Adapting driver behaviour for lower emissions

MODALES D6.3: Trial Data Integration and Analysis

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Glossary of terms

Term	Description
Eco-driving	The practice of driving in such a way as to minimise fuel consumption and the emission of carbon dioxide (CO_2)
Low-emission driving	The practice of driving in such a way as to minimise the emission of pollutant emissions (such as CO, NO_X, PM and PN)
MODALES	This EU Horizon 2020 project: "Modify Drivers' behaviour to Adapt for Lower Emissions" (2019-2022, http://modales-project.eu)
Phase 1	Baseline phase of the MODALES trials, before the training, in which drivers drove with the app in data collection mode only
Phase 2	Treatment phase of the MODALES trials, after the driver had viewed the training video and is using the app in full mode (giving on-trip and post-trip feedback)

List of abbreviations and acronyms

Abbreviation/acronym	Meaning
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVN	Calibration Identification Number
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EATS	Engine After Treatment Systems
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EV	Electric Vehicle
HDV	Heavy Duty Vehicle
GPS	Global Position System
ICT	Information & Communication Technology
ITS	Intelligent Transportation Systems
IUPR	In-use Performance Ratios
LDV	Light Duty Vehicle
NAEI	National Atmospheric Emissions Inventory (https://naei.beis.gov.uk/)
NEDC	New European Driving Cycle
NO_X	Nitrogen Oxides
OBD	On-Board Diagnostics
PEMS	Portable Emissions Measuring System
PM	Particle Matter
PM2.5	Particle Matter with a diameter of up to 2.5 micrometre
PM10	Particle Matter with a diameter of up to 10 micrometres

Abbreviation/acronym	Meaning
PN	Particle Number
SCR	Selective Catalytic Reduction
VIN	Vehicle Identification Number
WLTC/ WLTP	Worldwide harmonized Light vehicles Test Cycles/ Procedure
WP	Work Package

Executive Summary

One of the main objectives in the MODALES project was to improve driving behaviour to reduce the resultant vehicle emissions from three sources (i.e. powertrain, brake, and tyre), with a focus on Internal Combustion Engine vehicles. **On-road trials** (i.e. real-world naturalistic driving) were carried out in and around eight cities, namely Barcelona (Spain), Bergamo (Italy), Helsinki (Finland), Istanbul (Turkey), Leeds (UK), Luxembourg, Thessaloniki (Greece), and Nanjing (China), as described in detail in Deliverable 6.2. In the **first phase** of the trials, the drivers drove as normal (i.e. naturalistic driving) and data were collected as a baseline for before and after comparison). Later in the trials, the same drivers were asked to watch an online training video and follow low-emission driving recommendations via the MODALES Smartphone App while driving. Data collection continued in the **second phase**. All the data collected in both phases were then quality checked and integrated for a before and after comparison study. Any behavioural change – as a result of training and education for low-emission driving – was analysed and used to assess if it leads to a reduction in vehicle emissions. The results are presented in this deliverable.

The differential influences of driving behaviour on the three types of vehicle emissions were studied individually and in combination. The key findings are summarised as follows.

The differential influences of driving behaviour on exhaust emissions:

- Low-emission driving training programmes (training video and MODALES App) have shown the potential to contribute to reductions in mean values of NOx emissions in most of the seven European cities evaluated.
- Individual drivers displayed variations in their impact on NOx emissions. Nevertheless, the training programmes proved to be effective in reducing NOx emissions for the majority of participants across all road types.
- The low-emission driving training programmes successfully decreased NOx emissions for both female and male drivers. However, female drivers experienced more significant reductions compared to their male counterparts.
- Most novice and experienced drivers experienced a reduction in NOx emissions after participating in the training.

