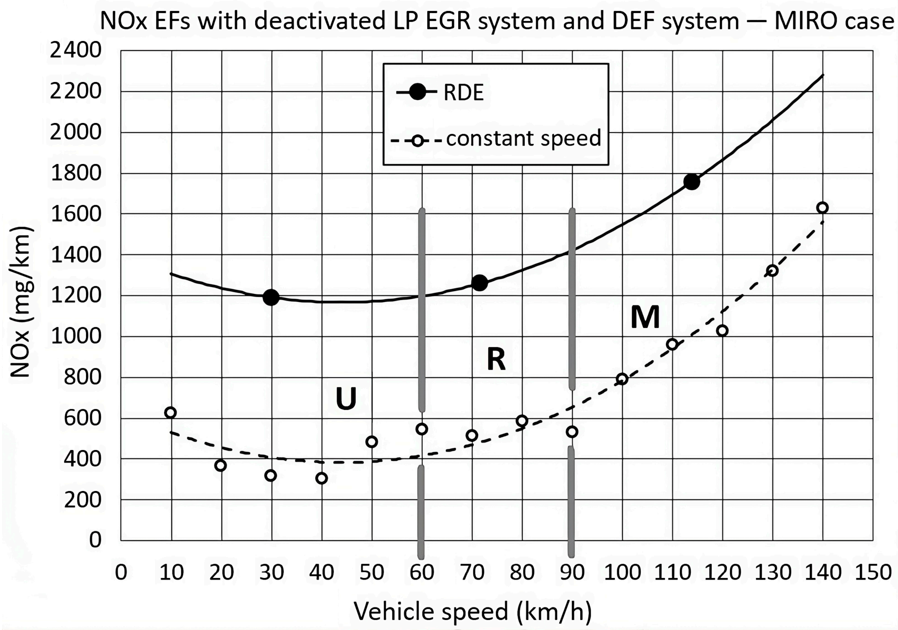


Figure 8. NO_X EFs of the car with the LP EGR valve and DEF system deactivated.

For the case of MIRO at a constant speed, when the LP EGR valve and DEF system were deactivated, the function NO_X EF fits the measured data with a coefficient of determination R^2 = 0.95.

3.7. Measurements with Deactivated HP and LP EGR Valve and DEF System

The influence of the simultaneous deactivation of HP and LP EGR and the DEF system on the emissions of NO_X is shown in Figure 9.

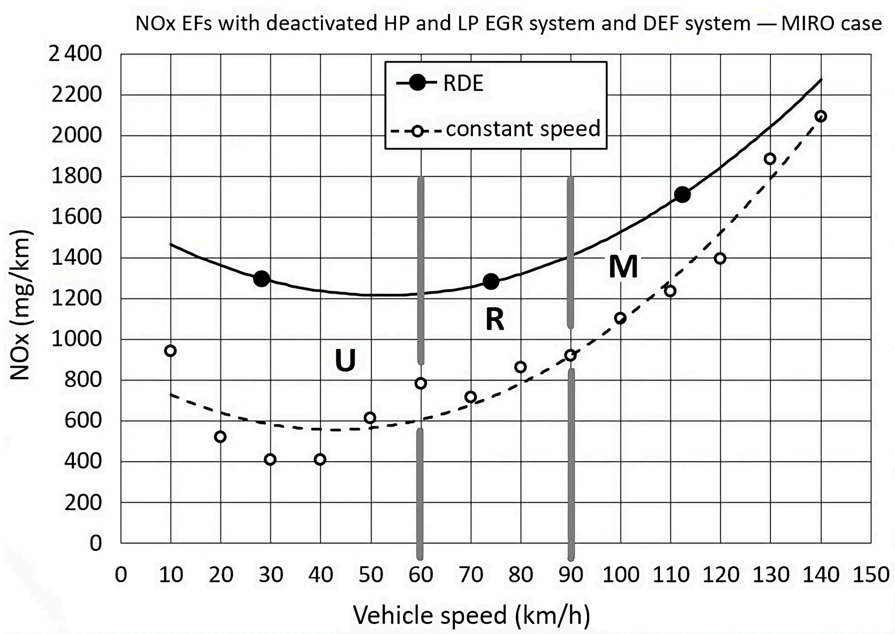


Figure 9. NO_X EFs with deactivated HP and LP EGR valves and the DEF system.

For the case of MIRO at a constant speed, when the HP and LP EGR valves and the DEF system were deactivated, the function NO_X EF fits the measured data with a coefficient of determination R^2 = 0.95.

3.8. Determination of the Relevant Euro Emission Standard from the COPERT Classification for the Test Vehicle When All ECSs Were Active

According to the COPERT Tier 3 method, NO_X hot Efs for N1 and M1 Euro 6 diesel vehicles are expressed in the form as shown in Equation (3) below [42].

$$EF_{\mathrm{Nox}}(v) = \frac{\alpha \cdot v^2 + \beta \cdot v + \gamma + \frac{\delta}{v}}{\varepsilon \cdot v^2 + \zeta \cdot v + \eta} \cdot (1 - \mathrm{RF}) \tag{3}$$

where:

$EF_{\mathrm{Nox}}(v)$ = NO_X EFs speed-dependent functions;

α, $\beta, \gamma, \delta, \varepsilon, \zeta, \eta$, RF = factors, related to the vehicle category and emission standard;

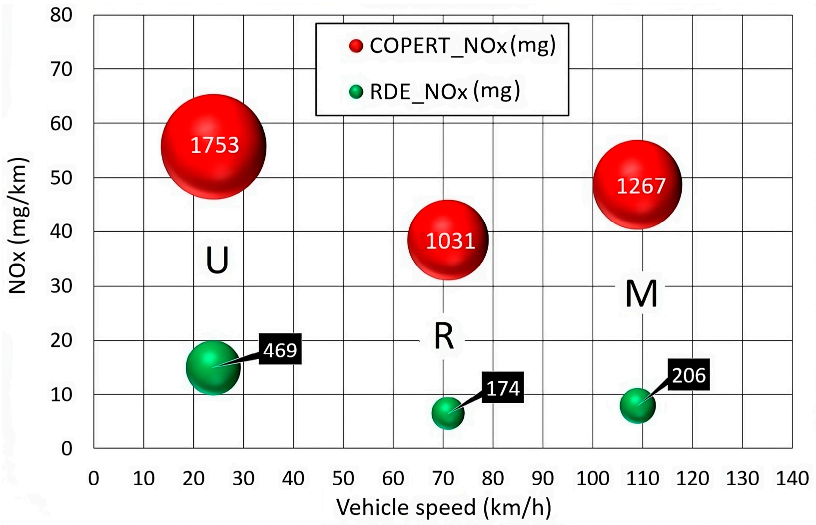
v = mean vehicle speed (km/h).

In an urban driving mode, driving dynamics, which include rapid speed variations and traffic congestion, cause high NO_X emissions. Cruising at moderate speeds in a rural mode leads to the lowest NO_X emissions, while air resistance significantly increases fuel consumption and emissions in general in the motorway mode.

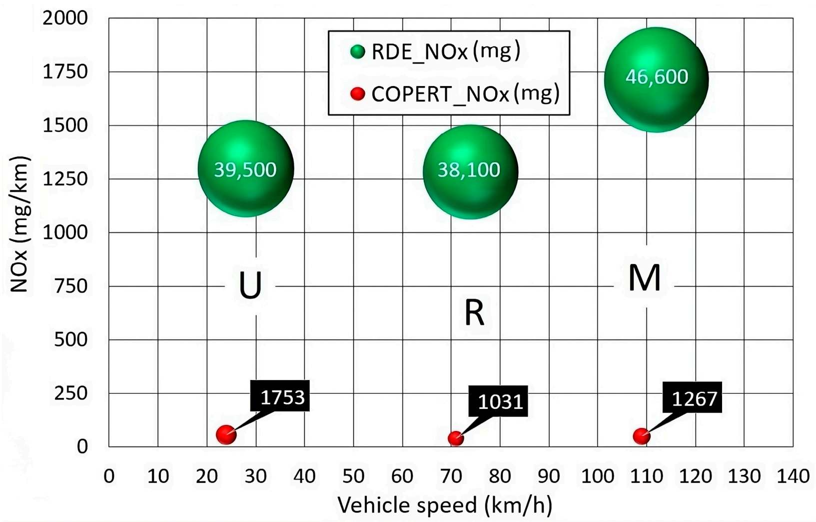
Although the test vehicle belongs to category N1—class III, it was approved according to the requirements of class II and received the exhaust emission standard Euro 6 d-TEMP-EVAP-ISC (https://dieselnet.com/standards/eu/ld.php). Comparing the NO_X EF polynomials obtained by measurements for the case when all ECSs were active, at a constant speed and during RDE driving, with the NO_X EF polynomials implemented in COPERT v.5.6.5, it can be concluded that the COPERT specification shows a significant overestimation. For this reason, the NO_X EFs of the Euro 6 d diesel vehicles of category M1 are better suited for further comparison.

3.9. Comparison of RDE NO_X Emissions of the Test Vehicle when ECSs Were Active/Inactive with the COPERT Calculation

It should be noted that the COPERT estimation is based on measurements conducted on a larger number of cars, and the NO_X EFs present the mean values of all tested vehicles. In the scenario where all ECSs were active, the RDE NO_X emissions were lower than the COPERT estimation by a factor of 3.7/5.9/6.2 for the U/R/M driving regime, as shown in Figure 10a. During the total RDE trip of 84.4 km, the PEMS counted 849 mg of NO_X emissions, while the COPERT calculated 4.051 g. Even in this case, the COPERT specification shows an overestimation.



(**a**)



(**b**)

Figure 10. Comparison of RDE NO_X emissions of the test vehicle when ECSs were active (**a**) and inactive (**b**) with the COPERT calculation.

In the scenario where NO_X ECSs were inactive, the RDE NO_X emissions were higher than the COPERT calculation by an increase factor of 23/37/37 for the U/R/M driving regime, as shown in Figure 10b. During the total RDE trip of 87.4 km, the PEMS counted 124.2 g of NO_X emissions.

3.10. Calculation of the Functions of Increased Emissions and NO_X Increase Factors for Euro 6 Diesel Vehicles with Manipulated ECSs

Based on the measurement results, Equation (2) was used to calculate the speed-dependent functions of increased emissions due to manipulation. The measurement results with deactivated ECSs indicated that the emissions from RDE trips were significantly higher than those from constant-speed trips. The above was to be expected, because RDE driving includes driving dynamics—acceleration, deceleration, and slope resistance—unlike driving at a constant speed. Therefore, the relevant results of the proposed calculation were those from RDE trips. The speed-dependent functions of the increased emissions due to the manipulation of certain ECSs of the tested vehicle with MIRO, together with the corresponding NO_X increase factors for the total RDE trips and the U/R/M sections, are shown in Table 6.

Table 6. Speed-dependent functions of the increased emissions due to manipulation of certain ECSs of the tested vehicle with MIRO and NO_X increase factors for the total RDE trips and the U/R/M sections.

ECS Scenario	$f_i^M(v)$	NO_X Increase Factor (-)			
		Total RDE Trip	U 30 km/h	R 70 km/h	M 110 km/h
(1) All ECSs active	0	1	1	1	1
(2) DEF OFF	$0.0008v^2 - 1.1199v + 306.95$	26	21	34	33
(3) HP EGR OFF	$0.0976v^2 - 15.737v + 1053.2$	58	51	67	64
(4) LP EGR OFF	$0.0727v^2 - 11.718v + 937.04$	56	49	73	67
(5) HP EGR OFF & DEF OFF	$0.1069v^2 - 10.794v + 1516.7$	144	99	200	208
(6) LP EGR OFF & DEF OFF	$0.1184v^2 - 10.23v + 1378.7$	139	90	193	216
(7) HP and LP EGR OFF & DEF OFF	$0.1354v^2 - 14.061v + 1573.8$	142	98	195	213

For the ECS scenario 2/3/4/5/6/7, the NO_X increase factors for the total RDE trip were 26/58/56/144/139/142. For the urban trip, the values of the NO_X increase factors for the same scenarios were 12–35% lower than for the total RDE trip, i.e., 21/51/49/99/90/98. For the rural trip, the NO_X increase factors were 15–39% higher than the values for the total RDE trip, i.e., 34/67/73/200/193/195. For the motorway trip, the increase factors were 33/64/67/208/216/213, i.e., 10–55% higher than the values for the total RDE trip.

For a more accurate determination of the increase in NO_X emissions due to manipulation, it is necessary to carry out a more significant number of measurements on different vehicles to the Euro standard, ECS types, and others. Considering the complexity and long duration of the conducted tests and the necessary resources for repeating the measurements on a larger number of vehicles, alternatively, in the absence of a sufficient number of measurements, the Euro standard of the manipulated vehicles can be lowered to the lowest level (Euro 0 or pre-Euro) to allow for a more accurate calculation of the total hot NO_X emissions, as shown in Figure 11.

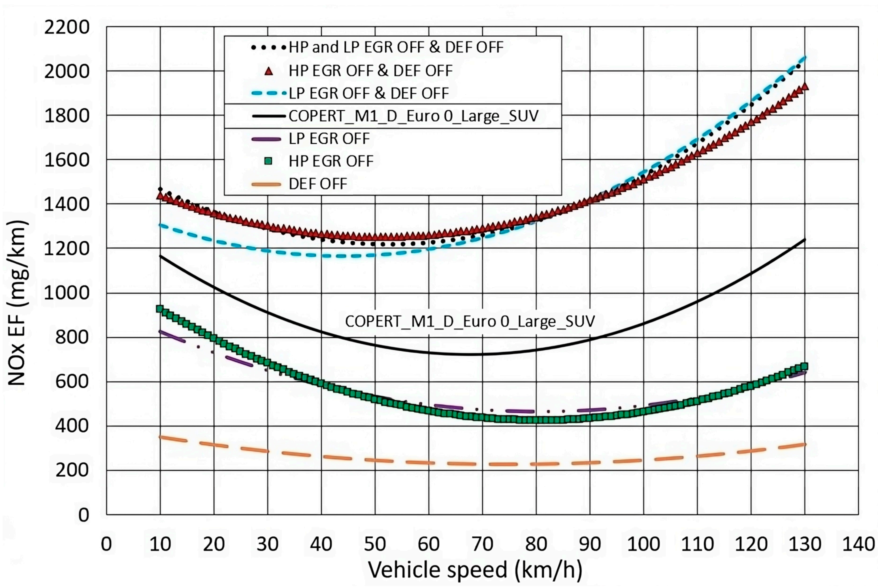


Figure 11. Comparison of the hot NO_X EFs of the test vehicle with manipulated ECSs with the COPERT NO_X EFs of a large/SUV diesel PC of the Euro 0 emission standard.

Knowing the proportion of vehicles that have been manipulated makes it possible to estimate the vehicle fleet's emissions inventory more accurately than existing models.

3.11. An Assessment of the Number of Manipulated PCs in the Republic of Croatia

A simple random sampling technique was used to estimate the number of manipulated PCs in the Croatian fleet as accurately as possible. An anonymous survey was conducted among PC owners by completing a Google form. The survey flyer with an access QR code was available to vehicle owners nationwide at PTI stations. In this way, an attempt was made to reduce bias regarding geographical location, so that the sample did not come from only one region. A total of 2000 people participated in the survey. Since no survey can be 100% accurate, the degree of uncertainty in the survey results is called the margin of error and was calculated using the formula in Equation (4) [43].

$$MoE = z\frac{\sigma}{\sqrt{n}}\sqrt{\frac{(N-n)}{(N-1)}} = z\sqrt{\frac{p(1-p)}{(N-1)\frac{n}{(N-n)}}} \cong z\frac{\sigma}{\sqrt{n}} \cong z\sqrt{\frac{p(1-p)}{n}} \quad (4)$$

where:

MoE = margin of error (%);
z = 1.96, z-value that corresponds to confidence level 95%;
σ = standard deviation of the sample;
n = 2000, sample size;
p = sample proportion (%);
N = 1,831,074, population size, i.e., number of registered PCs.

In a sample of 2000 respondents—owners of a PC with an internal combustion engine (ICE)—209 had carried out certain manipulations on the ECSs. The sample proportion for this sample was 10.45%, and the margin of error was ±1.34% at a 95% confidence level. Applying this to the total population of 1,831,074 PCs with ICE registered in Croatia in 2022, the total number of PCs with ECS manipulations would be 191,347. Of the 209 respondents who performed certain manipulations on their vehicles, 162 were owners of diesel PCs. This sample's proportion, i.e., the share of diesel PCs with manipulated ECSs in the total PC fleet, was 8.1%, and the margin of error was ±1.19% at a 95% confidence level. Applying this to the total population of 1,027,374 diesel PCs registered in Croatia in 2022, the total number of diesel PCs with ECS manipulations would be 148,317 (14.437%). Of the 162 respondents who performed certain manipulations on their diesel PC, 43 were owners of Euro 6 diesel PCs. The sample proportion for this sample was 2.15%, and the margin of error was ±0.63% at a 95% confidence level. Applying this to the total population of 240,537 Euro 6 diesel PCs registered in Croatia in 2022, the total number of Euro 6 diesel PCs with ECS manipulations would be 39,368 (16.367%). The results of the survey and other processed data are shown in Table 7. It should be noted that diesel plug-in hybrid electric vehicles are not included in the above statistics.

Table 7. The survey results and the processed data for manipulated passenger cars (PCs_m).

N = 1,831,074; *n* = 2000	*n*	*p* (%)	*MoE* (%)	*N*	*N* (%)
PCs_m with an ICE	209	10.45	±1.34	191,347	10.45
Diesel PCs_m	162	8.1	±1.19	148,317	14.437
Euro 6 diesel PCs_m	43	2.15	±0.63	39,368	16.367

3.12. An Assessment of the NO_X Emission Inventory of the Euro 6 Diesel PC Fleet in Croatia

The Euro 6 vehicle category is divided into three subcategories: Euro 6 a/b/c, Euro 6 d-TEMP, and Euro 6 d. The largest share of vehicles is represented in the Euro 6 a/b/c subcategory (≈76%), followed by Euro 6 d-TEMP (≈16.5%) and Euro 6 d (≈7.5%). Based on these proportions, the distribution of manipulated vehicles within the Euro 6 category was made, as shown in Table 8. According to the COPERT calculation, over 95% of the emissions from regular Euro 6 diesel PCs come from the Euro 6 a/b/c subcategory.

Table 8. Vehicle population and NO_X emissions for both total and the manipulated Euro 6 diesel PC fleet.

Diesel PCs	Vehicle Population (-)		NO_X Emissions (t)	
	Total	Manipulated	Total	Manipulated
Euro 6 a/b/c	182,754	29,911	1578	See Table 9.
Euro 6 d-TEMP	39,729	6502	52	
Euro 6 d	18,054	2955	19	
All Euro 6	240,537	39,368	1649	

Table 9. For different scenarios, there is a relative increase in hot NO_X emissions of the Euro 6 diesel PC fleet compared to the COPERT 5.

Scenario	Rel. Increase in Hot NO_X Emissions of Euro 6 Diesel PC Fleet According to the Proposed Calculation (%)			
	Euro 6 a/b/c	Euro 6 d-TEMP	Euro 6 d	Entire Euro 6 Diesel PC Fleet
(2) DEF OFF	−48	329	436	−5.0
(3) HP EGR OFF	9	802	1027	7.5
(4) LP EGR OFF	11	815	1043	7.9
(5) HP EGR OFF & DEF OFF	187	2262	2852	46.3
(6) LP EGR OFF & DEF OFF	182	2220	2800	45.1
(7) HP and LP EGR OFF & DEF OFF	187	2263	2854	46.3

Considering the emission measurement results and the survey results, six different scenarios were created to evaluate the NO_X emission inventory of the Euro 6 diesel PC fleet. It was assumed that the NO_X EFs of all the manipulated Euro 6 diesel PCs (Euro 6 a/b/c, Euro 6 d-TEMP, and Euro 6 d) were the same and matched the data obtained in this study. The proposed calculation results were applied to the fleet segment of manipulated Euro 6 diesel PCs (16.367%), i.e., 39,368 vehicles. Using the known data on the annual mileage of each vehicle, the average driving speed, and the share of the distance travelled in a given driving mode, U/R/M, according to the COPERT nomenclature, the relative increase in NO_X emissions was calculated at the level of the Euro 6 diesel PC fleet, as shown in Table 9.

Due to the high values of COPERT NO_X hot EFs of Euro 6 a/b/c PCs, and taking into account that the research was conducted on a Euro 6 d-TEMP vehicle and not on a Euro 6 a/b/c, the lowest increase in emissions with the proposed calculation was achieved precisely for Euro 6 a/b/c vehicles. Moreover, the proposed calculation indicated a decrease in NO_X emissions for the DEF OFF scenario. Since the largest number of Euro 6 vehicles belongs to this subcategory, the total emissions of the entire Euro 6 diesel PC fleet for the DEF OFF case scenario have a negative sign. In all other case scenarios, the proposed calculation showed an increase in emissions within each Euro 6 subcategory and for the category as a whole. For combinations of deactivated individual ECSs, the NO_X emissions increased by up to 46.3% at the Euro 6 diesel PC fleet level.