The differential influences of driving behaviour on brake wear emissions:

- Generally, there were significant reductions in brake wear emissions in various cities, while Istanbul had slight reductions. Barcelona demonstrated the most substantial improvements. Overall, the implementation of low-emission driving training contributes to a more sustainable and healthier environment.
- Motorways exhibited the highest mean values of brake wear $PM_{2.5}$ and PM_{10} emissions per stop, followed by rural and urban roads. This is likely due to the higher average speeds on motorways, leading to more intense braking and increased brake wear emissions per stop.
- Individual drivers exhibited variations in their impact on brake wear emissions. Overall, the training proved effective for most users in reducing brake wear emissions on all road types.
- The low-emission driving training effectively reduced brake wear $PM_{2.5}$ and PM_{10} emissions for both female and male drivers. However, male drivers experienced greater reductions compared to

female drivers. Further research is required to understand the underlying factors and develop targeted interventions to achieve comparable emission reductions for female drivers.

- Experienced drivers had lower initial brake wear emissions compared to novice drivers. After participating in low-emission driving training, both groups showed improvements, but novice drivers experienced a greater reduction in brake wear emissions.
- The results revealed a difference ranging from 4-10 % in the total concentration of 0.3-10.0 µm size particles emitted from the brakes when using the App. The reduction in brake particle emissions is strongly related to the smoother driving style that the driver has adopted following the MODALES recommendations (42 % - 140 % reduced median deceleration with the App activated).

The differential influences of driving behaviour on tyre wear emissions:

- Generally speaking, low-emission driving training programmes can contribute to reductions in tyre wear emissions. Bergamo demonstrated the most substantial improvements in tyre wear emissions, while there was the least improvement in Thessaloniki.
- The mean values of tyre wear emissions were highest on motorway roads, followed by rural and urban roads.
- There were variations among individual drivers in terms of their influence on tyre wear emissions. However, the training demonstrated overall effectiveness in reducing tyre wear emissions for the majority of users across all road types.
- The training and app successfully decreased tyre wear emissions for both female and male drivers. However, male drivers experienced more significant reductions compared to their female counterparts.
- Following the training, novice drivers experienced a more substantial reduction in tyre wear emissions compared to experienced drivers.

The differential influences of journey-based driving behaviour on combined emissions:

Overall, total scores have improved in Phase 2 as a result of the training intervention, while the level of improvement varies from site to site.

The greatest percentage change was shown by the Bergamo site (16%), followed by Barcelona (12%). Paired t-test and Wilcoxon test showed significant difference between Phase 1 vs. Phase 2 at all sites. In contrast, the levels of PM emission, total emissions and fuel consumption decreased in Phase 2. This demonstrates that the training and active recommendations by the MODALES App have helped drivers to improve their driving behaviour and as a result pollutant emissions have decreased in Phase 2.

Total scores have increased in Phase 2 for urban and urban-rural trips, whereas the score has decreased on urban-motorway and urban-motorway-rural trips in Leeds where such data was available.

Total score decreased in Phase 2 for the age groups 30 – 49 and 65+, whereas total score increased in Phase 2 for 20 – 29 and 50 – 64 for Leeds. The 30 – 49 age group also demonstrated a reduction in total score in Phase 2, whereas the score increased for the other two groups for Helsinki.

Regarding gender difference, the low-emission driving training and app successfully decreased NOx emissions for both female and male drivers. However, female drivers experienced more significant reductions compared to their male counterparts.

Also, most novice and experienced drivers experienced a reduction in NOx emissions after participating in the low-emission driving training.

The findings from the PEMS tests:

The aforementioned data analyses were carried out using the emissions data calculated by the mathematical models developed in Work Package 3 of MODALES (Impact of user behaviours). During the MODALES trials, an experimental study was performed for a limited set of trial site drivers in the area of Helsinki, Finland. The purpose of this experiment was to study and demonstrate the true potential of the MODALES App in real world conditions. To monitor the driving behaviour and vehicle emissions, both vehicles were equipped with a portable emission measurement system (PEMS).

The experimentally produced results indicated that by using the MODALES App, evident benefits in terms of both exhaust emissions and thus in fuel economy may be obtained. Yet, the results point out that the magnitude of effect is depends on a how well an individual driver performs to begin with. Well performing drivers have less potential for improvement, while drivers producing more emissions have a greater gap to improve. Another factor found affecting the achievable gain is how well the driver may be able to adopt and apply the recommendation provided by the MODALES App. Because of these factors, relatively great driver-to-driver variation was seen, and most gains were typically obtained for drivers with higher emitting baseline behaviour and vice versa.