4. Discussion

When all ECSs were active, the NO_X emissions when driving at a constant speed from 10 to 140 km/h were not significantly different from the emissions when driving the RDE route, as shown in Figure 3. However, when the ECSs were deactivated, there was a significant difference between the emissions at a constant speed and the RDE route, as shown in Table 10. From the results in Table 10, it can be concluded that driving dynamics during the RDE route significantly impacted the increase in vehicle emissions when the ECSs were deactivated. Given these results, the RDE data were used instead of the constant speed data to calculate the emissions from the manipulated vehicles.

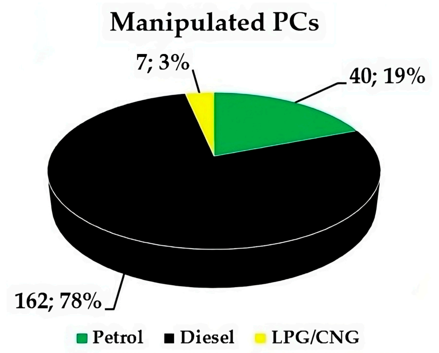
Table 10. Comparison of NO_X EFs when driving at a constant speed and driving the RDE route for different ECS scenarios.

ECS Scenario	NO_X EFs (mg/km)/Abs. Change (mg/km)					
	Constant Speed Drives			RDE Route		
	U 30 km/h	R 70 km/h	M 110 km/h	U 30 km/h	R 70 km/h	M 110 km/h
(1) All ECSs active	10	6	8	13/+3	6/0	8/0
(2) DEF OFF	53	36	62	287/+234	239/+203	201/+139
(3) HP EGR OFF	110	20	217	682/+572	436/+416	511/+294
(4) LP EGR OFF	224	21	260	651/+427	473/+452	528/+268
(5) HP EGR OFF &DEF OFF	113	548	912	1302/+1189	1291/+743	1631/+719
(6) LP EGR OFF & DEF OFF	316	516	960	1191/+875	1249/+733	1694/+734
(7) HP and LP EGR OFF & DEF OFF	405	715	1235	1287/+882	1259/+544	1673/+438

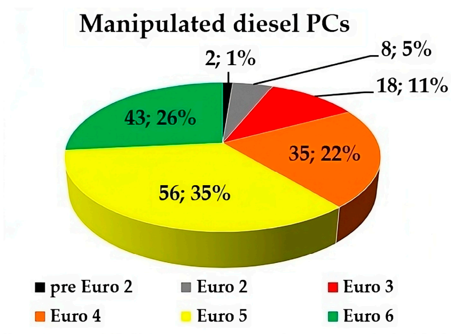
The effects of increasing the vehicle mass on emissions from MIRO (2050 kg) to GVWR (2350 kg) are shown in Figure 3 and Table 4 for the scenario with all ECSs activated, and in Figure 7 and Table 5 for the case with the HP EGR and DEF dosing system deactivated. From a comparison of the results, it can be concluded that the impact of an increase in vehicle mass on NO_X emissions is relatively more visible when the ECSs are activated than when they are deactivated. Furthermore, in the HP EGR and DEF OFF scenario, a decrease in NO_X emissions with an increasing vehicle mass was observed. However, since the values of NO_X emissions for the case when all ECSs are activated were small in absolute values, it can be concluded that the influence of the increase in vehicle mass on the rise in NO_X emissions was negligible compared to the upgrowth caused by the manipulations of the ECS. For this reason, MIRO was used instead of GVWR to calculate the NO_X emissions of the manipulated vehicles.

When comparing the results of the RDE runs for six different scenarios with the ECS deactivated, it can be seen that the smallest increase in NO_X emissions—with an increase factor of 26 for the total RDE trip—was obtained for the case where only the DEF system was deactivated. For the following two scenarios, HP EGR OFF and LP EGR OFF, slightly higher values of the increase factor—58 and 56—were obtained. Similar values of NO_X emissions for two test cases—EGR OFF and then DEF OFF—were obtained in a study conducted by the Joint Research Centre (JRC) of the European Commission in Italy [31]. Moreover, the JRC obtained slightly higher values, but was justified considering that the measurement was carried out on an older Euro 6d-Temp LDV, not Euro 6d. From Figure 11, it can be seen that their EF polynomials did not differ significantly. The highest values were obtained for three cases that were a combination of disabled ECSs—HP and LP EGR OFF and DEF OFF, LP EGR OFF and DEF OFF, and the case where both HP and LP EGR and the DEF system were disabled. The NOx increased factors for these three scenarios amounted to 144, 139, and 142. From Figure 11 can be seen that their EF polynomials were very similar. Since the NO_X EFs from RDE trips are second-order polynomials determined by only three measurement points, one each in U/R/M driving mode, it is proposed to improve the existing calculation by additional measurements targeting several different average driving speeds in the U/R/M driving mode. In this way, they would determine a polynomial that more accurately describes the dependence of emissions on average driving speed.

The survey results showed that, on average, one in ten registered PCs has some prohibited modifications to the ECS. Considering diesel cars, on average, 1 in 12 vehicles has some ECS modifications. For diesel cars of the latest Euro 6 standard, 1 in 50 vehicles, on average, has some illegal tampering with the ECS. This study on emissions calculation considered only the survey results for Euro 6 diesel PCs. However, since car owners of all subcategories of PCs participated in the survey, Figure 12 shows a pie chart with data by fuel type and Euro standard.



(**a**)



(**b**)

Figure 12. The proportion of manipulated PCs by fuel type (**a**) and the share of manipulated diesel PCs by Euro standard (**b**) from the survey sample.

Figure 12a shows that the largest share of manipulated PCs was vehicles powered by diesel fuel—78%. The largest share of manipulated diesel cars was of the Euro 5 standard—35%, followed by Euro 6/Euro 4/Euro 3/Euro 2/pre-Euro 2, with shares of 26%/22%/11%/5%/1%, as shown in Figure 12b. Therefore, it is proposed to extend this calculation to diesel cars with lower Euro standards—especially Euro 5 and Euro 4, which account for 29% of the total PC fleet. In that case, it is necessary to perform additional RDE measurements on vehicles of lower Euro standards and different types of installed ECSs and then compare their NO_X increase factors with the data of this study. As the existing survey is still retained, it is planned to update the emissions of the vehicle fleet considering the expanded number of respondents.

According to the data in Table 9, the NO_X emissions in scenarios 1–7 increased by 329–2263% for Euro 6 d-TEMP (https://dieselnet.com/standards/eu/ld.php) vehicles and by 436–2854% for Euro 6 d vehicles, while unexpectedly lower values—48–187%—were achieved for Euro 6 a/b/c. This raises the question of whether or not this study's results also apply to Euro 6 a/b/c diesel PCs. The NO_X EFs for diesel PCs of the Euro 6 a/b/c standard were several times higher than the EFs of those with higher Euro standards—Euro 6 d-TEMP and Euro 6 d. Although the test vehicle was type-approved with the Euro 6 d-TEMP standard, the RDE measurements indicated that the NO_X emission levels were significantly lower than those for Euro 6 d vehicles. It is presumed that the NO_X EFs of manipulated Euro 6 a/b/c vehicles are much higher than the EFs of the test vehicle with deactivated ECSs. Therefore, it is assumed that the data from Table 9 for Euro 6 a/b/c are underestimated in all seven scenarios. In addition, the data for the scenario DEF OFF were determined with a negative sign, which is contradictory, as the other results for Euro 6 d-TEMP and Euro 6 d indicated an increase in NO_X emissions due to DEF system manipulations. Since Euro 6 a/b/c vehicles make up 76% of the Croatian Euro 6 diesel PC fleet, a significantly higher emission inventory value is expected to be obtained. Due to that, it is necessary to perform RDE measurements on Euro 6 a/b/c vehicles and update the existing calculation of emissions from these vehicles.

Of the 209 respondents who made manipulations to their ECS, 48.8% said they had decided to make those modifications because of an ECS failure or engine malfunction. The prerequisite for chip tuning was the reason for 30.6% of the respondents, and the remaining 20.6% had another reason. It can be concluded that most owners had technical defects as triggers for tampering. Since the components of the ECS are mostly expensive, the owners opted for a cheaper option, namely deactivating the function, instead of buying and installing new parts. When asked about the age of the vehicle at the time of modification, 15.8% said it was less than five years old, 38.3% said the car was between five and ten years old, and 45.9% said the vehicle was more than ten years old. Although older vehicles are more susceptible to manipulation, it can be noted that the proportion of PCs younger than five years is nevertheless significant, and these are exclusively Euro 6 standard vehicles.

It can be concluded from this that even newer vehicles are not immune to the technical difficulties of the ECS that occur during vehicle use. As the average age of passenger cars in Croatia has shown an increasing trend since 2007 [39]—an increase from 9.8 to 13.3 years in 2022—it can be expected that this trend with manipulations will continue. As many as 77.1% of the respondents said the tampering was not detected during the PTI test, so the vehicle passed the emissions test. Only 10% of the respondents did not pass the emission test, while the remaining 12.9% stated that they had since deregistered or sold their vehicle. The biggest problem is that such manipulations are difficult or almost impossible to detect during the PTI.

Although the proposed calculation is limited to hot emissions and applied to Euro 6 diesel LDV with the EGR and DEF ECS, it can be extended to cold emissions and other vehicle categories, Euro standards, and ECSs. This research was necessary to show where significant amounts of "hidden" NO_X emissions from road transport come from and to encourage policymakers to develop methods to prevent such manipulations. Considering the results and conclusions of this study, it would be scientifically beneficial to continue research on the increased NO_X emissions from vehicles with manipulated ECSs.

5. Conclusions

This research aimed to investigate the influence of manipulations of the EGR valve and the DEF dosing system on the NO_X emissions of Euro 6 diesel PCs and to estimate the emissions of manipulated vehicles based on PEMS measurements. One of the main conclusions is that the emissions of the test vehicle, where both the EGR valve and the DEF system were tampered with, exceeded the values by more than two orders of magnitude compared to the case where all ECSs were active. This study's purposed to estimate accurately the proportion of manipulated vehicles in the vehicle fleet so that NO_X emissions calculations are as realistic as possible. For this reason, an anonymous survey was conducted among PC owners. Using the survey's results and extending them to the targeted fleet, the NO_X emissions from Euro 6 diesel PCs were calculated. The results showed that the hot emissions of this group of vehicles are up to 46.3% higher than the hot emissions calculated with the official computer program COPERT 5, with a tendency towards significantly higher values.

The essential conclusions that emerged from this study are as follows:

- When all ECSs were active, the NO_X EFs from constant speed runs were not significantly different from the values when driving an RDE route;
- When the ECSs were deactivated, the NO_X EFs on the RDE route were significantly higher than the values when driving at a constant speed;
- Since the driving dynamics during the RDE runs significantly impacted the increase in vehicle emissions, the more realistic RDE data were used instead of the constant speed data to calculate the emissions from manipulated vehicles;
- An increase in vehicle mass by 300 kg caused the NO_X emissions on the RDE trip to be 47% higher when the ECSs were activated and 4% lower when the HP EGR and DEF systems were deactivated;
- When the HP EGR and DEF systems were deactivated, increasing the vehicle mass by 300 kg did not significantly change the NO_X emissions. Therefore, due to the simplicity of and reduction in the number of measurements, only MIRO was used to calculate the emissions from the manipulated vehicle;
- The smallest increase in NO_X emissions of the test vehicle with manipulated ECSs, with an increase factor of 26 for the total RDE trip, was obtained for the case where only the DEF system was deactivated;
- Slightly higher values of the NO_X increase factor—58 and 56—were obtained for the HP EGR OFF and LP EGR OFF scenarios, and their EF polynomials did not differ significantly;
- The highest NO_X increase factors—144, 139, and 142—were obtained for three cases that were a combination of deactivated ECSs—HP and LP EGR OFF and DEF OFF, LP

EGR OFF and DEF OFF, and the case where both HP and LP EGR and the DEF system were deactivated—and their EF polynomials did not differ significantly;
- The survey results showed that, on average, one in ten registered PCs has some prohibited modifications to the ECS. Considering diesel cars, on average, 1 in 12 vehicles has some ECS modifications. For diesel cars of the latest Euro 6 standard, 1 in 50 vehicles, on average, has some illegal tampering with the ECS;
- The NO_X emissions inventory in scenarios 1–7 increased by 329–2263% for Euro 6 d-TEMP vehicles and by 436–2854% for Euro 6 d vehicles, while unexpectedly lower values—48–187%—were achieved for Euro 6 a/b/c. The reason for this is probably that the NO_X EFs for Euro 6 a/b/c vehicles in COPERT have been updated, so it is possible that they already include the impact of the operation of defeat devices;
- It is necessary to perform RDE measurements on Euro 6 a/b/c vehicles and update the existing calculation of emissions from these vehicles;
- As many as 77.1% of the survey respondents said that the tampering was not detected during the PTI test, only 10% did not pass the emission test, and the remaining 12.9% stated that they had since deregistered or sold their vehicle.

The limitation of the proposed calculation is that it was created based on the results of only one tested vehicle. To apply the calculation with greater certainty to the entire Euro 6 diesel PC fleet, additional measurements on Euro 6 a/b/c standard vehicles according to the same principle are planned. This method can also be applied to other NO_X emission control systems prone to manipulation, such as diesel oxidation catalysts, SCR catalysts, NO_X adsorbers, and others. Increasing the EGR causes diesel engines to produce more particulate matter (PM) [44]. Therefore, with a functional EGR system, it would be interesting to investigate the effects of the tampering of the DPF system on PM. Based on additional measurements, it is planned to create a model for calculating the emissions of manipulated vehicles.

These experimental findings indicate where significant amounts of "hidden" NO_X emissions from road transport come from. A contribution to the scientific literature derived from the experimental findings is the proposed calculation for determining the NO_X EFs of vehicles with deactivated ECSs. The idea is to encourage researchers to deal more with this topic and to create more functions of increased emissions due to the manipulation of ECSs to validate this method and improve the calculation of existing emission models. In addition, the study's benefit is the survey results, which indicated a share of manipulated vehicles in the fleet. Without these results, it would not be possible to estimate the real emissions of the PC fleet. With the joint efforts of the scientific community and policymakers, it is possible to create measures for preventing such manipulations and consequently improving air quality.

An important omission in the PTI system is because outdated technology is still consciously applied, which, in newer diesel vehicles—Euro 5 and Euro 6—generally cannot detect even smoke opacity, much less tampering [45]. What is even more important is that NO_X emissions are not checked at all during PTI [46,47]. A proposal for the International Motor Vehicle Inspection Committee (CITA) is to introduce obligatory new technologies into the PTI system, such as the PN counter for particle number detection and the NO_X analyser. Introducing road emissions control would increase awareness of the seriousness of the problem of harmful emissions as one of the main "silent" killers of the 21st century.

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Conference paper I

Road transport emissions of passenger cars in the Republic of Croatia

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Road Transport Emissions of Passenger Cars in the Republic of Croatia

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Abstract
During this research, the vehicle fleet structure of Croatia was closely analysed and implied emission factors and emissions of passenger cars were calculated for the period from 2007 to 2016 using COPERT 5, a Tier 3 capable program. Aside from air pollutants data CO, NO_x, PM, NH_3, VOC and NMVOC the data shown includes greenhouse gas CO_2 as well as fuel consumption. Tracking the passenger car fleet and their exploitation activities in the mentioned period shows that the change in the passenger car fleet has had a negative impact on total emissions.

Introduction

Data on road traffic exhaust emission particles is collected, processed and used for creating new emission models, and for updating existing ones. Some types of emissions models used today are average-speed, traffic-situation, traffic-variable, cycle-variable and the modal model. Validation of such models was studied by Smith et al. [1]. Borge et al. [2] compared two road traffic emissions models, the COPERT 4 (COmputer Programme to calculate Emissions from Road Transport) [3] and the HBEFA (Handbook Emission Factors for Road Transport) [4], in Madrid. Fontaras et al. [5] developed the Euro 5 PC (passenger car) EFs (emission factors) based on experiment results and compared them with HBEFA and COPERT. Latest HBEFA final report contains an update of EFs for Euro 5 and Euro 6 vehicles. By applying these emissions models it is possible to estimate the emissions generated on a defined geographic area in a given time period. Lang et al. [6] estimated air pollutant emissions from on-road vehicles in China for the time period since 1999 to 2011 using the COPERT emission model.

In order to apply these emission models, a significant amount of input data must be acquired. Therefore, a top-down approach is used in order to determine national emissions and most important data, along with emission factors, is precisely related to the vehicle fleet structure and activity data. The Republic of Croatia, like other EU member states, has an obligation to collect, process and deliver emission data (*Emission Inventory*) to the European Commission. Available emissions estimations for the Republic of Croatia are generally created using the Tier 1 methodology which includes national-level statistical data on fuel consumption for the needs of road transport. Seeing how the outdated Tier 1 technology errs on the side of overgeneralization, its use is strictly advised against, except in cases where no other data is available aside from the statistical fuel data. However, when lacking more detailed data, member states must employ all available measures so as to collect the data required for the use more advanced methods. With the goal of a more exact emissions estimate, it is advisable to use the Tier 3 methodology which includes a variety of influential parameters, such as the mean speed dependent EFs, and the classification of emissions into cold-start and hot emissions. Fameli and Assimakopoulos [7] use COPERT Tier 3 methodology, a top-down approach, for determining Greek national emissions inventory. Iodice and Senatore [8] also use the bottom-up approach COPERT Tier 3 methodology for emission inventory of the Italian Campania region. The most recent updates to the Tier 3 methodology are included in the 2016 EMEP/EEA Air Pollutant Emission Inventory Guidebook [9]. Seeing how the updated Tier 3 methodology is integrated in the COPERT 5 program package [10], the same is used as a tool to calculate implied EFs and the annual total emissions of PCs in Croatia. Data used in this calculation includes vehicle population and their activity provided by CVH (Centre for Vehicles of Croatia), annual fuel consumption data published by Croatian Ministry of Economy in Annual Energy Report [11], meteorological and other COPERT default data.

Through collecting and processing input data and by using an appropriate emissions model for the calculation of EFs and emissions from road transport it is possible, with adequate precision, to estimate emissions generated on a defined area in a given time period. What is the influence of the PC fleet and its activities on emissions in Croatia for the period from 2007 to 2016 and how to improve it in the future?

Specific Objectives

In the scope of this research, the structure of Croatia's vehicle fleet structure from 1996 to 2016 was thoroughly examined. Seeing how data on the number of registered vehicles is "sensitive" to legislative changes regarding vehicle registration and deregistration, it was not taken into account; instead, PTI (Periodical Technical Inspection) data was used, which also includes vehicle mileage data. CVH is one of the first PTI organizations in the EU to begin collecting and processing annual vehicle mileage data.

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Fig. 1 shows the vehicle fleet structure in Croatia in the given timespan.

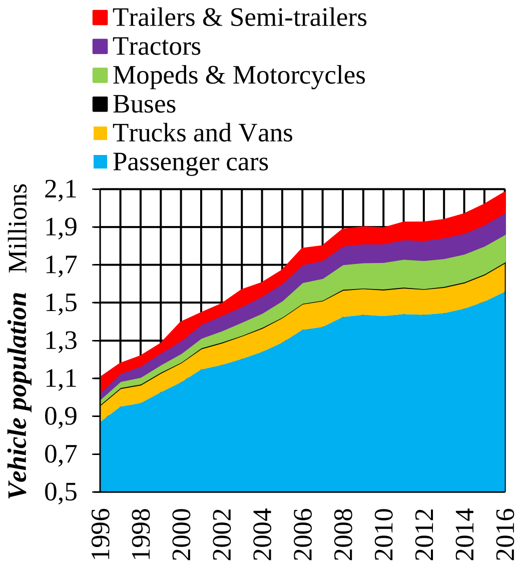

Fig. 1. Vehicle fleet structure from 1996 to 2016.

It can be observed from Fig. 1 that the PC category is 3.45 times larger than all other categories combined in 2016; therefore, their influence on emissions was chosen for this study. Also, due to the overall progressive increase of PC population, it is assumed that these vehicles produce significant amounts of air pollution, particularly in urban areas. The aim of this study was to show the influence PC fleet and its usage activities have had on emissions generated.

COPERT 5 (Tier 3) emissions model was used to estimate emissions from PCs. A simplified form of this model is shown in Fig. 2.

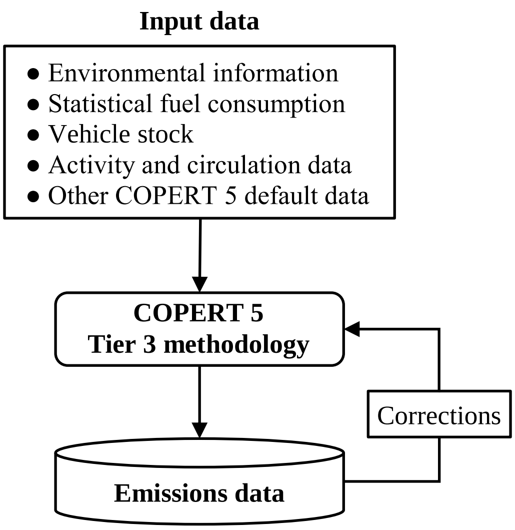

Fig. 2. Emissions calculation model.

Main input data included environmental information, statistical fuel consumption, vehicle stock, activity and circulation data and other COPERT 5 default data. Environmental information included monthly values of average minimum and maximum temperatures as well as relative humidity. Statistical fuel consumption converted to energy consumption can be used to calculate fuel balance. Considering that fuel consumption data accounts for the complete transport sector and not to a partial subsector like PCs, this data was not taken into account in the calculations. As previously mentioned, the vehicle stock was exclusively limited to PCs. Activity data taken into account means annual mileage along with mean lifetime cumulative mileage, whereas the assumed circulation data taken into account means the speed and the percentage of mileage driven by vehicles of each emission level per driving mode (urban/rural/highway).

Because the CVH database contains detailed PTI data only from 2007, the years prior to 2007 were not considered due to lack of detailed data. In the analysis of all PC emission sources, petrol, diesel, bi-fuel and hybrid vehicles were studied, except EVs. All emission levels before Euro 1 were classified into category Euro 0.

To estimate PC emissions, it was necessary to determine the number of PCs according to Euro emission level, Fig. 3.

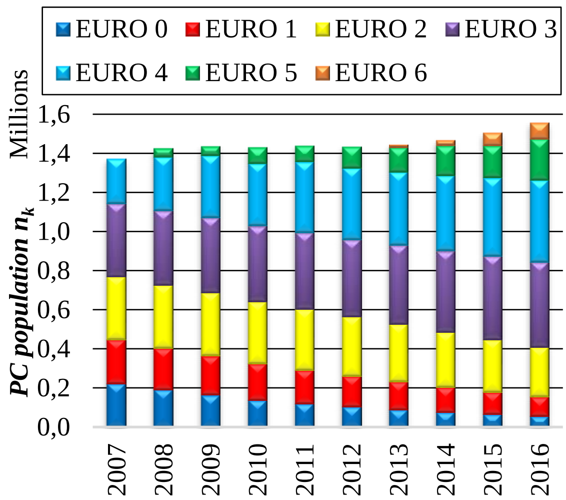

Fig. 3. PC population over the years according to Euro emission level.

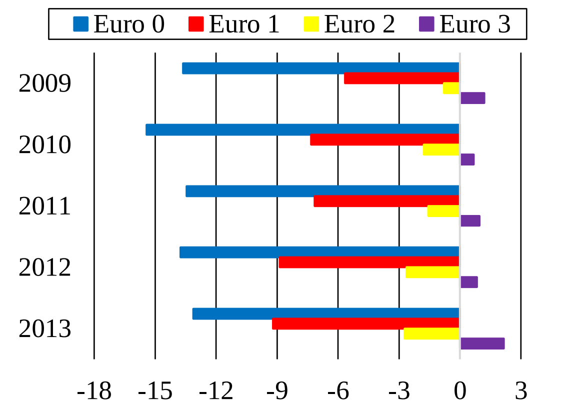

Fig. 4. Relative change [%] of PC population from 2008 to 2013 according to Euro emission level.

The 2008 global economic crisis is affected Croatia, just like it did other countries. However, the recovery from the economic crisis lasted significantly longer in Croatia when compared to the majority of other afflicted countries. As shown in Fig. 3, during the 2008 to 2013 period, the total PC population did not change significantly. However, a change in the PC fleet structure did occur, in which the number of Euro 0 and Euro 1 vehicles dropped significantly, while the number of Euro 2 vehicles decreased slightly and the number of Euro 3 vehicles rose slightly, Fig. 4.
For emission calculation, it was also necessary to determine the mean annual mileage for each Euro category, Fig. 5.

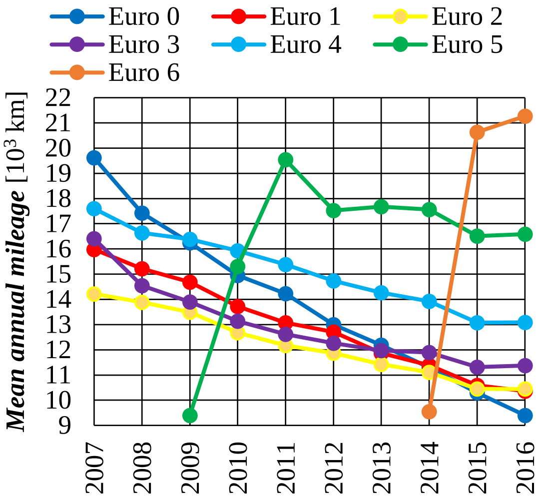

Fig. 5. Mean annual mileage of PCs over the years according to Euro emission level.

Total PC activity can be displayed as the produkt of the number of PCs and their annual mileage, Eq. (1)

$$m_k^{total} = n_k \times m_k \text{ , [km]} \qquad (1)$$

n_k – number of PCs with emission level k,

m_k – mean annual mileage [km] driven by PCs with emission level k

Total PC activity as the product of number of PCs and their annual mileage is shown in Fig. 6.

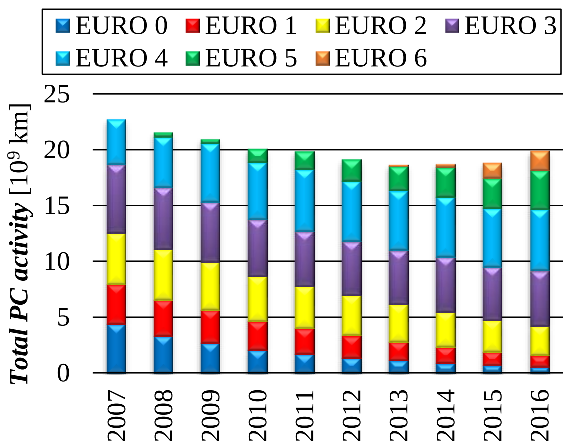

Fig. 6. Total PC activity over the years according to Euro emission level.

For the period up to 2014 the PC population was generally slowly increasing, while its mean annual mileage was decreasing significantly. This is the reason why the total PC activity decreased. After 2014, the PC population increased as well as its mean annual mileage. Due to this, total PC activity also increased.
Other input data used in the calculation were COPERT 5 default or was assumed.
The calculation model is based on Tier 3 methodology in which exhaust emissions are calculated using a combination of EFs and activity data. Total exhaust emissions are calculated as the sum of hot and cold emissions, Eq. (2)

$$E^{total} = E^{hot} + E^{cold} \text{ , [g]} \qquad (2)$$

Hot emissions indicate those emissions incurred during engine operation when the engine and exhaust aftertreatment components are heated at normal working temperature, Eq. (3)

$$E_{i,k,r}^{hot} = n_k \times m_{k,r} \times e_{i,k,r}^{hot} \text{ , [g]} \qquad (3)$$

$m_{k,r}$ – mean annual mileage [km] driven by vehicle with emission level k on roads type r,

$e_{i,k,r}^{hot}$ – hot EF [g/km] for pollutant i, relevant for the vehicle emission level k, operated on type r roads

Hot EFs as functions for each pollutant i, and vehicle emission level k are given in COPERT. Each of these functions depends on the mean vehicle speed which is defined through the road type r (urban/rural/highway). For example, Fig. 7 shows the speed dependent COPERT NO_x hot EFs for diesel PCs according to Euro emission level.

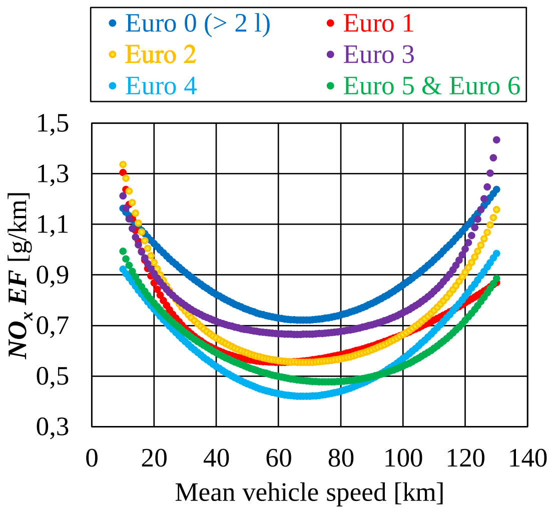

Fig. 7. COPERT NO_x hot EFs for diesel PCs according to Euro emission level.

Cold emissions indicate emissions incurred during engine operation when the engine and exhaust aftertreatment components are still in warm-up phase, Eq. (4).

$$E_{i,k}^{\text{cold}} = \beta_{i,k} \times n_k \times m_k \times e_{i,k}^{\text{hot}} \times \left(\frac{e^{\text{cold}}}{e_{i,k}^{\text{hot}}} - 1 \right), \text{[g]} \qquad (4)$$

$\beta_{i,k}$ – fraction of mileage driven when the engine and exhaust aftertreatment components are still in warm-up phase, for pollutant *i* and vehicle emission level *k*,

$e_{i,k}^{\text{hot}}$ – hot EF [g/km] for pollutant *i*, relevant for the vehicle emission level *k*,

$\frac{e^{\text{cold}}}{e_{i,k}^{\text{hot}}}$ – cold/hot emission quotient for pollutant *i* and vehicle emission level *k*.

Output emission data included EFs and total PC emissions for the period from 2007 to 2016. Aside from air pollutant data such as CO, NO_x, PM, NH_3, VOC and NMVOC, the data shown includes CO_2 greenhouse gas as well as fuel consumption. Following the first iteration, and after the required corrections, the following factors were included in the emission calculation: Air Conditioning and CO_2 emissions due to lube oil.

Results and Discussion

Hot EF mean values for the period from 2007 to 2016 for pollutant *i* (CO, NO_x and PM) and vehicle emission level *k* (Euro 0 … Euro 6) are calculated and shown in Fig. 8, Fig. 9 and Fig. 10. Values are expressed in grams per kilometre [g/km]. Also, cold EF mean values were calculated, but this data is not shown here.

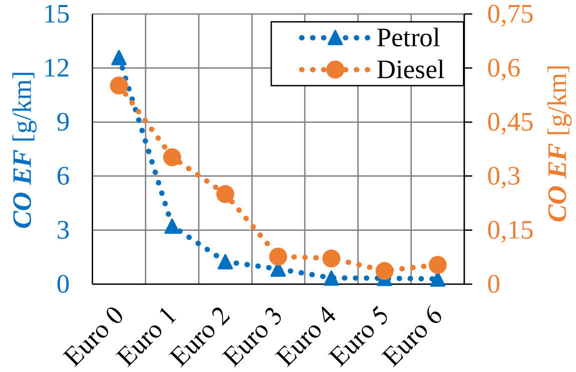

Fig. 8. Petrol and diesel CO hot EFs.

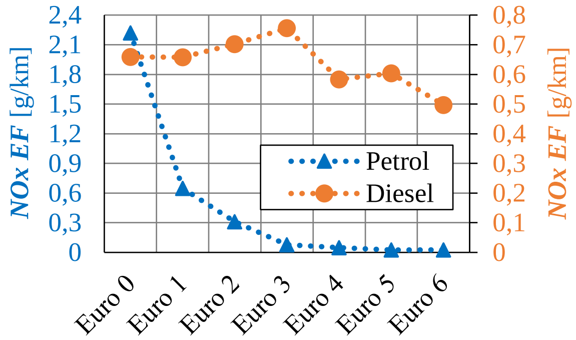

Fig. 9. Petrol and diesel NO_x hot EFs.

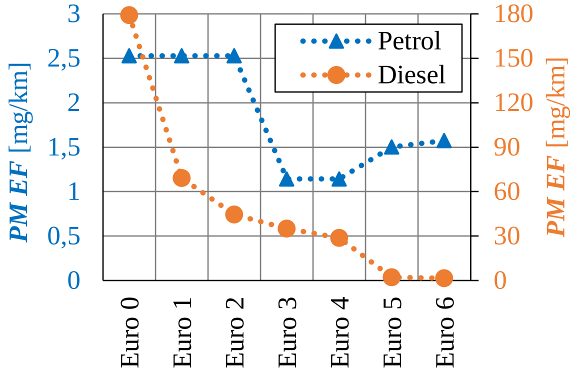

Fig. 10. Petrol and diesel PM hot EFs.

Total emissions for the period from 2007 to 2016 for pollutant *i* (CO, NO_x, PM 10, NH_3, VOC, NMVOC) including greenhouse gas CO_2 and vehicle emission level *k* (Euro 0 … Euro 6) are calculated according to Eq. (2), (3) and (4). All emissions are expressed in metric tons [t] and are shown in stacked area charts below, Fig. 11 to Fig. 17.

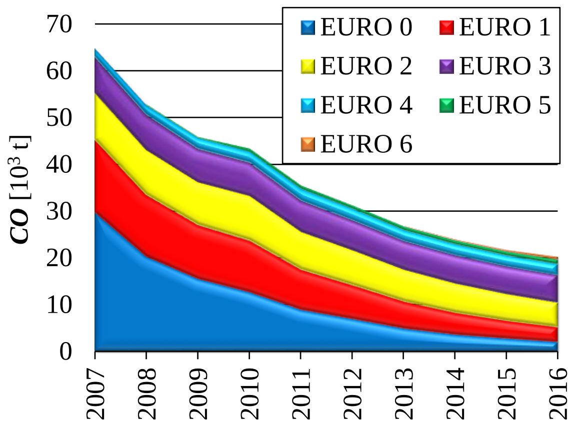

Fig. 11. Emission of carbon monoxide (CO) according to emission level of PCs for the period from 2007 to 2016.

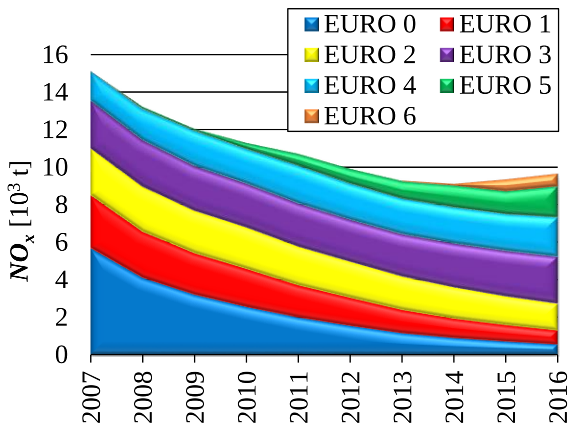

Fig. 12. Emission of nitrogen oxides (NO_x) according to emission level of PCs for the period from 2007 to 2016.

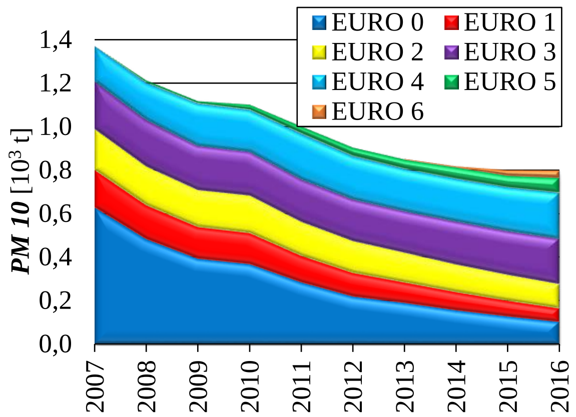

Fig. 13. Emission of particulate matter (PM 10) according to emission level of PCs for the period from 2007 to 2016.

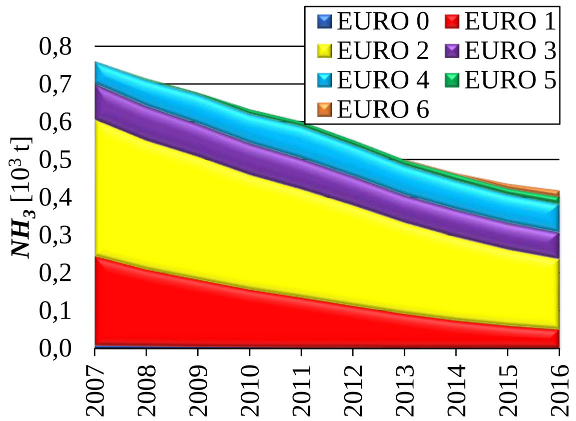

Fig. 14. Emission of ammonia (NH_3) according to emission level of PCs for the period from 2007 to 2016.

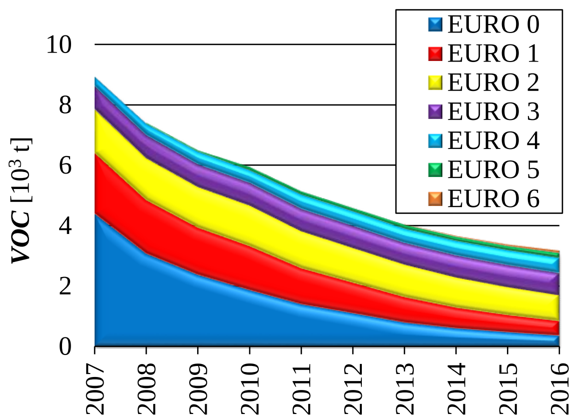

Fig. 15. Emission of volatile organic compounds (VOC) according to emission level of PCs for the period from 2007 to 2016.

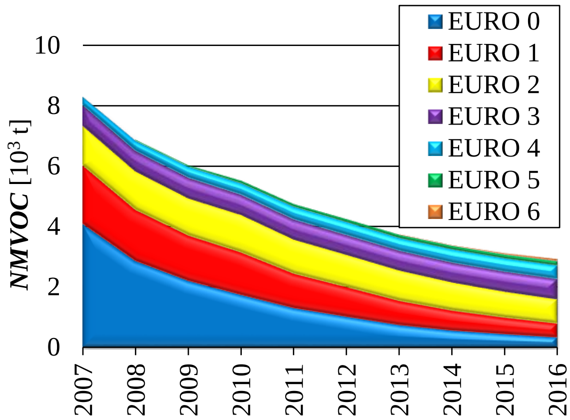

Fig. 16. Emission of non-methane volatile organic compounds (NMVOC) according to emission level of PCs for the period from 2007 to 2016

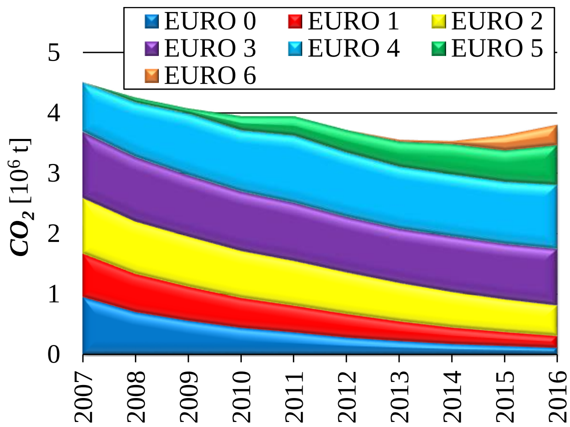

Fig. 17. Emission of carbon dioxide (CO_2) according to emission level of PCs for the period from 2007 to 2016.

Besides the mentioned air pollutants chart of fuel consumption for the same period is shown in Fig. 18. Units of fuel consumption are shown in the energy form in petajoules [PJ]. Chart of fuel consumption is qualitatively identical to CO_2 chart shown in Fig. 17.

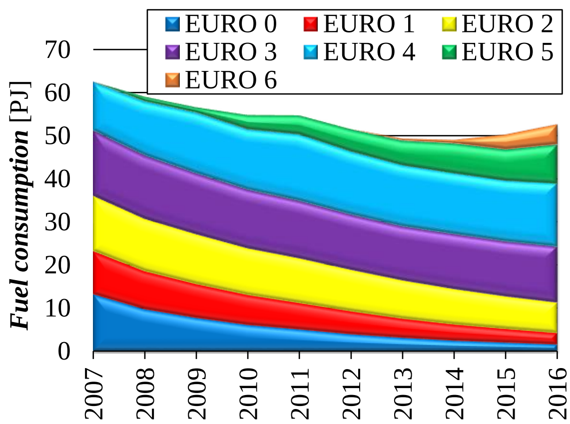

Fig. 18. Fuel consumption according to emission level of PCs for the period from 2007 to 2016.