Due to the differences in powertrain, fuel type and Engine After-Treatment Systems (EATS), the net gains obtained for the two test vehicles were found different. Because the petrol vehicle was equipped with a Three-way-catalyst (TWC) but lacked a Gasoline particulate filter (GPF), the net effect on NOx emissions was virtually non-existent, simultaneously as a reduction on 45% in PN emissions were achieved. Correspondingly, due to the EATS of the diesel vehicle, including Selective catalytic reduction (SCR) and a Diesel particulate filter (DPF), gains obtained in PN emissions were found insignificant, meanwhile an average NOx reduction of 47% was noted. The impact on fuel CO2 (and fuel economy) was between -8% to +2% for the petrol vehicle, with an average gain of ca. 2%. The corresponding gains for the diesel vehicle were between -2% to +10%, with and average improvement of ca. 7% over the total driver test pool.

The Nanjing case study:

The analysis of the Nanjing trial used real-world driving data and participant responses to pre- and post-training questionnaires to investigate the effectiveness of the MODALES low-emissions driving training video and awareness campaign (tips) by comparing driver behaviour before and after low-emissions driving training. The MODALES App could not be tested in China for legal reasons.

Analysis of the data from the questionnaire shows that training has a positive impact on driver behaviour such as prolonged idling situations, changing appropriate tyres in special weather conditions, maintenance, use of eco-driving modes while driving, and the degree and frequency of acceleration/deceleration.

Analysis of actual driving data showed that the low-emissions training had a positive impact on secondary roads during off-peak hours. Average speeds decreased for all road types and traffic conditions except for peak hour secondary roads. Depending on the type of road and traffic conditions, there were positive effects for each age group. In terms of gender differences, CO_2 emissions decreased during peak hours on secondary roads for both females and males; the training effect was particularly prominent for male drivers compared to females in terms of NOx emissions reduction during peak hours on primary roads, off-peak hours on primary roads and peak hours on secondary roads. In terms of the training effect with respect to driving experience, the greater the driving experience, the less likely the driver is to be influenced by the intervention.

The results of the questionnaire survey indicate that drivers have recognised the importance of reducing the degree and frequency of acceleration/deceleration for low-emissions driving; however, the steady driving habits have not yet been developed and will take time to progressively implement. To further develop low-emission driving habits, monitoring and awareness measures may be needed to reach the goal.

A case study of hybrid/electric vehicles:

In the trials, there were a few electric and hybrid vehicles. Although these types of vehicles were not targeted within the scope of MODALES, it was decided to investigate if the MODALES training programmes and recommendations made any behavioural change to the drivers of these vehicles. It should be noted that these results need to be validated with more of these types of vehicles.

- Low-emission driving training programmes exhibited positive effects on brake wear $PM_{2.5}$ emissions from hybrid/electric vehicles. For hybrid vehicles, the mean values of brake wear $PM_{2.5}$ emissions reduced from 9.10 mg/stop to 4.63 mg/stop, with a substantial reduction of 49.1%. In the case of electric vehicles (EVs), the corresponding mean value of brake wear $PM_{2.5}$ emissions experienced a significant reduction of 36.2%, with mean values decreasing from 8.24 mg/stop to 5.26 mg/stop.
- Also, low-emission driving training programmes had a positive impact on tyre wear emissions from hybrid/electric vehicles. In the case of hybrid vehicles, the mean tyre wear emissions decreased from 93.55 mg/km to 88.36 mg/km, representing a significant reduction of 5.5%. For EVs, there was a decrease of 6.5% in the mean tyre wear emissions, with mean values dropping from 89.35 mg/km to 83.50 mg/km.
- With reference to the performance of hybrid/electric vehicles on total scores, data for hybrid vehicles for both phases was only available for Leeds and Thessaloniki, where the score in Phase 2 increased for Leeds and decreased for Thessaloniki. Data for EVs for both phases was only available for Luxembourg and Thessaloniki, where both sites showed improvement in total score in Phase 2. Analysis of variance test demonstrated significant difference (p-value < 0.05) in total scores between vehicle types at different sites. The top 5 highest percent increase in scores were 29% for the EV in Luxembourg, 25% for unknown vehicles at Barcelona, 18% for diesel vehicles at Bergamo, 16% for petrol vehicle at Barcelona, and 16% for unknown vehicles at Bergamo.