Conclusions

It is evident from the results shown that the PC fleet has recorded a decrease in emissions for all pollutants and CO_2 as well as fuel consumption up to 2014. However, there has been a notable increase of NO_x, CO_2 and fuel consumption since 2014. Also, PM 10 has not significantly changed the trend from constantly decreasing to a practically constant value. There is a variety of reasons for this. One of the reasons is the influence of the global economic crisis that affected Croatia, causing a decrease of vehicle exploitation from 2008 to 2014. However, as opposed to other countries, it took longer for Croatia to recover and overcome the financial crisis. As shown in Fig. 3, in the period from 2008 to 2013 the total PC population practically remained unchanged. And yet, a change in the structure of the PC structure did occur, in which the number of Euro 0 and Euro 1 vehicles decreased significantly, while the number of Euro 2 vehicles decreased slightly and the number of Euro 3 vehicles rose slightly, Fig. 4. Decreasing the number of PCs with lower emission levels (Euro 0/1/2) and fleet renewal also acted positively on reducing emissions. Also, outdated vehicles with a lower emission level are much less used compared to newer vehicles. At first, the results appear positive, but they are not reflective of the real state of things. After 2014, PC population increased along with its mean annual mileage. Also, with Croatia entering the EU in 2013, the number of imported older second-hand vehicles increased, which added to the rise of NO_x and CO_2 emissions, as well as to the stagnation of PM emissions and a slower decrease in other pollutants. Croatian vehicle fleet is aging and these vehicles generate the most emissions. In order to decrease emissions, the vehicle fleet has to be renewed. One hypothesis claims that the PC population will increase significantly in the future. Therefore, the types of these vehicles are of great importance. The goal is that these vehicles be new vehicles, largely lower and mid-class, with low fuel consumption and low CO_2 emissions, and not older second-hand vehicles. The increase in CO_2 emissions could thusly be constrained, while air pollution emissions could even be lowered. This would require definite state policy measures which would instigate tax cuts for new vehicles, while new tax levies would be redirected to older, mostly technically faulty and ecologically unfit vehicles, and specifically to importing of such vehicles.

In order to assess the total road transport emissions, other vehicle categories have to be taken into account. Consequently, the data from CVH will be further collected and processed. Future studies will include more precise circulation data and CO_2 correction.

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8TH EUROPEAN COMBUSTION MEETING 2017

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Road Transport Emissions of Passenger Cars in the Republic of Croatia

M. Resetar, G. Pejic, Z. Lulic

Introduction

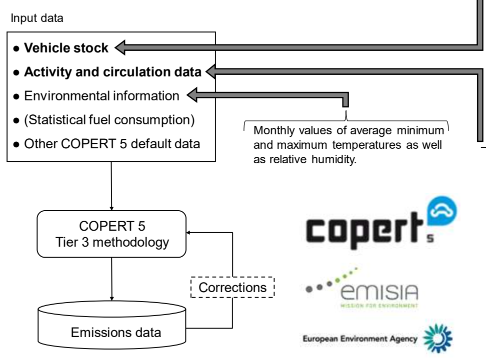
Despite many efforts, total emissions from passenger cars (PCs) have been increasing for the last few years. One reason for this is the rise in the number of PCs and their exploitation activities, but another one is the aging vehicle fleet, whose average age has risen since 2005. The 2008 global economic crisis affected new PC registrations, decreasing the number from nearly 90 000 that year to 45 000 in 2009. After Croatia became a member of the EU in 2013, the number of first registered second-hand PCs exceeded the number of newly registered PCs. Trends and changes in vehicle structure are unfavourable, the vehicle fleet is aging, and emissions generated by those vehicles are also increasing. More than 2 million vehicles were registered in Croatia in 2016, around 1.57 million of which were PCs. The average age of all registered vehicles in 2016 was 13.76 years. PCs had a slightly lower average age of 12.76 years. Croatia, like all other EU member states, is obligated to collect, analyse and deliver emissions data (emissions inventory) to various institutions and bodies of the EU. Current emission estimations in Croatia were calculated using Tier 1 method which includes statistical fuel data for national road transport. Tier 1 is a simple method that uses basic data, so its usage is recommended only when no data other than fuel statistical data is available. If there is lack of data, EU member states ought to take measures in order to acquire more detailed data required for the application of improved methods. In order to estimate emissions more precisely, Tier 3 method is used which includes a variety of parameters like emission factors that take into account the average vehicle speed, and which divides emissions into hot and cold-start emissions. During this research, the vehicle fleet structure of Croatia was closely analysed and PC emissions were calculated for the period from 2007 to 2016 using COPERT 5, a Tier 3 capable program. Aside from data on air pollutants CO, NO_x, PM, NH_3, VOC and NMVOC the data shown includes greenhouse gas CO_2 as well as fuel consumption. Tracking the PC fleet and their exploitation activities for the mentioned period has shown a negative impact of the change of PC fleet has had on total emissions.

Aim of the Study

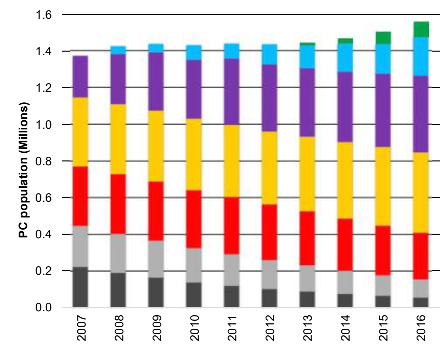
The aim of the study was to investigate the influence of the PC fleet and its activities on emissions in Croatia for the period from 2007 to 2016 and how to improve it in the future.

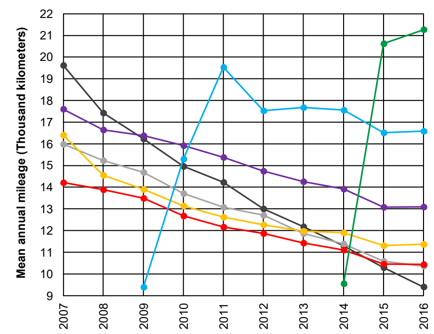
Methodology

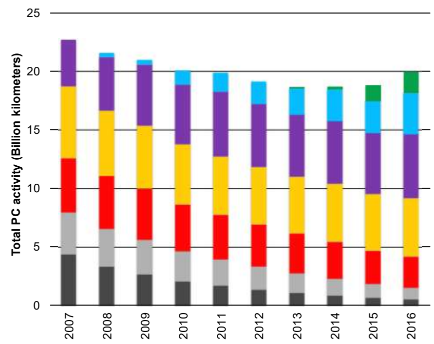
Road transport emissions from PCs in Croatia were calculated following the top-down approach based on the Tier 3 methodology (EMEP/EEA 2016) using the programme COPERT 5 (EMISIA 2016).



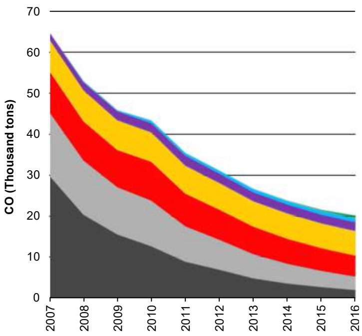
Scheme of emission calculation model.

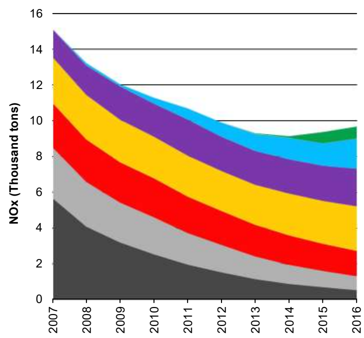






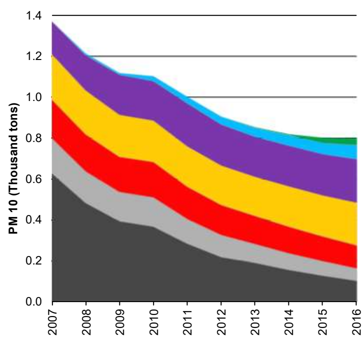
Results

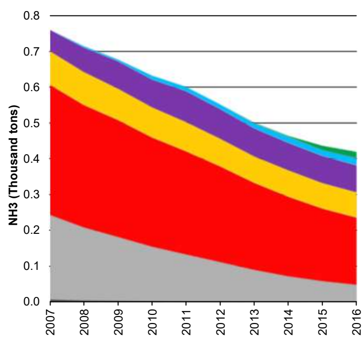


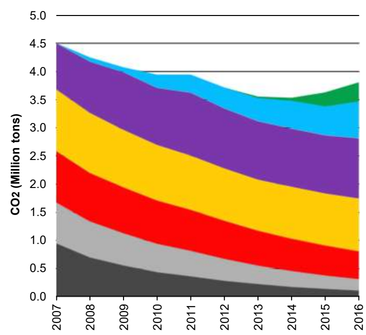


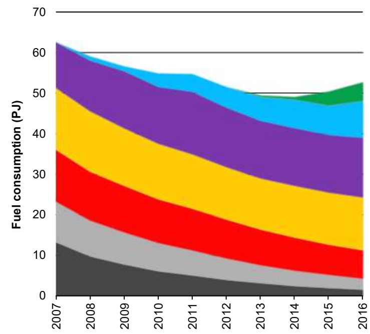
Emission levels
(Legend for all figures)

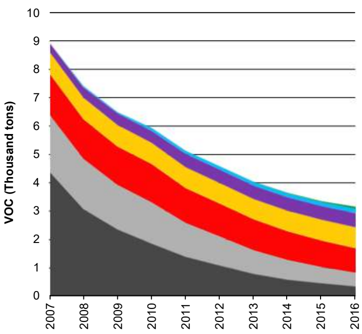
- EURO 6
- EURO 5
- EURO 4
- EURO 3
- EURO 2
- EURO 1
- EURO 0

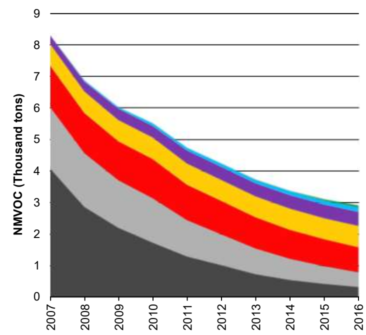












Conclusion

It is evident from the results shown that the PC fleet has recorded a decrease in emissions for all pollutants and CO_2 as well as fuel consumption up to 2014. However, there has been a notable increase of NO_X, CO_2 and fuel consumption since 2014. Also, PM 10 has not significantly changed the trend from constantly decreasing to a practically constant value. There is a variety of reasons for this. One of the reasons is the influence of the global economic crisis that affected Croatia, causing a decrease of vehicle exploitation from 2008 to 2014. In the period from 2008 to 2013 the total PC population practically remained unchanged. Decreasing the number of PCs with lower emission levels (Euro 0/1/2) and fleet renewal also acted positively on reducing emissions. Also, outdated vehicles with a lower emission level are much less used compared to newer vehicles. At first, the results appear positive, but they are not reflective of the real state of things. After 2014, PC population increased along with its mean annual mileage. Also, with Croatia entering the EU in 2013, the number of imported older second-hand vehicles increased, which added to the rise of NO_X and CO_2 emissions, as well as to the stagnation of PM emissions and a slower decrease in other pollutants. Croatian vehicle fleet is aging and these vehicles generate the most emissions. In order to decrease emissions, the vehicle fleet has to be renewed. The goal is that these vehicles be new vehicles with low fuel consumption and low CO_2 emissions, and not older second-hand vehicles. This would require definite state policy measures which would instigate tax cuts for new vehicles, while new tax levies would be redirected to older, mostly technically faulty and ecologically unfit vehicles, and specifically to importing of such vehicles.

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Conference paper II

The influence of passenger car population and their activities on NO_X and PM emissions (Data from Croatia)

TAP 2017

22^{nd} International Transport and Air Pollution Conference

Proceedings

Contents

The Influence of Passenger Car Population and Their Activities on NO_X and PM Emissions (Data from Croatia)

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Introduction

For the past few years special attention has been given to harmful road transport emissions, nitrogen oxides (NO_X) and particulate matter (PM). Exposure to increased concentrations of NO_X and PM emissions is known to cause respiratory ailments, heart diseases, stroke and can be the cause of premature death (Guttikunda and Goel, 2013; Li et al., 2017; Stockfelt et al., 2017). The time series results of real driving emission measurements have shown a significant difference in NO_X emissions of diesel cars compared to the type approval limit values. However, this does not apply to petrol cars (Chen and Borken-Kleefeld, 2014). Remote sensing measurements indicate that NO_X emissions from Euro 5 petrol cars are about a factor of 20 lower than Euro 0 cars. However, there has not been a significant change in NO_X emission reduction for diesel cars from Euro 0 to Euro 5 (Carslaw and Rhys-Tyler, 2013). Particulate matter emissions are rising in many of the world's populated cities and exceeding World Health Organization guidelines (Guttikunda and Goel, 2013; Ma and Jia, 2016). However, the emission control policies implemented in the last decade could result in noticeable reduction in PM emissions (Wang et al., 2017). Not only policy measures, but also the implementation of DPF (Diesel Particulate Filter) technology on vehicles enabled a large reduction in PM emissions (Tzamkiozis et al., 2010). However, some countries like Croatia have an aged vehicle fleet and exhaust PM emissions have a significant role in total emissions. The most severe problem is found in urban areas with high traffic density. One of the methods to reduce NO_X and PM emissions in urban areas is to introduce a low emission zones. The study from the University of Sydney shows the impact of London's low emission zone on NO_X and PM10 emissions (Ellison et al., 2013). Not only tailpipe exhaust emissions but also non-exhaust PM emissions (road dust resuspension, road surface wear, abrasion of tyres, brakes and clutch) have a significant impact on air quality in urban areas (Amato et al., 2016; Pant and Harrison, 2013). Although electric vehicles are not included in this study, exploitation of such vehicles also results in non-exhaust emissions. Because of the significantly larger mass of electric vehicles in comparison to vehicles equipped with an internal combustion engine, electric vehicles generate more non-exhaust emissions than conventional vehicles (Timmers and Achten, 2016).

Most popular vehicle emission models such as COPERT (Computer Programme to calculate Emissions from Road Transport), HBEFA (The Handbook Emission Factors for Road Transport) and VERSIT+ are used for estimating road transport emissions (Borge et al., 2012; Smit et al., 2007). By applying these emissions models, it is possible to estimate emissions generated on a defined geographic area in a given time period. Air pollutant emissions from on-road vehicles in China for the time period from 1999 to 2011 were estimated using COPERT emission model (Lang et al., 2014). Considering that NO_X RDE from Euro 6 diesel cars exceed emission levels used in COPERT by two times, it was necessary to update NO_X emission factors (EFs) (Ntziachristos et al., 2016). In Croatia, an emissions study has already been made, which, among other things, provided NO_X and PM emissions of passenger cars (PCs) for the period from 2007 to 2016 (Resetar et al., 2017). In order to apply COPERT model, a significant amount of input data must be acquired. Therefore, a top-down approach is used in order to determine national emissions and the most important data, along with emission factors, is precisely related to the PC fleet structure and activity data.

Based on the above-mentioned information it is obvious that NO_X and PM emissions present a major problem today with diesel cars as the major source of the above pollutants. Therefore, the study focused on the influence of PC population and their activities on NO_X and PM emissions in the Republic of Croatia. For relevant PC subcategories, emissions and implied emission factors for pollutants NO_X and PM for the year 2016 were calculated using COPERT 5 computer program.

Methodology and input data

The processed data on the PC fleet that underwent technical inspection in 2016 was collected from the database of Centre for Vehicles of Croatia (CVH), the company whose primary activity is performing periodical technical inspections on vehicles in Croatia. This is a unique database that contains data on all vehicles registered in Croatia, including periodical technical inspection data and annual vehicle activity data. These data have the greatest impact on the calculation of emissions and as such were used as COPERT 5 input data. Activity data taken into account means annual mileage along with mean lifetime cumulative mileage, whereas the assumed circulation data taken into account means the speed and the percentage of mileage driven by vehicles of each emission level per driving mode (urban/rural/highway). In addition to the above data, input data also included environmental information with monthly values of average minimum and maximum temperatures as well as relative humidity. Tier 3 methodology, which is described in *EMEP/EEA air pollutant emission inventory guidebook*, was applied in the scope of this research (Ntziachristos and Samaras, 2016). A simplified form of COPERT emissions calculation model is shown in Figure 1.

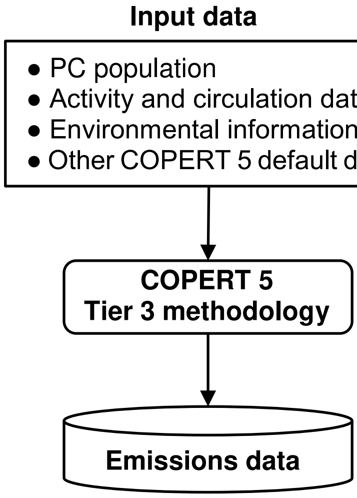

Figure 1: COPERT emissions calculation model.

Passenger car population and their activity data for the year 2016 were processed and prepared for COPERT calculation. Figure 2 shows PC population, mean annual activity and total annual activity for petrol and diesel PCs in 2016, according to each of the European emission standards. Over 779,000 petrol and over 718,000 diesel cars were registered in Croatia in 2016. Almost 61,000 other vehicles included hybrid, LPG bi-fuel and CNG bi-fuel cars, while 224 registered cars were electric. If we look at the top-left chart in Figure 2, it can be noted that there is a numerically small difference between the total number of petrol and diesel cars. Older cars, up to Euro 4, are mainly petrol, while newer cars, Euro 5 and Euro 6, are mainly diesel. There are roughly twice as many Euro 2 petrol cars as there are Euro 2 diesel cars. The top-right chart in Figure 2 indicates that diesel cars are exploited much more than petrol cars. When comparing all petrol and diesel PCs, diesel cars drive 6,750 km a year more than petrol cars. It is also apparent that newer vehicles, both petrol and diesel, are exploited much more than older vehicles. In order to calculate emissions on an annual basis, it was necessary to consider total annual activity (bottom chart in Figure 2). Total annual activity is the product of PC population and mean annual activity. This data is very useful because it shows a fleet's activity in a broader sense. Although the number of petrol cars is greater than the number of diesel cars, due to considerably greater exploitation of diesel cars compared to petrol cars, diesel cars drive 1.53 times more kilometres a year then petrol cars. The main causes of significantly higher activity of diesel cars are lower fuel consumption and lower fuel costs when compared to petrol cars.

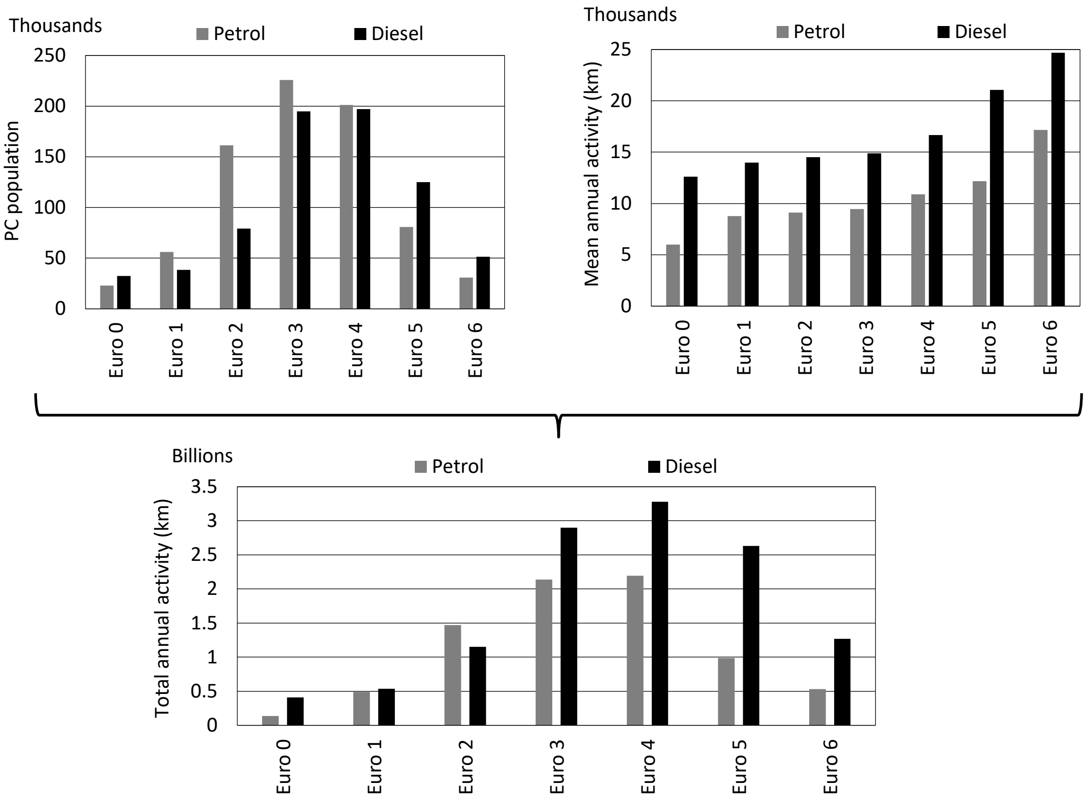

Figure 2: Population, mean annual activity and total annual activity for petrol and diesel PCs in 2016, according to European emission standards.

As mentioned above, circulation data were taken as an assumption. Therefore, the distribution of emissions generated in separate driving modes (urban/rural/highway) has not been considered. This paper presents total emissions generated in all mentioned driving modes. Table 1 shows the mean speed and the percentage of mileage driven by vehicles per driving mode (urban/rural/highway).

Table 1: The mean speed and percentage of mileage driven by vehicles per driving mode.