1 Introduction

1.1 Background to MODALES

With the rapid growth of vehicles worldwide, road traffic is a significant source of urban air pollution. As a result, numerous solutions – both technological and legal/organisational – have therefore widely emerged to help reduce pollution, which has led to improved air quality in recent years. Despite this progress, people are still exposed to excessive air pollution, which means it continues to threaten people's lives.

While many efforts have focused on the implementation of policies and technologies, some studies reveal that modifications in driver behaviour can also help reduce traffic-related exhaust emissions resulting from vehicle fuel consumption. The correlation between driver behaviour and fuel consumption has been extensively evaluated through driving simulator (Morello, E., 2016), in real world condition through smartphone applications (González, N., et al., 2010), and on-board tests (De Vlieger, I., 1997). De Vlieger investigated the exhaust emission effects of three driving behaviours: Calm, Normal and Aggressive and found that aggressive driving gained four times higher emissions than normal driving in urban and rural traffic, and that it increased fuel consumption by 30 to 40 percent compared to normal driving. A study of the correlation results in (Ma, et al., 2022) showed that even under the same traffic conditions, the difference in fuel consumption between various driving behaviours can be as high as 29% for light trucks and 15% for cars.

Although many research studies reveal that driver behaviour has strong correlation with fuel consumption, promoting eco-driving behaviour requires transferring knowledge to practical skills procedures that can change driver behaviour to boost the fuel efficiency of their vehicles, thereby reducing fuel-related emissions. Different training programmes, such as simulators with multimedia learning tool interfaces embedded in immersive simulation environments, and real-time assistance systems, emerged with the aim of enhancing eco-driving behaviour using these tools. In (Voort, M. et al., 2001), the effectiveness of a prototype fuel efficiency support tool used to influence driver behaviour to induce desired behaviour was evaluated through a driver simulator experiment where positive results were observed.

Both traffic-related exhaust and non-exhaust sources have been estimated to contribute almost equally to their associated PM_{10} emissions (Grigoratos, T., 2015). Following stringent exhaust emission controls, the relative contribution of non-exhaust emission becomes more significant. Research evidence suggests that particles from brake and tyre wear particles have a higher oxidative potential than other traffic-related sources and are estimated to be a major contributor to non-exhaust emissions together with road wear (Padoan, E., 2018; Harrison, R.M., 2012). However, non-exhaust traffic-related emissions has not been adequately studied in comparison to vehicle exhaust emission. Driving behaviour geared towards eco-driving does not mean optimized for low-emissions driving.

Responding to the challenge of significantly reducing air pollution, MODALES takes a user-centric approach, drawing on the research findings of the project, with a focus on exhaust and non-exhaust traffic related emission from brake and tyre wear in particular, to demonstrate the correlation between driver behaviour and vehicle emissions, explore state-of-art after-treatment diesel retrofit technologies, highlight the importance of effective anti-tampering legislation through in-depth analysis of OBD, periodic inspection and legal issues on tampering, and conduct months of large scale real world trials of low emissions (with both driving and maintenance practices) in eight cities, seven of them in

Europe and one in China, supported by concurrent large-scale awareness campaigns together with low emission driving training to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in a variety of situations to ensure that knowledge of low-emissions driving is made into practical skills that change driver behaviour to lower traffic-related exhaust and non-exhaust emissions. The cites and countries in the real-world user trial are highlighted in Figure 1.1.