DRIVING MODE	MEAN SPEED (km/h)	SHARE (%)
Urban Off Peak	38	20
Urban Peak	28	20
Rural	60	35
Highway	110	25

Environmental information includes monthly values of average minimum and maximum temperatures as well as relative humidity. The data were taken from *The GLOBE Program of Croatia* and are shown in Table 2 (Jurić et al., 2012).

Table 2: Monthly values of average minimum and maximum temperatures as well as relative humidity (data for Zagreb, 2012).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min Temp (°C)	0.7	-0.2	4.5	10	12.5	16.9	18.1	19	16.4	8	2.2	2.1
Max Temp (°C)	5.6	6.4	13	20.4	24.1	27.5	28.6	30.3	26.8	16.1	7.1	7.9
Relative Humidity (%)	68	56	44	48	49	52	49	45	47	56	75	70

Results

Total (hot and cold) NO_X emissions from both petrol and diesel PCs in 2016 according to each Euro emission standard (Euro 0 to Euro 6) are calculated and presented in the top-left chart in Figure 3. Emissions are expressed in kilotons (kt). The top-right chart in Figure 3 shows implied NO_X EFs for petrol and diesel cars. Implied NO_X EFs are defined as total NO_X emission produced by cars with the relevant Euro standard, divided by the total annual activity of these cars. Nitrogen oxides EFs are provided in grams per kilometre (g/km). The comparison between implied NO_X EFs and type approval limit values for both petrol and diesel cars are presented in the bottom charts in Figure 3.

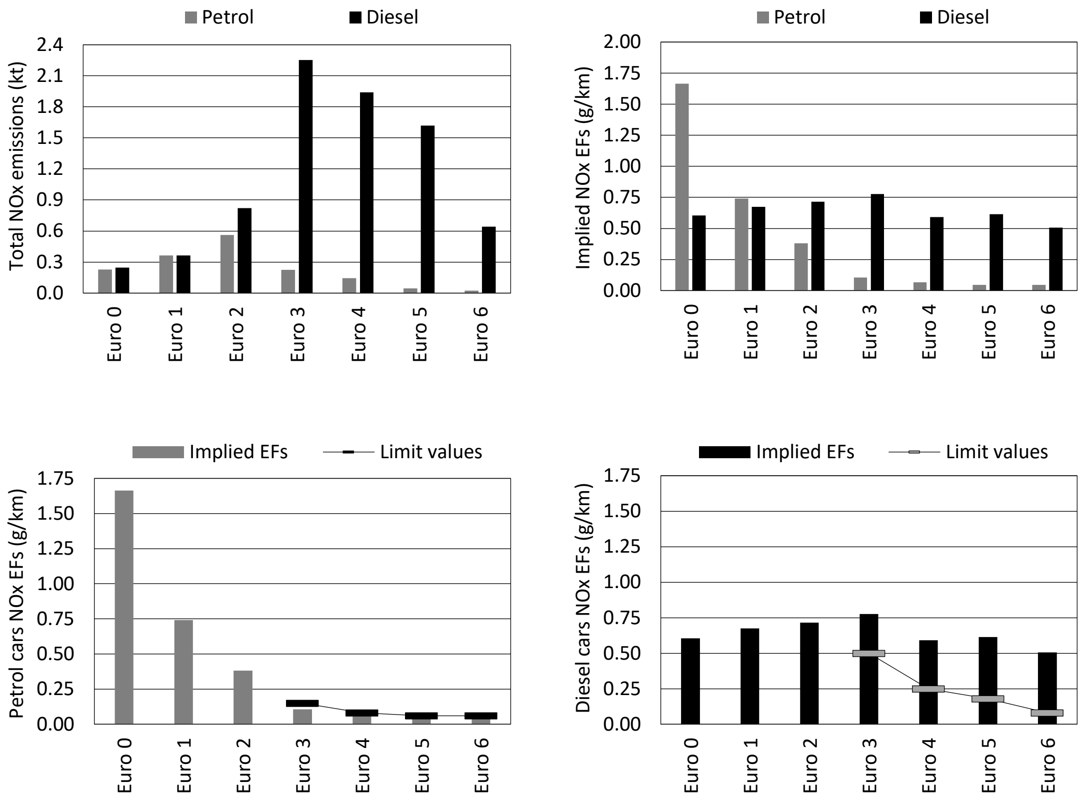

Figure 3: Total NO_X emissions, implied NO_X EFs and comparison of calculated NO_X EFs with type approval limit values.

Tailpipe emission of particulate matter PM10 from both petrol and diesel PCs in 2016 according to each Euro emission standard (Euro 0 to Euro 6) are calculated and presented in the top-left chart in Figure 4. Emissions are expressed in tons (t). The top-right chart in Figure 4 shows implied PM10 EFs for petrol and diesel cars. Implied PM10 EFs are defined as total PM10 emission produced by cars with the relevant Euro standard, divided by the total annual activity of these cars. Particulate matter EFs are provided in milligrams per kilometre (mg/km). The comparison between implied PM10 EFs and type approval limit values for both petrol and diesel cars are presented in the bottom charts in Figure 4.

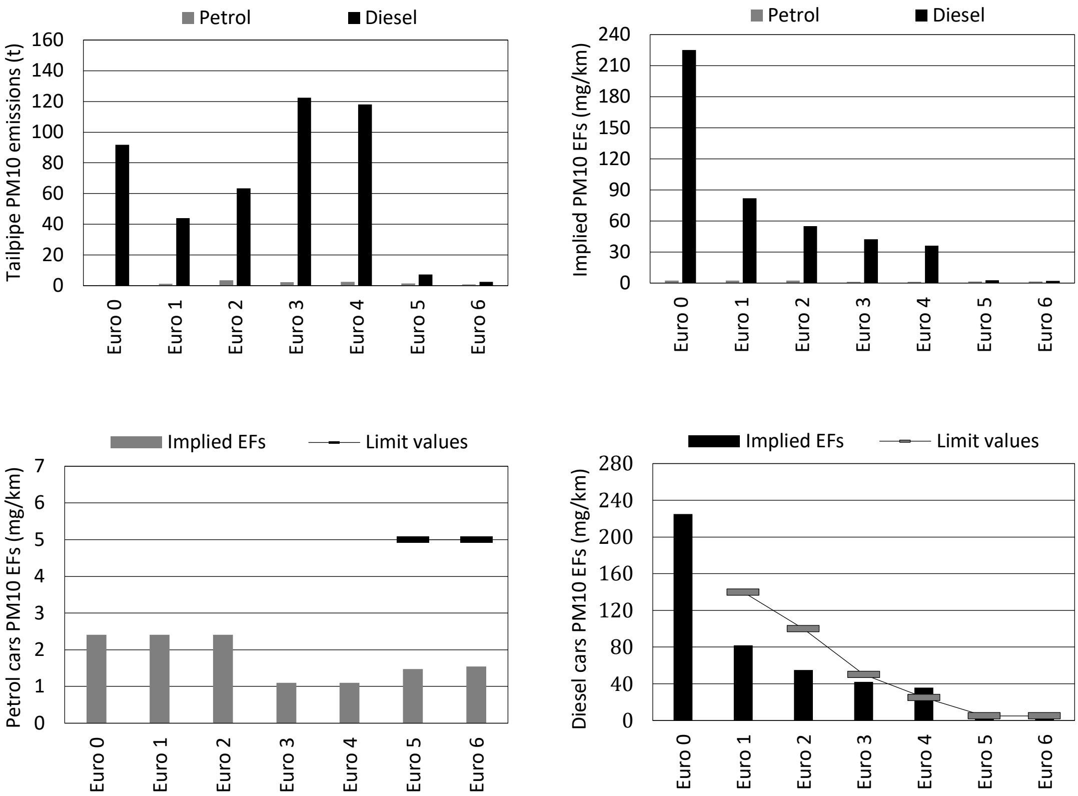

Figure 4: Tailpipe PM10 emissions, implied PM10 EFs and comparison of calculated PM10 EFs with type approval limit values.

Discussion and conclusions

The study investigated the influence of PC population and their activities on NO_X and PM emissions. As petrol and diesel PCs made up 96 % of the Croatian PC fleet in 2016, only these two PC subcategories were taken into account. Petrol cars make up 52 %, while diesel cars make up 48 % of the total number of vehicles considered. However, petrol cars drive 40 %, while diesel cars drive 60 % of the total annual mileage considered. Euro 3, Euro 4 and Euro 5 diesel cars are exploited much more than other PCs and these vehicles generated more than 60 % of total NO_X emissions of PCs. It is evident from Figure 3 that Euro 3/4/5/6 diesel cars exceed type approval limit values. Although diesel Euro 6 implied NO_X EF is the lowest in total diesel PC subcategory, its value exceeds Euro 6 emission limit by more than 6 times. Euro 0 petrol cars have the biggest implied NO_X EF, but the number of these vehicles is negligible compared to other PC subcategories. In addition, this subcategory is only marginally exploited. Regarding PM10 emissions, petrol cars do not play a significant role. Diesel cars Euro 0 up to, and including, Euro 4 emission standard produced 95 % of tailpipe PM10 emissions. It is only with the implementation of DPF technology on diesel Euro 5 and Euro 6 cars enabled that the PM emissions were significantly reduced. In order to reduce NO_X and PM emissions, it is necessary to lower the number of diesel PCs and/or their activity. The introduction of levies for diesel PCs is a method that would surely contribute to a reduced number of diesel vehicles and consequently to reduction of NO_X and PM emissions. In Croatia most levies are being considered through the carbon dioxide (CO_2) as a criterion. Diesel vehicles, due to lower fuel consumption compared to petrol cars, have the advantage when CO_2 EFs are taken as a criterion. But along with CO_2 as a criterion, it is necessary to introduce additional criteria related to harmful emissions, primarily NO_X and PM. Therefore, it is necessary to change the national policy measures. In order to decrease emissions, the vehicle fleet has to be renewed as well, by replacing older second-hand vehicles with new ones with low emissions. This would require definite national policy measures which would introduce tax cuts for new vehicles, while new tax levies would be redirected to older, mostly technically faulty and environmentally unfit vehicles, and specifically to the import of such vehicles.

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The Influence of Passenger Car Population and Their Activities on NO_X and PM Emissions (Data from Croatia)

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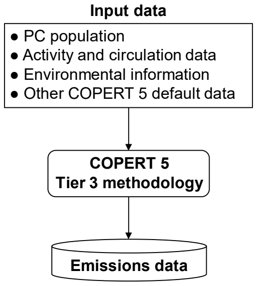
Introduction

Nitrogen oxide (NO_x) emissions from passenger cars (PCs) in the Republic of Croatia have been on the increase since 2014. Additionally, particulate matter (PM) emissions are not on the decline, but have been stagnating since 2015. The reason for this is the increase in vehicle exploitation that comes as a result of Croatia's recovery from the 2008 – 2013 economic crisis. Aside from that, Croatia's 2013 entry into the EU has resulted in an increased number of used PCs imported from the EU. Emissions from these used PCs are substantially higher than those of new PCs, whose sales have been slashed in half after 2008. The current trend is an increase of PCs in Croatia, which is bound to result in an overall increase of emissions. In order to apply justified emission reducing measures it is necessary to assess the main sources of pollution. In the case of harmful emissions, NO_x and PM emissions are the ones that were examined.

The processed data on the PC fleet that underwent technical inspection in 2016 was gathered from the database of Centre for Vehicles of Croatia (CVH), the company whose primary activity is performing periodical technical inspections on vehicles in Croatia. This is a unique database that contains data on all vehicles registered in Croatia, including periodic technical inspection data and annual vehicle activity data. For relevant PC subcategories, emissions and implied emission factors for pollutants NO_x and PM were calculated for the year 2016 using the COPERT 5 computer program.

Methodology

COPERT Tier 3 methodology, which is described in EMEP/EEA air pollutant emission inventory guidebook, was applied in the scope of this research.



A simplified form of COPERT emissions calculation model.

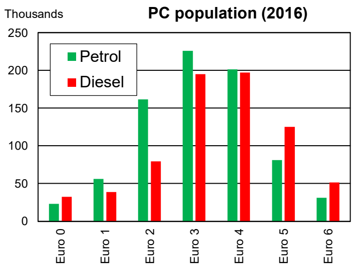
Input data

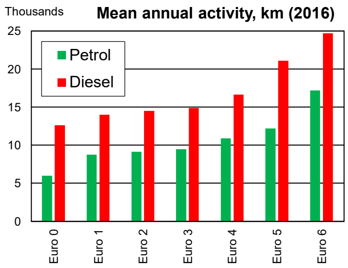
Circulation data (assumed)

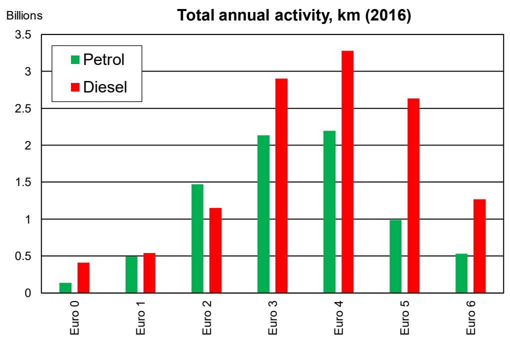
DRIVING MODE	MEAN SPEED (km/h)	SHARE (%)
Urban Off Peak	38	20
Urban Peak	28	20
Rural	60	35
Highway	110	25

Environmental information (data for Zagreb, 2012)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min Temp (°C)	0.7	-0.2	4.5	10	12.5	16.9	18.1	19	16.4	8	2.2	2.1
Max Temp (°C)	5.6	6.4	13	20.4	24.1	27.5	28.6	30.3	26.8	16.1	7.1	7.9
Rel. Humidity (%)	68	56	44	48	49	52	49	45	47	56	75	70

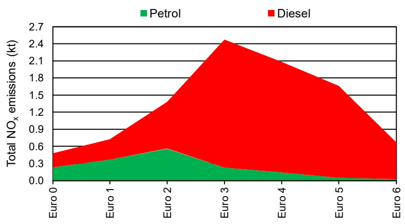


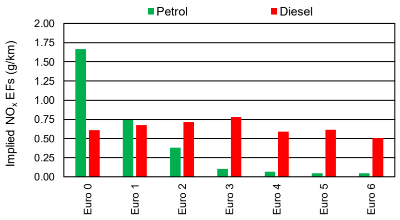


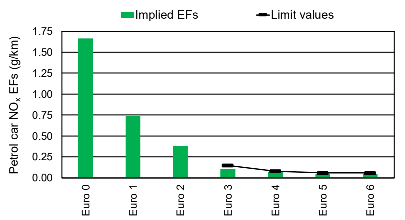


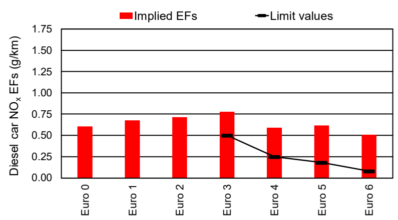
Results

NO_x

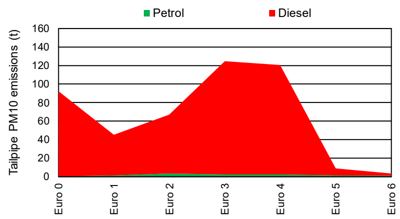


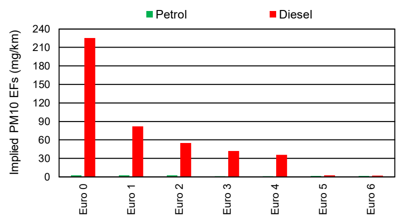


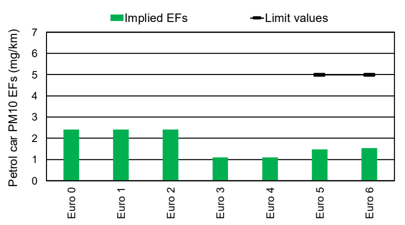


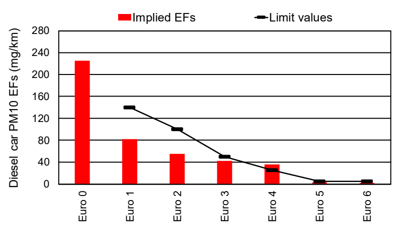


PM10









Discussion and conclusions

The study investigated the influence of PC population and their activities on NO_x and PM emissions. Petrol cars make up 52 %, while diesel cars make up 48 % of the total number of vehicles considered. However, petrol cars drive 40 %, while diesel cars drive 60 % of the total annual mileage considered. Euro 3, Euro 4 and Euro 5 diesel cars are exploited much more than other PCs and these vehicles generated more than 60 % of total NO_x emissions of PCs. The results shown that Euro 3/4/5/6 diesel cars exceed type approval limit values. Although diesel Euro 6 implied NO_x EF is the lowest in total diesel PC subcategory, its value exceeds Euro 6 emission limit by more than 6 times. Euro 0 petrol cars have the biggest implied NO_x EF, but the number of these vehicles is negligible compared to other PC subcategories. In addition, this subcategory is only marginally exploited. Regarding PM10 emissions, petrol cars do not play a significant role. Diesel cars Euro 0 up to, and including, Euro 4 emission standard produced 95 % of tailpipe PM10 emissions. It is only with the implementation of DPF technology on diesel Euro 5 and Euro 6 cars enabled that the PM emissions were significantly reduced.

In order to reduce NO_x and PM emissions, it is necessary to lower the number of diesel PCs and/or their activity. The introduction of levies for diesel PCs is a method that would surely contribute to a reduced number of diesel vehicles and consequently to reduction of NO_x and PM emissions. In Croatia most levies are charged by CO_2 emissions as a criterion. Diesel vehicles, due to lower fuel consumption compared to petrol cars, have the advantage when CO_2 EFs are taken as a criterion. But along with CO_2 as a criterion, it is necessary to introduce additional criteria related to harmful emissions, primarily NO_x and PM.

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Conference paper III

A new method for emission control system malfunction detection during the periodic technical inspection

A New Method for Emission Control System Malfunction Detection During the Periodic Technical Inspection

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Abstract

The paper shows a new method for detecting emission control system malfunction during periodic technical inspection (PTI). The on-board diagnostic (OBD) test results were collected and processed during the PTI of vehicles in Croatia in 2020. The study included petrol and diesel passenger cars that passed the tailpipe test and for which an OBD test had also been performed. In 11.5% of the tested cars, at least one stored diagnostic trouble code (DTC) was found. Due to the significant number of vehicles with identified DTCs, a new and more efficient method for the detection of potentially defective vehicles has been suggested. The introduction of the OBD test mandatory for all vehicles equipped with a European on-board diagnostic (EOBD) system is proposed. In addition to the existing OBD data, it is recommended to introduce the number of DTCs as mandatory, and such data should be relevant for passing the roadworthiness test.

Keywords: On-board diagnostic (OBD); Diagnostic trouble code (DTC); Periodic technical inspection (PTI); Emission control; Emission standard

1. Introduction

Due to the relatively expensive repair and replacement costs of exhaust after-treatment system components, vehicle owners, especially in countries with lower income, often decide to disable their functionality or completely remove them from the vehicle. Although such manipulations are often presented as "not illegal", they conflict with the European regulations' requirements that prohibit the use of defeat devices (Official Journal of the European Union, 2007). Before placing a vehicle on the market, prescribed emission limit values must be met during the type approval emission test. In most cases, in later phases of exploitation, they are no longer monitored.

The periodic technical inspection (PTI) of vehicles in Croatia is performed by the Centre for Vehicles of Croatia (CVH) (Rešetar et al., 2018). During the PTI, a tailpipe emission test is compulsory. For diesel vehicles, only the opacity of exhaust gas is measured, and the K-value is calculated. For petrol vehicles, the volume concentration of carbon monoxide is measured, and the lambda value is calculated. Because of limited technical capabilities, existing emission testers in PTI stations cannot be used for the detection of emission control system malfunction. The International Motor Vehicle Inspection Committee (CITA), based on their research, proposed the introduction of emission testing for diesel vehicles involving NO_X measurements (CITA, 2019). However, testers that can additionally measure NO_X emissions are quite expensive. Equipping all PTI stations, all over the country, with such testers would require significant financial resources and only diesel vehicles would be covered with this new test.

According to the European legislation, all petrol PCs sold within Europe since 2001, and diesel PCs manufactured from 2004, must be fitted with an on-board diagnostic (OBD) system for emission control (Official Journal of the European Communities, 1998). According to the *Directive 2014/45/EU*, for roadworthiness tests, the OBD test can be used as an equivalent to standard tailpipe emission testing for Euro 6/VI vehicles (Official Journal of the European Union, 2014). Since 2019, OBD testing methods have been performed in Croatia during the PTI (Rešetar et al., 2019). During the OBD test, the following data relating to the proper operation of the emission control system are collected: malfunction indicator lamp (MIL) status, readiness-code status, number of diagnostic trouble codes (DTCs), and others. The MIL status indicates a malfunction of any emission-related component connected to the OBD system or the OBD system itself. Malfunction means the failure of an emission-related component or system that would result in exceeded emissions. The readiness code is a set of 8 bits, each corresponding to one monitored emissions system in a vehicle. It indicates which of the vehicle's systems were checked during the diagnostics procedure. The number of DTCs shows the number of faults that the vehicle's OBD system uses to notify about an issue. When the OBD detects a fault, it will activate the corresponding trouble code. Each code indicates a specific issue. The DTCs are standardized and explained in ISO 15031-6:2015.

In the Republic of Croatia, the OBD test is currently used as an optional alternative to the tailpipe test for Euro6/VI vehicles where results indicate MIL OFF and readiness-code status OK. To improve the tailpipe test for Euro 5 and older vehicles with a European on-board diagnostic (EOBD) connection available, coolant temperature and engine speed can be collected via the OBD diagnostic tool. An OBD test is also performed by connecting a diagnostic tool, but it does not have to be accepted as a tailpipe test. By collecting and processing OBD data, it is possible to identify vehicles with potential malfunctions in emission control systems. This study is aimed at developing a method for the detection of such vehicles during the PTI.

2. Method

In order to check the functionality of electronic devices and physically inaccessible components embedded in the vehicle, new inspection methods should be introduced. With the application of vehicle diagnostics, it is possible to easily and quickly determine faults and malfunctions of individual components in the vehicle, and primarily the components of the emission control system. The existing method, self-initiated and introduced by the CVH, was used to collect the OBD data (Rešetar et al., 2019). In this study, data for PCs that underwent PTI in 2020 were collected and processed. Since the OBD test is currently not mandatory, the data of all PCs that attended the OBD test were used.

A new method proposed by this study would include the introduction of a mandatory OBD test for all vehicles equipped with an EOBD system. In addition to the existing OBD data, it is proposed to introduce the number of DTCs as mandatory, and such data should be relevant for passing the roadworthiness test, Figure 1.

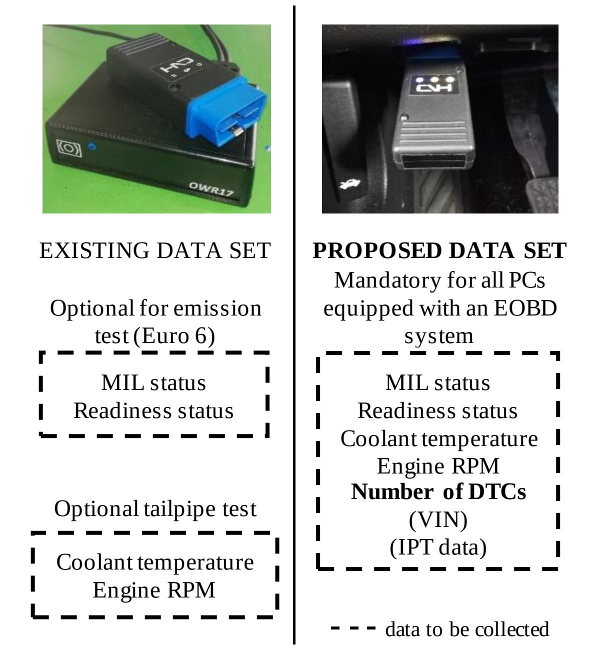
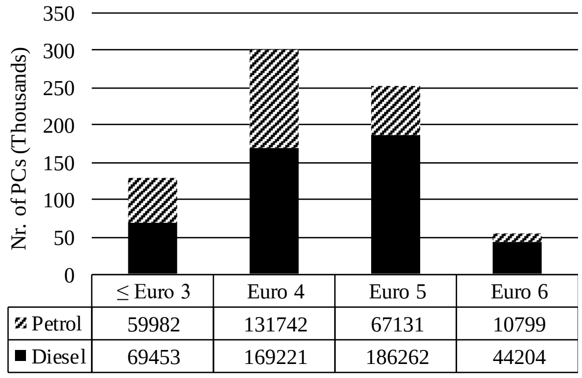


Figure 1. The existing and proposed PTI OBD test.

3. Results and discussion

3.1. Results

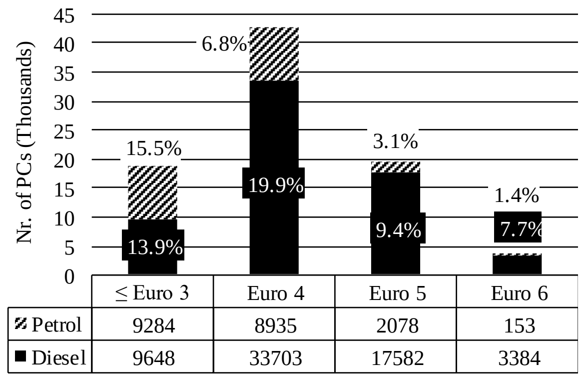
In 2020, a total of 1.733 million PCs were registered in the Republic of Croatia. Out of the total number of registered PCs, 1.594 million must undergo the emission test. Due to an identified or potential engine failure, 53 thousand PCs were not tested and they failed the PTI. The remaining 1.541 million PCs were tested either through a tailpipe or an OBD test. Out of the total number of PCs tested, 1.365 million passed the tailpipe test, slightly more than 164 thousand Euro 6 PCs passed the OBD test, and almost 12 thousand PCs did not pass the tailpipe test. The number of PCs that passed the tailpipe test, and for which an OBD test was also performed to collect coolant temperature and engine RPM data, is shown in Figure 2.



	≤ Euro 3	Euro 4	Euro 5	Euro 6
Petrol	59982	131742	67131	10799
Diesel	69453	169221	186262	44204

Figure 2. The number of PCs that passed the tailpipe test, and for which an OBD test was also performed.

The total number of PCs in Figure 2 amounts to 738,794, which is only 42,6% of the total PC fleet. Out of the total number of vehicles that passed the tailpipe test, at least 1 DTC was detected in 84,767 vehicles, which is about 11.5%. The number of vehicles with at least 1 DTC according to emission standards and fuel is shown in Figure 3.



	≤ Euro 3	Euro 4	Euro 5	Euro 6
Petrol	9284	8935	2078	153
Diesel	9648	33703	17582	3384

Figure 3. The number of PCs that passed the tailpipe test, for which an OBD test was also performed, and where at least 1 DTC was found.

Figure 3 also shows the percentage of such vehicles concerning the number of vehicles in Figure 2. If the OBD test was performed on all PCs that passed the tailpipe test, the total number of PCs with DTCs could be determined by the extrapolation method, Figure 4.

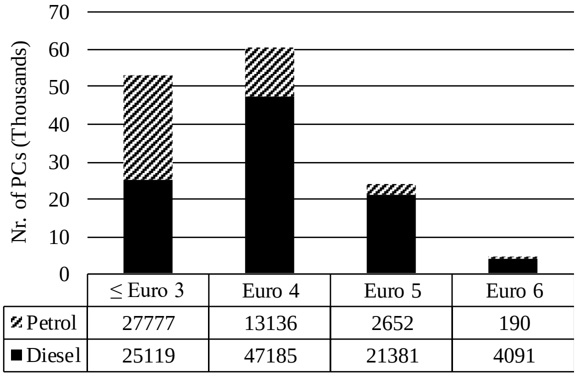


Figure 4. The total number of PCs with identified DTCs extrapolated to the group of PCs that passed the tailpipe test.

The average age of PCs registered in Croatia in 2020 was almost 13 years. Due to this, it is interesting to consider the influence of vehicle age on the PC fleet with identified DTCs. Figures 5 and 6 show the number of PCs that passed the tailpipe test, for which an OBD test was also performed, and the percentage of PCs where at least 1 DTC was found, in relation to vehicle age.

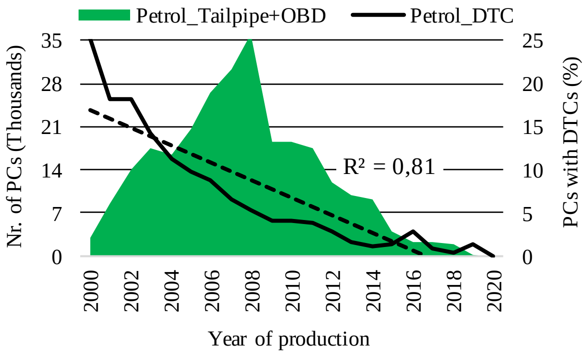


Figure 5. The number of petrol PCs that passed the tailpipe test, for which an OBD test was also performed, and the percentage of petrol PCs where at least 1 DTC was found, in relation to vehicle age.

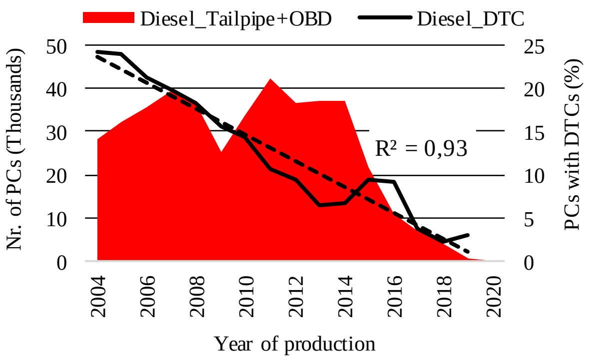


Figure 6. The number of diesel PCs that passed the tailpipe test, for which an OBD test was also performed, and the percentage of diesel PCs where at least 1 DTC was found, in relation to vehicle age.

The OBD test was performed on a total of 918,970 PCs. Of these vehicles, 332,203 were petrol and 586,767 were diesel. The status MIL OFF was recorded in 326,185 petrol and 581,310 diesel PCs. The total number of petrol and diesel PCs with the MIL ON status is shown in Figure 7.

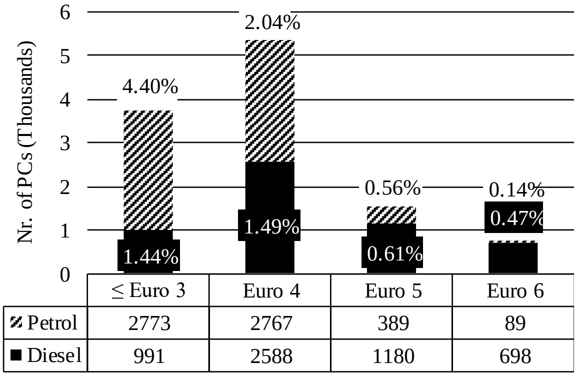


Figure 7. The total number of PCs with the MIL ON status, and the percentage of such vehicles in the PC fleet that took the OBD test.

3.2. Discussion

Although OBD tests are not mandatory, the results of this study indicate that there is a good reason to make them mandatory. By conducting OBD tests, a significant number of vehicles with MIL ON status and stored DTCs were identified, and such vehicles are potentially technically defective. Only 42.6% of the total PC fleet are cars that passed the tailpipe test, and for which an OBD test was also performed. On a sample of 738,794 tested PCs, 84,767 of those with stored DTCs were identified. Thus, 11.5% of vehicles that passed the tailpipe test stored at least one DTC. Although the Euro 3 emission category of vehicles is the second most numerous, a significant number of such vehicles did not take the OBD test. Considering vehicles with emission standards Euro 4, Euro 5, and Euro 6, it was found that the percentage of diesel PCs with stored DTCs is much higher compared to petrol ones, as shown in Figure 3. If all vehicles that passed the tailpipe test also underwent an OBD test, it is estimated that over 140 thousand vehicles would have stored DTCs, as shown in Figure 4. A significant and positive correlation between vehicle age and the percentage of vehicles with identified DTCs is shown in Figures 5 and 6. The older the vehicle is, the more likely it is that DTCs will occur. It can be concluded from Figure 3 and Figure 7 that the number of vehicles with the MIL ON status is much smaller than those with identified DTCs. This difference is to be expected, as not every DTC causes the MIL to activate. However, DTCs indicate a broader picture of possible failures on the body, chassis, powertrain, and other embedded systems. Given the above, the number of DTCs should become mandatory and relevant for passing the roadworthiness test.

4. Conclusion

Based on the results of this study, the introduction of a mandatory OBD test for all vehicles equipped with an EOBD system is proposed. The number of DTCs along with the MIL status should be relevant for passing the roadworthiness test. For emission tests, it is recommended to introduce an additional criterion that the vehicle must not have DTCs. The developed method can be implemented in a much broader set of vehicles and everywhere in the world on vehicles that have a built-in OBD2 system (EOBD for the European market, JOBD for the Japanese market, etc.). In this way, vehicle maintenance would be encouraged, and potential tampering prevented. Such measures would increase traffic safety and reduce the impact of vehicles on the environment and human health.

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17 INTERNATIONAL CONFERENCE ON ENVIRONMENTAL SCIENCE & TECHNOLOGY

A New Method for Emission Control System Malfunction Detection During the Periodic Technical Inspection

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INTRODUCTION

Due to the relatively expensive repair and replacement costs of exhaust after-treatment system components, vehicle owners, especially in countries with lower income, often decide to disable their functionality or completely remove them from the vehicle. Although such manipulations are often presented as "not illegal", they conflict with the European regulations' requirements that prohibit the use of defeat devices (Official Journal of the European Union, 2007). Before placing a vehicle on the market, prescribed emission limit values must be met during the type approval emission test. In most cases, in later phases of exploitation, they are no longer monitored.

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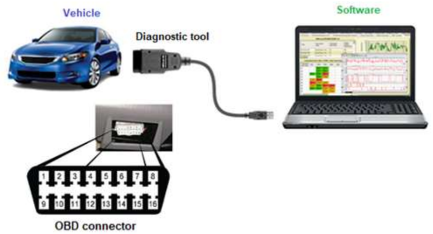
According to the European legislation, all petrol passenger cars (PCs) sold within Europe since 2001, and diesel PCs manufactured from 2004, must be fitted with an on-board diagnostic (OBD) system for emission control (Official Journal of the European Communities, 1998). According to the *Directive 2014/45/EU*, for roadworthiness tests, the OBD test can be used as an equivalent to standard tailpipe emission testing for Euro 6/VI vehicles (Official Journal of the European Union, 2014). Since 2019, OBD testing methods have been performed in Croatia during the PTI (Rešetar et al., 2019).

In the Republic of Croatia, the OBD test is currently used as an optional alternative to the tailpipe test for Euro 6/VI vehicles where results indicate MIL OFF and readiness-code status OK. To improve the tailpipe test for Euro 5 and older vehicles with a European on-board diagnostic (EOBD) connection available, coolant temperature and engine speed can be collected via the OBD diagnostic tool. An OBD test is also performed by connecting a diagnostic tool, but it does not have to be accepted as a tailpipe test. By collecting and processing OBD data, it is possible to identify vehicles with potential malfunctions in emission control systems. This study is aimed at developing a method for the detection of such vehicles during the PTI.

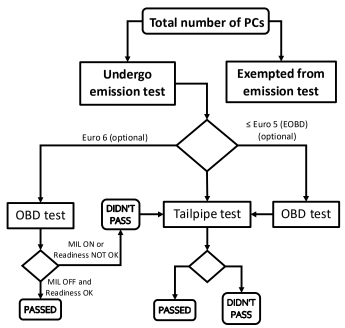


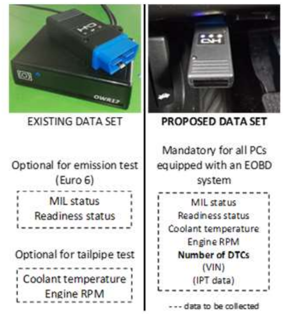
METHOD

With the application of vehicle diagnostics, it is possible to easily and quickly determine faults and malfunctions of individual components in the vehicle, and primarily the components of the emission control system. The existing method, self-initiated and introduced by the CVH, was used to collect the OBD data (Rešetar et al., 2019). In this study, data for PCs that underwent PTI in 2020 were collected and processed. Since the OBD test is currently not mandatory, the data of all PCs that attended the OBD test were used.

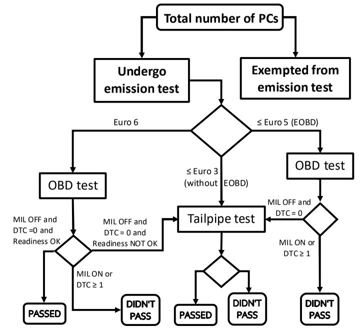
A new method proposed by this study would include the introduction of a mandatory OBD test for all vehicles equipped with an EOBD system. In addition to the existing OBD data, it is proposed to introduce the number of DTCs as mandatory, and such data should be relevant for passing the roadworthiness test.

EXISTING METHOD



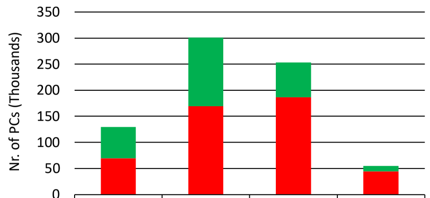


PROPOSED METHOD



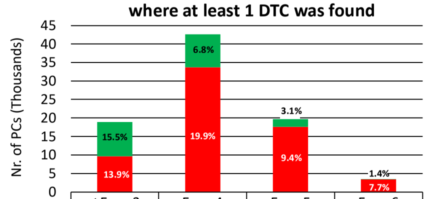
RESULTS

Passenger cars that passed the tailpipe test, for which an OBD test was also performed



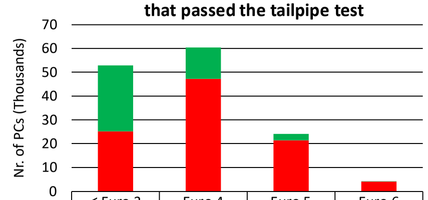
	≤ Euro 3	Euro 4	Euro 5	Euro 6
Petrol	59982	131742	67131	10799
Diesel	69453	169221	186262	44204

Passenger cars that passed the tailpipe test, for which an OBD test was also performed, where at least 1 DTC was found



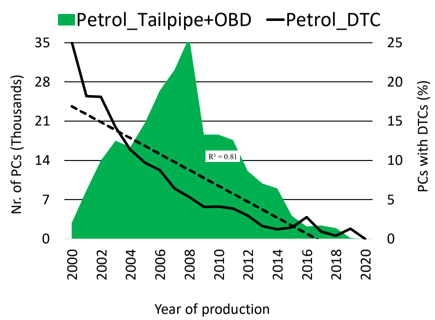
	≤ Euro 3	Euro 4	Euro 5	Euro 6
Petrol	9284	8935	2078	153
Diesel	9648	33703	17582	3384

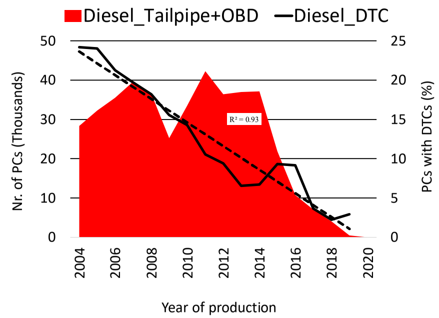
Passenger cars with identified DTCs, extrapolated to the group of passenger cars that passed the tailpipe test



	≤ Euro 3	Euro 4	Euro 5	Euro 6
Petrol	27777	13136	2652	190
Diesel	25119	47185	21381	4091

Passenger cars that passed the tailpipe test, for which an OBD test was also performed, and the percentage of passenger cars where at least 1 DTC was found, in relation to vehicle age.





CONCLUSION

Based on the results of this study, the introduction of a mandatory OBD test for all vehicles equipped with an EOBD system is proposed. The number of DTCs along with the MIL status should be relevant for passing the roadworthiness test. For emission tests, it is recommended to introduce an additional criterion that the vehicle must not have DTCs. The developed method can be implemented in a much broader set of vehicles and everywhere in the world on vehicles that have a built-in OBD2 system (EOBD for the European market, JOBD for the Japanese market, etc.). In this way, vehicle maintenance would be encouraged, and potential tampering prevented. Such measures would increase traffic safety and reduce the impact of vehicles on the environment and human health.

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Conference paper IV

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Table of Contents

Non-professional modifications of passenger cars

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Abstract

Vehicle roadworthiness is one of the preconditions for ensuring safety of all road users. The purpose of the paper is to call attention to the importance of the quality of modifications made to passenger cars (PCs) and the control thereof aimed at improving road traffic safety. In Croatia, vehicles and modifications made to such vehicles are tested and approved by the Centre for Vehicles of Croatia (CVH). In 2017, 107 out of 159 PTI stations carried out 15.376 various tests of modified PCs. Despite a significant increase in the number of tests of modified PCs in the last 7 years, the number of tests resulting in certain defect observations has not changed considerably. In 2017, merely 5.2 % of tests have resulted in certain defects observations and 107 tests resulted in a non-compliance certificate. Statistically, the number of tests resulting in certain defect observations is not significant. However, all the defects which have been determined during the testing and which have been remedied during the testing procedure are not included in the final statistics. This research includes an overview and analysis of non-professional modifications to various vehicle components that have a direct impact on road traffic safety. Results include an overview of defects of tested vehicles, non-professional modifications to such vehicles and the solutions for remedying the defects.