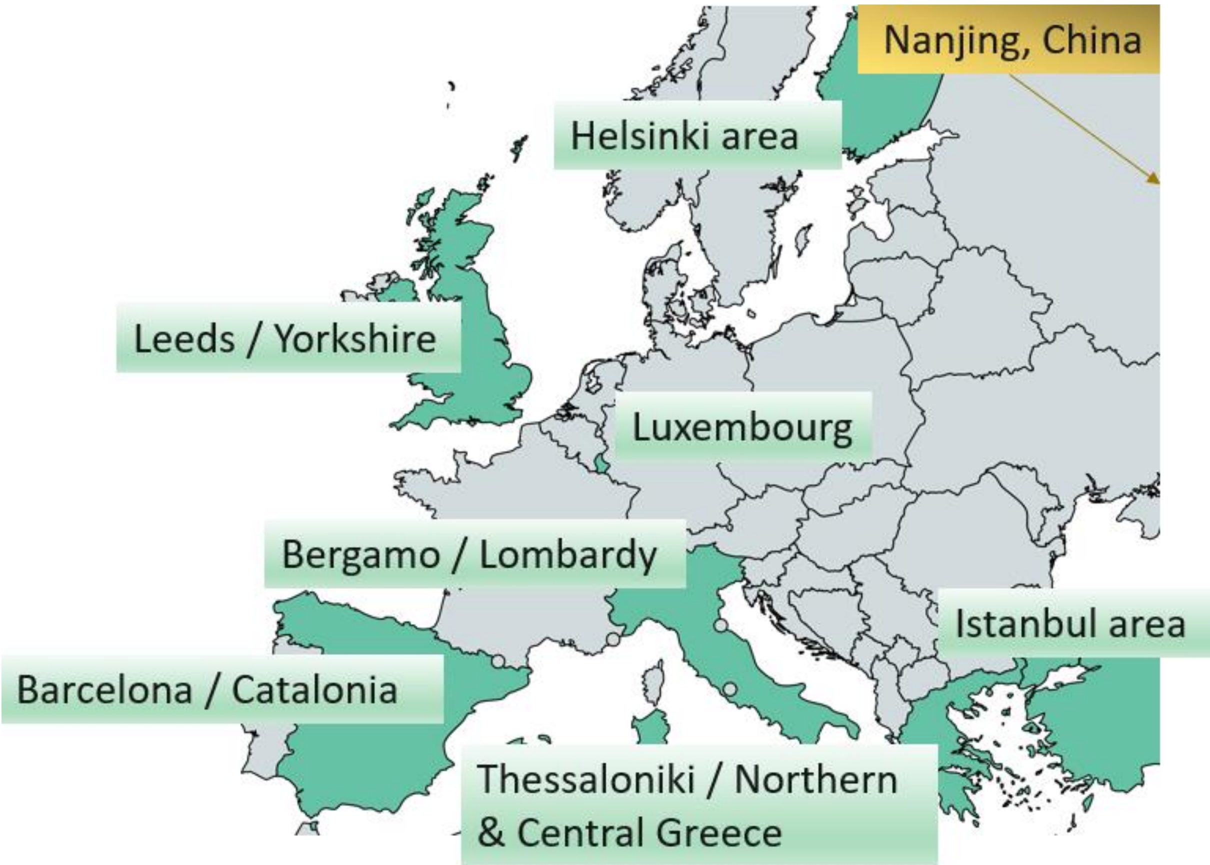


Figure 1.1: Cities and countries in MODALES real world trials

Understanding the influence of these efforts on driver behaviours under different traffic conditions is essential to build countermeasures for future improvements on developing tools to promoting low emission driving. Under this context, this study provides insight into its influence through a sophisticated analysis.

1.2 Purpose of this document

With the development of the MODALES mobile application (Smartphone app described in deliverable d5.3), which allows the collection of driving and vehicle data via smartphone accelerometers, gyroscope, GPS sensors, and/or OBD devices, it has become possible to extract or derive data associated to driving behaviour. By following the recommendations and guidance on low-emissions driving in the current research evidence, receiving training in low-emissions driving and vehicle maintenance and inspection, which includes videos and driver assistance apps, and being encouraged by awareness campaigns, a shift in driver behaviour toward low-emissions driving may result from the use of these initiatives.

In addition to examining whether low-emission driving behaviour can be encouraged by offering drivers the initiatives advocated by MODALES, this study also provides insights into the important influence factors that induce changes in driver behaviour from data collected in a large scale real world trial, before and after the MODALES low-emission initiatives. The results of the study not only demonstrate the need for these initiatives, but also highlight further improvements with more effective solutions.

1.3 Scope and intended audience

The work reported in this document has made different kinds of contributions including:

- Empirical contribution, the results of the particular trials conducted and analysed, which has important implications for the future design of low-emission driving guidelines and policy interventions;
- Methodological contribution, in terms of how the user behaviour analysis was conducted, which others interested in user acceptance of low-emission driving could reference in the future;
- Research contribution, in identifying important gaps in knowledge and/or unexpected outcomes of the trials;
- Policy contribution, in terms of providing evidence that may guide future policy on regulating or promoting adoption of low-emission driving and maintenance.

The main audiences for this document is European Commission services and the consortium members of the MODALES project, specifically partners responsible for analysing the datasets and information collected during the execution of these trials. They can profit from the context in which the data were gathered and potentially measure the impact of deviations of any kind on the responses participants gave.

Furthermore, this document can be understood as a guideline for future research involving the use of data from real-world on-road trials. The lessons learnt during this process are invaluable for behavioural analysis, as well as the future design, planning and execution of low-emission driving guidelines.

Finally, the results of the trial analysis can be of interest to the following professional groups:

- Vehicle manufactures and developers of driving assistance technologies;
- Researchers and academic bodies;
- Policy makers and legislative bodies;
- Public transport planners and operators;
- Developers of Information & Communication Technology (ICT), Human-Machine Interfaces (HMIs), Intelligent Transportation Systems (ITS).

The following figure shows how this deliverable (D6.3) fits into the project and highlights related deliverables.