Zusammenfassung

Technische Vorschriftsmäßigkeit der Fahrzeuge ist eine der Voraussetzungen für die Sicherheit aller Verkehrsteilnehmer. Das Ziel dieser Arbeit ist, auf die Wichtigkeit der Qualität von technischen Änderungen an Personenkraftwagen (PKW) und deren Kontrolle zur Gewährleistung der Verkehrssicherheit hinzuweisen. In Kroatien wird das Begutachtungs- und Genehmigungsverfahren vom Kroatischen Zentrum für Fahrzeuge (CVH) durchgeführt. Im Jahr 2017 wurden in 107 von insgesamt 159 Technischen Prüfstellen 15.376 unterschiedliche Fahrzeugumbauten begutachtet. Obwohl die Zahl dieser Begutachtungen in den letzten sieben Jahren erheblich gestiegen ist, hat sich die Anzahl der Begutachtungen, bei denen Mängel festgestellt wurden, kaum verändert. Im Jahr 2017 wurden bei lediglich 5,2 Prozent der Begutachtungen Mängel festgestellt, und bei 107 Begutachtungen wurde die Ausstellung der Konformitätsbescheinigung verweigert. Statistisch betrachtet, wurde keine bedeutende Anzahl von Begutachtungen verzeichnet, bei denen bestimmte Mängel festgestellt wurden. Die Mängel, die bei den Begutachtungen festgestellt und im Laufe des Begutachtungsverfahrens beseitigt wurden, sind in der Endauswertung jedoch nicht erfasst. Die vorliegende Untersuchung analysiert und bietet einen Überblick über unsachgemäß durchgeführte Änderungen an diversen Fahrzeugbauteilen, die für die Straßenverkehrssicherheit unmittelbar relevant sind. Die Ergebnisse beinhalten einen Überblick über festgestellte Mängel an begutachteten Fahrzeugen, unsachgemäß durchgeführte Änderungen an diesen Fahrzeugen sowie Lösungen für die Mängelbeseitigung.

Introduction

It is stated in the 2015 report by the World Health Organization that more than 1.2 million people die due to traffic accidents and that traffic accidents are the leading cause of death in the 15-29 age group [1]. A research carried out in Macedonia used relative risk indicators to demonstrate the lack of a specific pattern in the change of the number of fatalities in the period from 2005 to 2014, primarily as a consequence of the lack of target measures and policies for the improvement of road traffic safety [2]. The lack of investment in projects for the road traffic safety improvements has also been recorded in the Philippines [3]. A similar situation exists in other countries with a low GDP per capita. Increasing the safety of all road users remains a continuing challenge for experts in the field of transport and traffic science. Along with the behavioral patterns of all road users, transport infrastructure, etc., vehicle roadworthiness is one of the key factors that have a direct impact on road traffic safety. A cost-benefit assessment of switching from annual vehicle inspections to six-month inspections for vehicles over 6 years of age has been made in New Zealand [4]The results of the research indicate that the said change in the frequency of technical inspections is not cost-beneficial in terms of safety. However, it should be noted that in 2013 New Zealand had road traffic fatality rate of 6 per 100 000 population, compared to the world average rate above 17 [1]. The research carried out in Norway did not demonstrate the effect of technical inspections on the rate of traffic accidents. However, it demonstrated the effect of technical inspections on the increase in vehicle roadworthiness [5]. A project named "Roadworthiness Inspection of Vehicles Involved in Traffic Accidents with Fatalities" was implemented in Croatia from 2012 to 2015 [6]. The project results indicate that as many as 42% of inspected vehicles which are participated in accidents with fatalities were technically defective. It is almost twice as high as the 2017 average technical defectiveness rate of the Croatian vehicle fleet amounting to 22%. The fact is that technical defectiveness of vehicles reduces road traffic safety. Therefore, it is necessary to underline the paramount importance of procedures for testing and approving vehicles and vehicle modifications, in addition to regular technical inspections of vehicles, in order to ensure technical roadworthiness of vehicles and maintain as high a level of road traffic safety as possible. Figure 1 shows the total number of tests performed on passenger cars (PCs) and the number of tests resulting in certain defect observations, for the period 2007 – 2017.

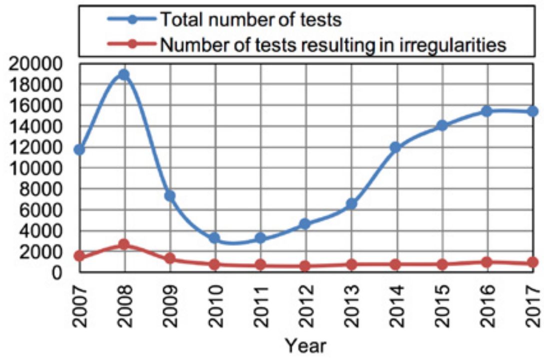

Figure 1: The total number of tests on PCs and the number of tests resulting in certain defect observations.

The curve for the total number of tests follows the economic situation in the country. The greatest number of tests was recorded in 2008, the same year the world economic crisis began. As early as 2009, the impact of the said crisis resulted in multiple reductions in the number of tests. Since 2011, there has been an increase in the number of tests. Due to the constant technological advancement in the manufacture of vehicles and their separate technical units, the requirements for vehicle modifications are becoming increasingly stringent. However, despite the multiple increase in the number of tests on PCs since 2011, the number of tests resulting in defect observations has not changed significantly. In other words, the system functions well and people i.e. customers are becoming more aware of the fact that any modification to the vehicle has to meet the relevant requirements pertaining to such modification. Testing and approving vehicle modifications helps achieve a high level of vehicle roadworthiness, increases the safety of all road users and constitutes a preventive action aimed at reducing the number of traffic accidents.

Testing and approval procedure

First of all, it should be noted that there is no mass production of PCs in the Republic of Croatia. Hence the term "testing and approval of vehicle modifications" instead of "testing and approval of vehicles" is used herein. Vehicles manufactured individually or in small series, which mainly include vehicles of other categories that are not covered by this research, are subject to vehicle testing and approval in the Republic of Croatia. The procedure for testing modifications to PCs begins with a preliminary inspection of the vehicle and the visual inspection of vehicle modifications in one of the PTI stations authorized to carry out such procedures (see Figure 2).

Figure 2: Preliminary inspection of the vehicle and visual inspection of all modifications to the vehicle.

If no significant defects are observed during the visual inspection, the vehicle undergoes the chassis number identification / Vehicle Identification Number (VIN) procedure followed by the test registration. Documentation on the ownership or the origin of the vehicle and documentation describing all interventions on the vehicle, including a technical description of the vehicle modification, type-approvals of installed parts/assemblies/devices, etc., are submitted to the PTI station inspector. After registering the test and receiving all necessary documentation, a detailed inspection of modifications to the vehicle is conducted. The said modifications are photographed and the test forms are filled out according to the actual condition of the vehicle. All components that are installed on the vehicle have to be approved or tested. After determining the identification codes (marks) of the installed components, the dimensions and the position of installation with respect to the typical parts on the vehicle and external dimensions of the vehicle, it is necessary to physically check how the installed components have been secured and fastened onto the vehicle. As an example, Figure 3 shows the procedure for testing the mounted wheel rims and tires of unapproved dimensions.

Figure 3: Procedure for testing the mounted wheel rims and tires of unapproved dimensions.

Functionality of the components, where possible, is tested by using the appropriate testing equipment. The testing equipment includes the brake tester, decelerometer, brake fluid boiling point tester, suspension tester, speedometer, emissions tester, sound level meter, headlight tester, gas leak detector, manometer, thermometer etc. For example, Figure 4 shows comparison of vehicle speed measured by the performance meter after the mounting of wheel rims and tires of unapproved dimensions deviating in diameter by more than 3% from the approved dimensions.

Figure 4: Comparison of vehicle speed measured by the performance meter after the mounting of wheel rims and tires of unapproved dimensions.

The testing procedure at the PTI station ends by entering all required documentation, test forms, test results and photographs into the digital database of the tested vehicles, together with the identification code of the subject of testing C-xxxxxx, where xxxxxx is the sequence number of the testing. If the inspector determines non-professional interventions or any of the defects observed during the visual inspection, which cannot be remedied fast and easily at the testing site, the inspector will instruct the client to remedy the aforementioned defects and will not register the testing until the observed defects are remedied.

The procedure for approving modifications to vehicles is carried out by CVH's Testing Department. The approval procedure begins with the inspection of photographs of the modifications to the vehicle and with the verification of all necessary documentation. If the inspector at the PTI station has done his job properly, photographed everything needed, adequately filled out the required test forms, enclosed the test results together with all necessary documentation on vehicle modification, a detailed review of everything submitted may follow. It is verified whether the modification to the vehicle complies with all the requirements pertaining to this modification in accordance with the applicable regulations, directives, ordinances, national regulations, type-approvals, assembly instructions, standards, CVH's internal operating instructions and the rules of the profession. If all the requirements are met, the data will be entered into the computer program for issuing the vehicle test certificate. The approval procedure ends by applying the digital signature and issuing the test certificate. Each issued certificate can be printed and downloaded at any of the 159 PTI stations. If certain defects are observed in the approval procedure, the client will be informed in writing about all the defects on the vehicle and will be instructed to remedy them within 30 days.

In specific cases, if radical modifications have been made to the vehicle, the personnel of CVH's Testing Department will conduct an additional inspection and further testing of the vehicle. A chassis dynamometer is used for this purpose and tests are conducted in dynamic driving conditions on a test track using the performance meter (see Figure 5).

Figure 5: Testing of radically modified vehicles.

A significant number of various non-professional interventions on vehicles is observed on a daily basis through the procedure for testing and approving vehicle modifications. However, this research covers only some of the most common non-professional interventions that have a significant impact on the safety of all road users, as shown and described in results.

Results

It is not uncommon for the testing procedure to result in observations of defects arising from improper and untimely vehicle maintenance. However, such defects have not been examined herein. Thus, the paper illustrates only non-professional interventions on PCs observed during the testing and approval procedure. Non-professional interventions include the following:

1) Replacement of wheel rims and tires with wheel rims and tires of unapproved dimensions;
2) Replacement of suspension components;
3) Replacement of powertrain system components;
4) Replacement of brake system components;
5) Replacement and subsequent installation of exterior accessories of the vehicle body (lights, windshield, bumpers, spoilers, winches, towbars);
6) Replacement of exhaust system components;
7) Installation of seats, bench seats and seatbelts;
8) Installation of LPG and CNG systems;
9) Radically modified vehicles.

Replacement of wheel rims and tires with wheel rims and tires of unapproved dimensions

A total of 1.605 tests of the replaced wheel rims and tires of unapproved dimensions was performed in the period from 2010 to 2017. A defect was observed in 306 of these tests (see Figure 6).

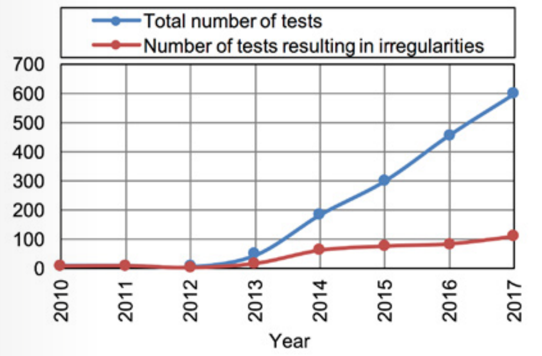

Figure 6: Testing of replaced wheel rims and tires of unapproved dimensions.

The most common irregularities include mounted wheel rims and tires of incompatible dimensions, which are laterally bulging outside the exterior dimensions of the vehicle or getting caught under the vehicle body parts. Another irregularity also refers to the poor condition of tires, mounting of unapproved type of wheel rims, mounting of wheel rims without a certificate or without load rating, etc. Figure 7 shows some of the most common defects related to wheel rims and tires.

Figure 7: Tires that are too narrow with respect to the width of the wheel rim (top left), tires that get caught under the mudguards (top right), cracked and worn-out tires (bottom left), excessively worn-out tires (bottom right).

Other defects include improper tire pressure, poor condition of wheel rims, improper fastening of wheel rims onto the vehicle, etc.

Replacement of suspension components

A total of 453 tests of the replaced suspension components was performed in the period from 2010 to 2017. An irregularity was observed in 182 of these tests (see Figure 8).

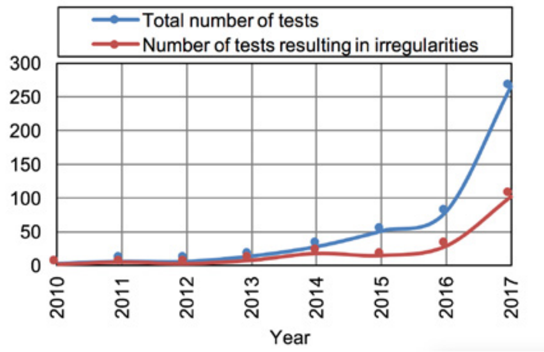

Figure 8: Testing of replaced suspension components.

The most common irregularities include the installation of used suspension components that cannot be identified and compared with the submitted certificate and the installation of suspension components that are not intended for the tested vehicle. Figure 9 (left) shows installed suspension components that do not meet the testing requirements and the assembly of suspension components after the remedy of defects (right).

Figure 9: Improperly mounted suspension components (top left) and suspension components properly mounted by replacing the threaded nut which is compatible with the mounted spring (top right). Unauthorized mounting of used springs without identification codes (bottom left) and authorized mounting of new springs with identification codes (bottom right).

Even if approved suspension components are fitted onto the vehicle, there is no guarantee that the vehicle will comply with the requirements during the testing. For example, if wheel rims and tires have been replaced together with the suspension components, the possibility of wheel rims getting caught under the vehicle body is not excluded.

Replacement of powertrain system components

A total of 2.346 tests of the replaced powertrain system components was performed in the period from 2010 to 2017. An irregularity was observed in 805 of these tests (see Figure 10).

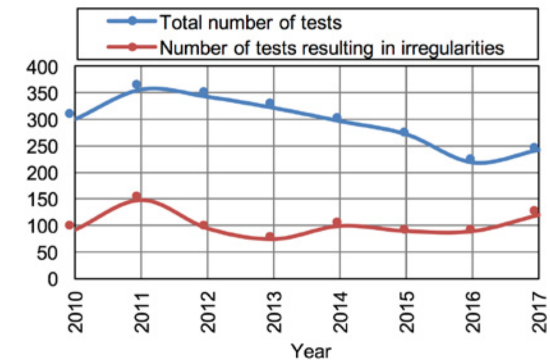

Figure 10: Testing of replaced powertrain system components.

The most common defect in this type of test was the lack of complete documentation on the origin of the installed components and technical description of the intervention on the vehicle (administrative, not technical defects).

The most common case of replacing powertrain system components refers to the engine or gearbox that are replaced due to wear and tear or malfunctions not cost-effective for any repair or due to engine tuning.

One of the most common defects observed during such modifications to the vehicle includes improper fastening of the engine or gearbox onto the vehicle body (see Figure 11).

Figure 11: Improperly (left) and properly (right) fastened gearbox on the vehicle body.

In addition, frequent defects include non-professional assembly of self-built engine mount or gearbox mount, absence of engine components (air filter, fluid lines, disconnected connectors), excessive lubrication of the engine or gearbox, activation of the "check engine" indicator light, etc. (see Figure 12).

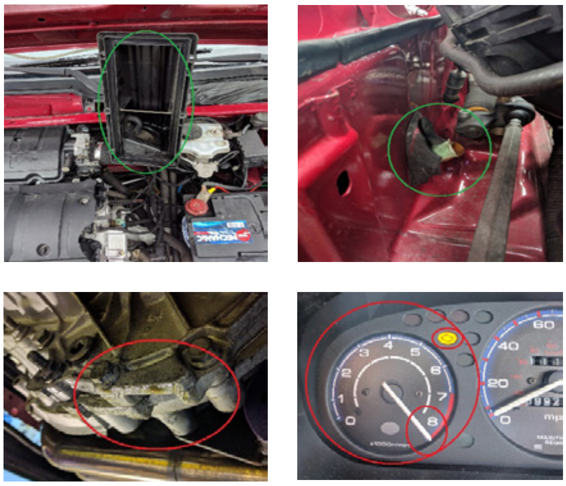

Figure 12: Absence of air filter for the engine (top left), disconnected coolant fluid line (top right), oil leaking on the gearbox casing (bottom left), activation of the "check engine" indicator light.

Due to improper engine tuning or catalyst disassembly upon engine replacement, some vehicles did not meet the requirements for the exhaust gas testing (Figure 13).

Figure 13: Bosch device for testing exhaust gases (left) and a print-out of the test results for exhaust gases (right).

In the case of radically modified vehicles, one of the most common defects refers to the vehicles with installed powertrain system components that do not conform to the power of the new engine installed (clutch, gearbox, differential drive/axle drive, drive shaft/cardan shaft, differential output shafts).

Replacement of brake system components

Brake system components are most often replaced when the powertrain system is replaced and the engine power is significantly increased. In that case, the brake system of the modified vehicle should be reduced at least to the default brake system of the powertrain system donor vehicle. There are also cases of drum brake assembly and disc brake installation, or the replacement of the existing disc brakes with more robust disc brakes. Sometimes, the ABS system is additionally installed on vehicles that have not been equipped with an ABS system in a regular serial production.

The most common irregularities include the installation of used parts that have been excessively worn and torn (discs and brake linings), excessively decreased boiling point of the brake fluid (brake fluid absorbing too much moisture), insufficiently high brake coefficients on brake rollers or excessive difference in the brake force of wheels on the same shaft (most often the brake system has not been adjusted and vented well), malfunctions on the electronics (ABS system is not functional), etc. Figure 14 shows some of the most common defects related to the replacement of brake system components.

Roller brake test	Front axle	Rear axle
Mass (kg)	700	420
Brake force, left wheel (N)	1.515	531
Brake force, right wheel (N)	1.125	882
Left-right difference (%)	**25.7** (<25)	**39.8** (<25)
Brake coef. (%)	**36.9** (>50)	

Figure 14: Excessively worn and torn discs and brake linings (top left), excessively decreased boiling point of the brake fluid (top right), defective brake system on brake rollers (bottom left), defective parking brakes, ABS and ESP (bottom right).

Radically modified vehicles with replaced brake system are additionally tested on the test track. In addition to the vehicle maneuverability test, suspension tuning, speedometer test, etc., the brake test is performed at different speeds ranging from 40 to 100 km/h. Figure 15 illustrates the initial results of braking performance at 60 km/h for Opel Astra F 1.4i which has been modified with a 2.0i 16v engine.

Main Run

Channel	Opel Astra.DBN Start Value	End Value	Difference	Average
Time (secs)	907,680	911,500	3,820	------
Speed (km/h)	60,010	0,000	-60,010	26,901
Distance (metres)	6402,597	6511,640	29,051	------
Longitudinal Acceleration (g)	-0,130	-0,150	-0,020	-0,429

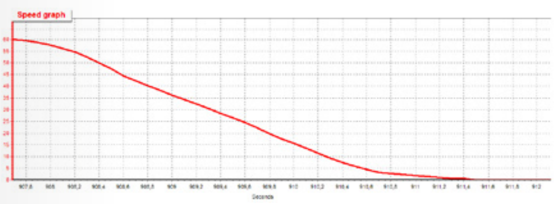

Figure 15: Initial results of braking performance for Opel Astra F 1.4i / 2.0i 16v.

$$Deceler. = \frac{(v1-v2)}{3.6\cdot(t2-t1)} = \frac{60.010}{3.6\cdot(911.5-907.68)} = 4.36\ \mathrm{m/s^2} < 5\ \mathrm{m/s^2}$$

Since the vehicle did not meet the test requirements, the owner of the vehicle was instructed to correct the stated defects. After the defects had been remedied, the vehicle was tested again on the track and the following results were measured (see Figure 16).

Main Run

Channel	Opel Astra (serviced).DBN Start Value	End Value	Difference	Average
Time (secs)	165,200	167,690	2,490	------
Speed (km/h)	59,630	0,000	-59,630	32,196
Distance (metres)	248,551	270,066	21,515	------
Longitudinal Acceleration (g)	-0,063	-0,312	-0,249	-0,666

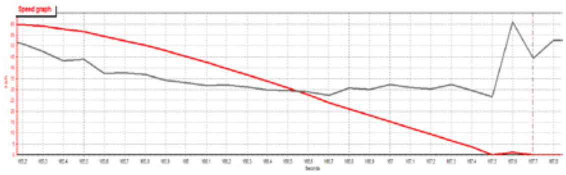

Figure 16: Braking performance results for Opel Astra F 1.4i / 2.0i 16v after brake servicing.

$$Deceler. = \frac{(v1-v2)}{3.6\cdot(t2-t1)} = \frac{59.63}{3.6\cdot(167.69-165.2)} = 6.65\ \mathrm{m/s^2} > 5\ \mathrm{m/s^2}$$

Replacement and subsequent installation of exterior accessories of the vehicle body

This group of tests includes replaced and subsequently installed lights, bumpers, spoilers, winches and towbars, as well as the modifications to vehicle body and glass surfaces.