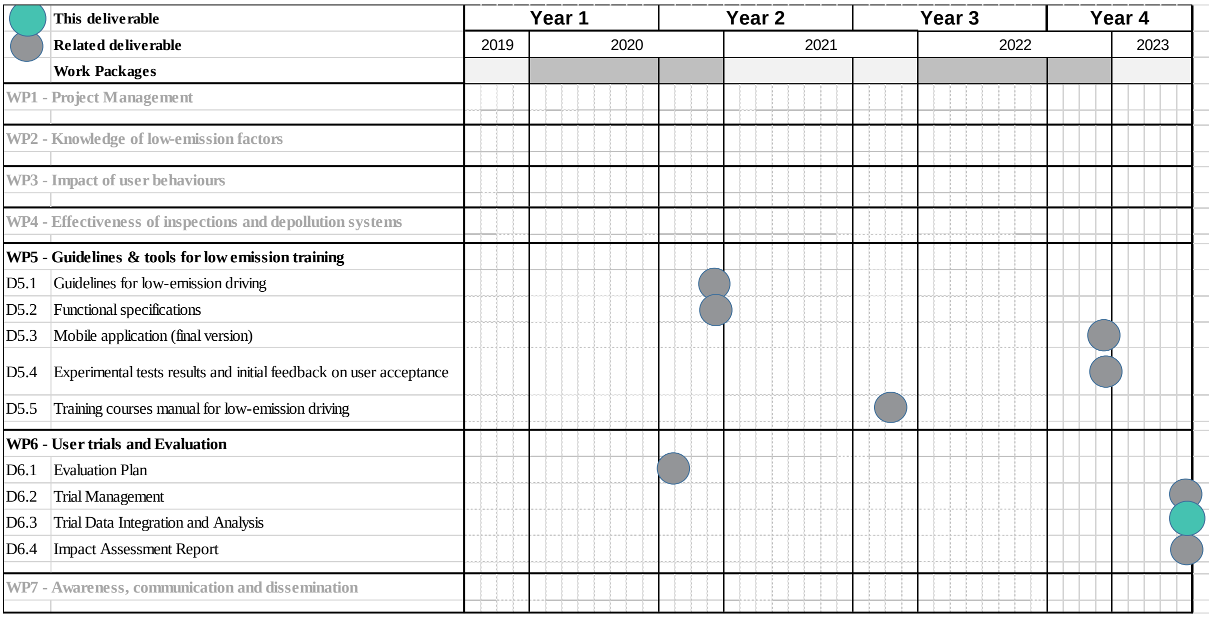


Figure 1.2: D6.3 in the context of related MODALES deliverables

1.4 Document structure

All the activities specified in Task 6.3 have been carried out and their objectives have been fulfilled. There are no deviations regarding the content. In fact, MODALES added a special use case of hybrid/electric vehicles during its trials to assess if its recommendations for low-emission driving of ICE vehicles could also be valid for the newer counterparts.

This deliverable is structured as follows.

Chapter 2 describes the methodology for data collection, integration and analysis. It also presents background information for the data analysis reported in this deliverable, including influencing factors for low-emission driving as studied in WP 2, and the relationship between driving behaviour indicators and Emissions from WP3.

Chapter 3 focuses on the differential influences of driving behaviour on exhaust emissions, investigating factors such as road types, individual drivers, gender, and experience. It also presents a real-world emissions study using the PEMS facility provided by the project partner VTT.

Chapters 4 and 5 study the differential influences of driving behaviour on particle emissions from brakes and tyres, respectively.

Chapter 6 uses journey-based scores to study the differential influences of journey-based driving behaviour on emissions.

Chapter 7 presents the Nanjing case study which has a different experimental setting and driving conditions. It shows how international cooperation can help reduce vehicle emissions worldwide.

Chapter 8 reports a small case study of hybrid/electric vehicles which were available in the MODALES trials. It aims to demonstrate that the MODALES low-emission driving guidelines, online and offline recommendations are also valid to the newer vehicles.

2 Methodology for data collection, integration and analysis

2.1 Influencing factors for low-emission driving

Here we build on the evidence gathered and described in MODALES Deliverable 2.1 on the Variability of driving behaviours and Low emission driving requirements (D2.1) on the main influential factors anticipated in low-emission driving and its emission impacts. The purpose of this section is to explain how these factors affected the design of the analysis, and how combinations of factors may be correlated with available explanatory variables in the data.

2.1.1 Road type

As discussed in MODALES D2.1 (§2.3), from real-world measurements it is known that road type can have a particular influence on the speed profile adopted by drivers, with speeds on regional and interurban roads much more evenly distributed than for other road types. Furthermore, analyses of driver behaviour after low-emission driver training have shown heterogeneous effects across road sections with different features, such as gradient and curvature. These effects have been seen in the choice of gear, the overall speed adopted and the rate of accelerating/decelerating. The ecoDriver project, which had a particular focus on CO_2 and fuel consumption reduction, found that different technologies could perform differently across urban, rural and motorway sections. All of this evidence implies that any analysis of the effectiveness of measures to improve eco-driving needs to distinguish between driver behaviour on different areas of the road network.

In addition, the impacts on emissions of these differing behaviours may vary by road type, firstly through the different speed, acceleration and braking profiles adopted on these different road types, affecting exhaust (D2.1, §3), brake (D2.1, §4.3.1 and §4.3.3), tyre (D2.1, §5.3.1) emissions. The nature of the route followed (e.g. in terms of lane width, geometry, curvature, maximum speed) will partially affect the style of driving and thus acceleration levels, which in turn modify the forces acting on tyres, and so impact on tyre emissions (D2.1, §5.3.1). A further road-type specific effect is the nature of the pavement, with tyre wear strongly dependent on the micro-roughness of the ground materials (D2.1, §5.3.2).