The most common technical defects arising from the replacement or subsequent installation of lights are the installed non-homologated lights, other types of light bulbs installed into headlights intended for halogen light bulbs, incomplete installation of xenon lights (without ballast, headlamp washers, angle sensors and headlamp levelling actuator), improper alignment of headlights, etc. (see Figure 17).

Figure 17: Installation of non-homologated LED daytime running lights (top left), front direction indicators that are not visible – excessive recessing into the bumper (top right), improper alignment of halogen high beam headlights (bottom left), improper installation of xenon lights without ballast, headlamp washers and angle sensors in the headlights intended for halogen light bulbs (bottom right).

The most common technical defects arising from the replacement or subsequent installation of bumpers and spoilers are compromised structural integrity (cracking) and improper fastening onto the vehicle (see Figure 18).

Figure 18: Cracked front bumper (left) and a roof spoiler improperly mounted by rear window drilling (right).

Moreover, the assembly of bumpers and spoilers with protruding parts and sharp edges, as well as incomplete assemblies, are not permitted (see Figure 19).

Figure 19: Improperly assembled rear spoiler with protruding parts and sharp edges (top left) and the appearance of the vehicle after removing of such spoiler to meet the test criteria (top right). A protective mesh grille missing on the front bumper (bottom left), and the assembled bumper with a fitted protective mesh grille and registration plate holder (bottom right).

The testing of mounted winches and towbars began in 2013. A total of 60 tests of mounted winches and 28,956 tests of mounted towbars was performed in the period from 2013 to 2017 (see Table 1).

Table 1: The total number of tests for mounted winches and towbars in the period from 2013 to 2017.

Year	Winch tests	Towbar tests
2013	1	2261
2014	9	6104
2015	10	6285
2016	17	7070
2017	23	7236

The most common technical defects arising from the mounting of winches and towbars are the following: incorrect fastening onto the chassis or body of the vehicle, winches and towbars mounted outside the exterior dimensions of the vehicle, the tested vehicle fitted with a winch and a towbar not intended for such vehicle, unapproved type of winch and towbar mounted on a vehicle, etc. (see Figure 20).

Figure 20: Improperly mounted winch protruding on the front bumper (top) and towbar holder improperly fastened onto the vehicle (bottom).

Unauthorized modifications to windscreen have often been found in the course of testing and approving vehicle modifications – tinting or completely reduced visibility in the area of driver's field of vision (films, labels, etc.) (see Figure 21).

Figure 21: Prohibited application of films and stickers to the windscreen.

Replacement of exhaust system components

A total of 107 tests of the replaced exhaust system components was performed in the period from 2013 to 2017. An irregularity was observed in 53 of these tests (see Figure 22).

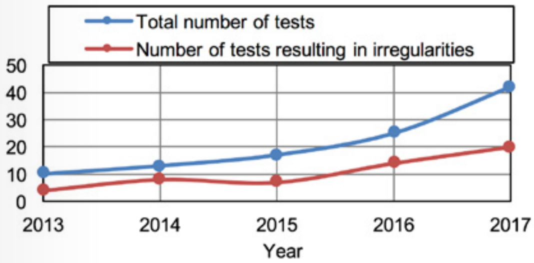

Figure 22: Testing of replaced exhaust system components.

The most common technical defects in this type of testing refer to the unapproved exhaust silencers and mufflers installed on the vehicles, as well as removing of standard exhaust components from an exhaust. (see Figure 23).

Figure 23: Unapproved type of self-built exhaust silencer and muffler mounted onto the vehicle (left) and unapproved modification – removing the exhaust silencer and muffler from the exhaust (right).

For such unauthorized modifications, it is not necessary to measure the noise of the vehicle until the approved type of exhaust silencers and mufflers is installed.

Various other irregularities on the exhaust system components, such as the removal of catalyst, oxygen (O2) sensor, DPF filter, mounting of asbestos strips on the exhaust manifold, etc., are often found during such tests (see Figure 24).

Figure 24: Assembled catalyst and oxygen sensor, and asbestos strips mounted onto the exhaust manifold.

Installation of seats, bench seats and seatbelts

When converting a light commercial vehicle (freight vehicle) into a passenger vehicle or changing the number of seats in a vehicle, the vehicle has to undergo the test and approval procedure.

The most common technical defects in these types of tests are improperly secured bench seats, improperly fitted seatbelts, installed seatbelts without marks and homologation codes, etc. (see Figure 25).

Figure 25: Improperly secured bench seat (top), improperly fitted third seatbelt on the rear bench seat of Renault Clio III (bottom left) and properly fitted third seatbelt on the rear bench seat of Renault Clio III (bottom right).

It is not uncommon for the owners of radically modified vehicles to replace the factory driver and passenger seats with sports racing seats that are not approved for road use (see Figure 26). Such modification to vehicles is not permitted.

Figure 26: Unauthorized installation of sports seats unapproved for road use.

Installation of LPG and CNG systems

In Croatia, LPG and CNG systems may be installed into vehicles only by authorized service workshops. In 2017, there were 143 authorized service workshops for the installation of the abovementioned systems in the Republic of Croatia. Although this type of testing is by far the most frequent one (Table 2), no significant number of tests resulting in defects that seriously undermine road traffic safety has been recorded precisely due to the warranted installation by professionals.

Table 2: The total number of tests of the LPG and CNG systems installed into PCs in the period from 2008 to 2017.

Year		The number of tests of the installed LPG and CNG systems	
2008	2013	18.678	2.700
2009	2014	6.122	3.140
2010	2015	1.957	4.924
2011	2016	1.676	4.853
2012	2017	3.086	3.819

Nevertheless, some of the most significant technical defects are definitely gas leakage, improperly installed and fastened gas tanks, inadequately protected gas tanks, damaged gas tight housing, etc. (Figure 27).

Figure 27: Cracked gas installation pipes and detected gas leakage (top). Inadequately protected gas tank (bottom left) and damaged gas tight housing (bottom right).

Radically modified vehicles

Radically modified vehicles refer to the vehicles whose engine has been replaced with an engine with a much higher power output, which naturally involves the replacement of other power transmission components, brake system components, etc. The steering system, suspension components, exhaust system components, wheel rims and tires, etc. are most often also replaced on such vehicles. Such vehicles are additionally tested on the test track in dynamic driving conditions.

The most common defects observed on the test track are the malfunctioning steering system components, suspension components, brake system components, and malfunctioning speed indicators. Malfunctions are usually manifested through uneven motion of the vehicle (the vehicle is pulled to the side), improper response of the engine during accelerator pedal activation (throttle), improper response of brakes during brake pedal activation, clunking noise of wheels, wheel lock during braking (ABS is not functioning), vehicle rotation during braking, wheels getting stuck under the vehicle body components, incorrect indication of vehicle speed and engine speed, activation of warning lights, etc. Figure 28 shows a Renault Clio I 1.2 that has been modified with a 1.8i 16v engine. The vehicle is shown while braking at 80 km/h with a malfunctioning brake system (left) and a functioning brake system after the performed servicing (right). The vehicle is not equipped with ABS.

Figure 28: Stopped vehicle after braking at 80 km/h with defective brake system (left) and functioning brake system after the performed servicing (right).

If it is established that the technical characteristics of the engine have to be measured due to the radical modification to the engine in relation to the factory builit-in engine, such vehicles are further tested on the chassis dynamometer (Figure 29).

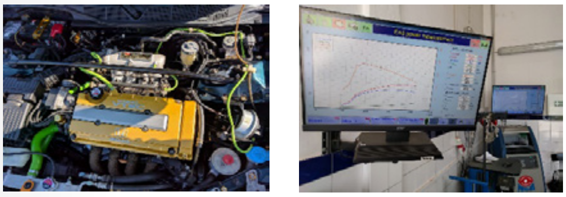

Figure 29: Radically modified engine of Honda Civic 1.8 VTI (left). Diagrams of engine power and torque measured during the test (right).

Discussion and conclusions

In spite of the fact that merely 5-6% of tests have resulted in certain defect observations in the past few years, the actual situation is quite different. Owners of vehicles undergoing the testing procedure are provided with free technical support from CVH before and during the testing procedure, which significantly reduces the number of potential defects. Additionally, the complete statistics of non-professional interventions includes only the tests for which the vehicle owners have received the test reports stating the defects to be remedied. All the defects which have been determined during the testing and which have been remedied during the testing procedure are not included in the statistics. Therefore, it is concluded that the actual number of tests resulting in defect observations is considerably higher than the one illustrated, for the whole period from 2007 to 2017. It can be concluded by reviewing the results that since 2013 there has been a favorable trend in the ratio between the number of tests resulting in defect observations and the total number of tests related to the replacement of wheel rims and tires and suspension components. However, the same cannot be claimed for the replacement of the powertrain system components. In the case of such interventions there is a great number of defects related to incomplete documentation. Proposals for solutions are drafted in order to reverse the negative trend and reduce the number of administrative irregularities. When replacing the exhaust system components, on average, every other testing results in defect observations. Despite the small number of such tests that are performed every year, it is evident that the owners of such vehicles are insufficiently informed and further efforts should be devoted to this issue. The greatest number of tests refers to the testing of installed towbars. Based on the large number of tests performed on the installed towbars and the experience gained since 2013, the established standard procedures have made the installation of towbars a routine work. The same applies to the types of tests that include the change in the number of seating positions, as well as to the installation of LPG and CNG systems. This is not a coincidence, considering that these types of tests have precise operating instructions and Regulations providing vehicle owners with necessary information. The plan is to reduce the number of defects while maintaining the quality of testing and approval, which is possible through greater public awareness.

This research examines various non-professional interventions on PCs which have been observed during the testing and approval procedure. The purpose of the research is to point out the importance of the quality of modifications to PCs and the justification of the procedure for testing and approving such modifications, with the aim of improving road traffic safety. Based on the illustrated results, it can be concluded that a great number of various non-professional interventions have been observed on PCs and most of these interventions have a direct impact on road traffic safety. This gives importance to and considerable justification for the testing and approval procedure. In order to educate the public and reduce the number of non-professional interventions on vehicles, CVH will continue issuing operating instructions related to different vehicle modifications, in addition to adopting and implementing the latest regulations. This will additionally help ensure greater roadworthiness of the vehicle fleet and improve the safety of all road users.

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Conference poster I

Primary results of OBD tests collected during PTI of vehicles in Croatia

European Commission

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Proceedings of the 23rd Transport and Air Pollution (TAP) conference – Part III

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3.8 Emission control technologies of primary air pollutants of road and non-road transport

This section includes posters presented in the context of the “Emission control technologies of primary air pollutants of road and non-road transport” sessions of the TAP conference. Table 20 provides an overview of these posters, as they are listed in the following sub-sections.

Table 20. Titles and authors of “Emission control technologies of primary air pollutants of road and non-road transport” posters

	Title	**Authors**
3.8.1	Primary results of OBD tests collected during PTI of vehicles in Croatia	M. Rešetar, G. Pejić, P. Ilinčić and Z. Lulić
3.8.2	How to reduce engine exhaust related secondary organic aerosol formation potential?	P. Karjalainen, P. Simonen, H. Timonen, S. Saarikoski, P. Aakko-Saksa, M. Lauren, T. Rönkkö, and J. Keskinen
3.8.3	Simulation of DPF failures for vehicle type-approval of PM On-Board Diagnostics	S. Geivanidis, D. Kontses, D. Katsaounis and Z. Samaras

3.8.1 Primary results of OBD tests collected during PTI of vehicles in Croatia

TAP 2019

15th to 17th May 2019
Thessaloniki, Greece

23rd International Transport and Air Pollution Conference

Primary results of OBD tests collected during PTI of vehicles in Croatia

M. Rešetar [1], G. Pejić [1], P. Ilinčić [2], Z. Lulić [2]

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Introduction

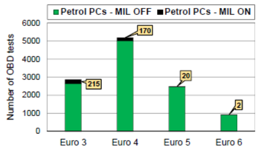
Due to resolution or measurement precision limitations, existing emission testers used in periodic technical inspection (PTI) stations often cannot measure neither the CO volume fraction of Euro 6 petrol engine vehicles, nor the opacity of the Euro 6/VI diesel engine vehicles. The fact is that it is much more difficult to measure smoke opacity in DPF equipped vehicles. (Giechaskiel et al., 2014). Therefore, the application of these devices to the Euro 6/VI vehicles becomes less important. Also, today's electronic units continuously control the correct operation of several exhaust system components as well as the emissions. For vehicles complying with emission classes Euro 6/VI, OBD systems are becoming more effective in assessing emissions. According to the Directive 2014/45/EU, for roadworthiness tests the OBD test can be used as an equivalent to standard tailpipe emission testing for vehicles of emission classes Euro 6/VI (Official Journal of the European Union, 2014).

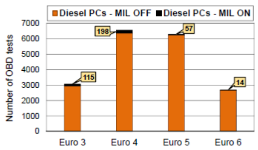
Effective from 1st January 2019 OBD testing methods are implemented in Croatia. An OBD connection is required in vehicles belonging to emission classes Euro 3 and newer wherein the following data are collected: MIL status, Readiness-code status, number of DTCs, coolant temperature and engine speed. In addition to the OBD test, the classic tailpipe test is also performed on vehicles of all Euro classes. Data on the passenger car (PC) fleet that underwent PTI during January 2019 was gathered from the database of Centre for Vehicles of Croatia (CVH), the company whose primary activity is performing PTI on vehicles in Croatia. Tailpipe and OBD test results were processed for both petrol and diesel PCs, as shown below.

OBD test results

The lower the Euro emission class is, the higher is the percentage of PCs with MIL status ON (1st row). These vehicles do not undergo the tailpipe test but nevertheless are declared technically defective.

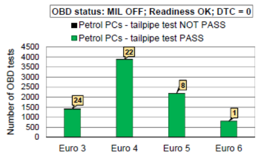
1st

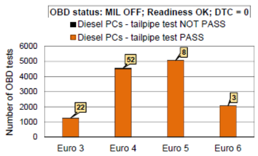




Vehicles with MIL status OFF undergo both OBD and tailpipe tests. The majority of vehicles meets the following requirements: MIL OFF, Readiness OK and DTC counter = 0. There is a certain number of PCs that, despite passing the OBD test, did not pass the tailpipe test. The data also shows the following: The lower the Euro emission class is, the higher is the percentage of PCs which did not pass the tailpipe test (2nd row).

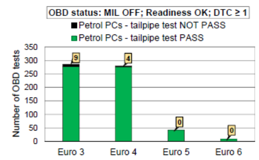
2nd

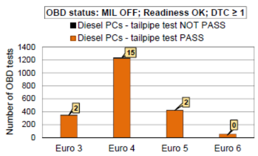




Vehicles with OBD status MIL OFF, Readiness OK and DTC counter ≥ 1 also passed the OBD test. There is also a certain number of PCs that, despite passing the OBD test, did not pass the tailpipe test (3rd row).

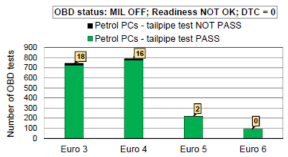
3rd

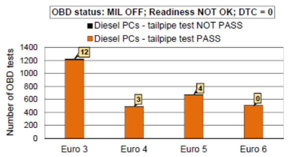




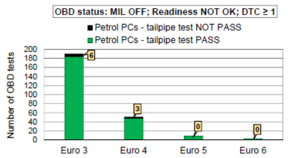
All Euro 6 vehicles with OBD status MIL OFF and Readiness NOT OK passed the tailpipe test (4th and 5th row).

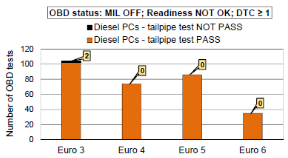
4th





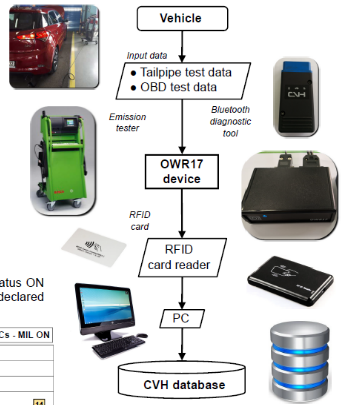
5th





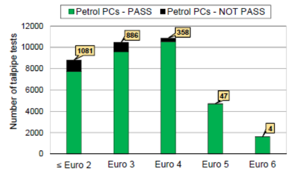
Method

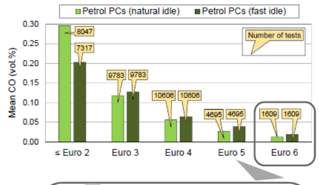
During the PTI, the emission tester and OBD diagnostic tool should be connected to the vehicle. Tailpipe and OBD test results are collected and stored on the OWR17 device. Then all the collected data is transferred to CVH database using RFID card. Tailpipe and OBD test data collecting procedure is shown below.

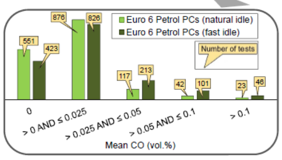


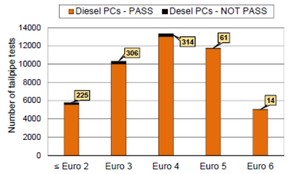
Make	Number of OBD tests				
	Total	MIL OFF (%)	MIL ON (%)	0 DTC (%)	≥ 1 DTC (%)
VOLKSWAGEN	5442	96.88	3.12	94.06	5.94
OPEL	3156	96.29	3.71	92.55	7.45
RENAULT	3104	98.84	1.16	75.10	24.90
PEUGEOT	1918	97.91	2.09	68.98	31.02
ŠKODA	1781	97.25	2.75	92.59	7.41
CITROEN	1717	96.68	3.32	68.55	31.45
FORD	1550	98.00	2.00	93.61	6.39
AUDI	1367	97.59	2.41	93.78	6.22
MERCEDES	1243	96.86	3.14	87.77	12.23
BMW	1242	98.79	1.21	86.55	13.45
HYUNDAI	1120	98.04	1.96	91.43	8.57
TOYOTA	1064	98.12	1.88	95.49	4.51
FIAT	783	96.81	3.19	68.33	31.67
MAZDA	716	96.79	3.21	91.34	8.66
KIA	615	99.51	0.49	96.91	3.09
CHEVROLET	575	95.65	4.35	86.09	13.91
SEAT	516	95.35	4.65	90.12	9.88
NISSAN	455	98.68	1.32	83.96	16.04
DACIA	405	99.01	0.99	83.21	16.79
SUZUKI	390	97.69	2.31	94.62	5.38
HONDA	275	98.91	1.09	88.73	11.27
VOLVO	236	97.46	2.54	81.78	18.22
SMART	151	91.39	8.61	84.11	15.89
ALFA ROMEO	96	92.71	7.29	82.29	17.71
MITSUBISHI	83	93.98	6.02	85.54	14.46
MINI	77	97.40	2.60	85.71	14.29
JEEP	46	97.83	2.17	89.13	10.87
LAND ROVER	37	100.00	0.00	97.30	2.70
LANCIA	24	91.67	8.33	83.33	16.67
DAEWOO	21	85.71	14.29	71.43	28.57
SUBARU	21	100.00	0.00	100.00	0.00
JAGUAR	17	76.47	23.53	76.47	23.53
PORSCHE	16	100.00	0.00	100.00	0.00
CHRYSLER	12	91.67	8.33	58.33	41.67
SAAB	11	100.00	0.00	90.91	9.09
SSANGYONG	10	90.00	10.00	30.00	70.00
All other	32	94.00	6.00	81.25	18.75
Σ	30324				

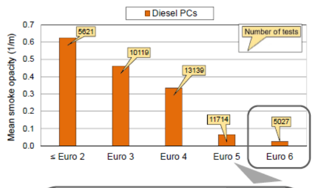
Tailpipe test results

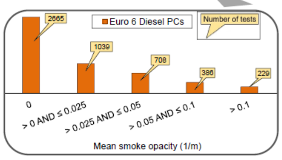












Discussion and conclusions

In order to ensure a higher quality of PTI of vehicles, it is necessary to introduce new testing methods. The OBD test can be a viable method of verifying proper operation of a large number of electronic devices and components in a vehicle, including the devices and components that affect the quality of exhaust emissions. This research includes OBD test results gathered from the PTI of PCs in Croatia, collected during January 2019. Before the implementation of OBD tests, an inspector could check the MIL status only visually on the dashboard. This is why owners whose MIL would turn on would often thinker with the system so as to conceal the MIL status. Using the OBD test, the amount of unprofessional tinkering has been greatly reduced because the necessary information is gathered straight from the ECU, regardless of the MIL status on the dashboard. The ECU is also used to gather the VIN, which makes it easier to ascertain whether it matches with the VIN in the documents and on the chassis itself. The OBD system can also show the vehicle's Readiness-code, according to which it is possible to establish which of the vehicle's systems were checked during the diagnostics procedure. Furthermore, the DTC counter shows the total number of faults in the system. It is planned to integrate other functions, i.e. the OBD2 PID codes used to request data available from the vehicle, into existing OWR17 devices. The implementation of OBD tests not only improves the quality of PTI procedures, but also adds to the overall traffic safety. Finally, these tests can help reduce the negative impact of exhaust emissions on the environment and human health.

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