2.1.2 User type

There are many reasons that users may differ in their response to low-emission driving technologies/training. The effects of Gender, Age and Driving Experience are explicitly considered in sub-sections 2.1.4, 2.1.5 and 2.1.6 below. In addition, there are other factors that could influence the impacts by user type. Firstly, studies of variability in driving behaviour across geographical regions have attributed differences to not only different traffic, road and weather conditions, but also to cultural differences in driving behaviour (D2.1, §2.4). Secondly, users may tend to use their vehicles to travel for different kinds of activity at different times of day (D2.1, §2.2). Studies have shown significant differences in both mean speeds and speed variability between periods of the day and between day and night, and thus users with different characteristic activity patterns by time of day may manifest substantially different pre-training speed profiles across their collection of journeys, and thereby potentially significantly different effects of low-emission driver training. Thirdly, studies have shown the existence of different types of users in terms of whether they are 'sensation-seeking', and this has been to be an important explanatory factor in differences in mean speed between users (D2.1, §2.8).

2.1.3 Vehicle type

As noted in D2.1 (§2.1), mean speeds vary across vehicle type, including across different sizes of truck and bus, and also between private cars and taxis. In addition, the kind of driving varies depending on the performance of the vehicle, particularly in terms of acceleration time and distance, and with significant differences observed also between petrol and diesel cars. Vehicle type is also an important factor in the types and levels of exhaust emissions produced (D2.1, §3.1.1), with levels of carbon dioxide, carbon monoxide, nitrogen oxide, hydrocarbons, aldehyde, and particulate matter all depending on the type of fuel used (fuel aromatic content, biodiesel additions, diesel/petrol) and the operating conditions (engine load, speed, ambient temperature). These exhaust emissions also vary according to vehicle age, and for petrol engines according to the fuel injection technology used (D2.1, §3.1.2). In addition, the level and types of brake emissions have been shown to be highly dependent on the type of friction material used in the brake itself (D2.1, §4.3.1), the mass of the vehicle (D2.1, §4.3.2), and on whether the vehicle uses regenerative braking as in hybrid or electric vehicles (D2.1, §4.3.4). Finally, tyre wear emissions are known to depend significantly on the vehicle mass, suspension, and steering geometry (D2.1, §5.3.4) and the rigidity, width, diameter, tread and materials of the tyres themselves (D2.1, §5.3.5). Thus, taking all this evidence together, it is clear vehicle type is an important variable to monitor, both in terms of effectiveness of the low-emission driving training, and in terms of its ultimate impacts on the levels and nature of exhaust, brake and tyre emissions.

2.1.4 Gender

Previous studies of the effectiveness of low-emission driving technologies have observed significant differences between women and men in terms of their impacts, such as differences in the impacts on average speed, speed profile over a journey and idling times (D2.1, §2.6). These impacts are against a backdrop of heterogeneous driving styles across genders *before* such training/technology assistance. This supports the importance of studying gender as a key variable in understanding the effect of the MODALES technology.

2.1.5 Age

Age is known to be a significant variable in describing heterogeneity in driver behaviour, over and above the issue of simply driving experience (covered in section 2.1.6, below). Age has been observed as an important explanatory factor in differences among drivers in their average speed, the number of steering applications and the amount and length of braking (D2.1, §2.7). These differences are particularly apparent when comparing young (25-35 years' old) with old (65+) drivers. Thus, low emission driver training has a different 'base' position to work on with respect to age, and so might be expected to have differing levels of effectiveness across the age range.

2.1.6 Driving experience

Previous studies have confirmed an important influence of the level of driving experience on driver behaviour, e.g. in terms of mean speed and in terms of speed variation (D2.1, §2.8). Such an effect may be confounded with whether a driver is professional or non-professional, since professional drivers typically are more experienced, yet studies have shown potentially conflicting evidence with the effect of experience alone. Nevertheless, all such studies point to the fact that driving experience is an important factor in driving behaviour, and thus it may also be an important factor in the effectiveness of low emission driving training/technologies.

2.1.7 Geographical Region

As noted in §2.1.2 above, previous studies have observed variability in driver behaviour by geographical region. Cultural differences in driving behaviour (D2.1, §2.4) and general differences in traffic conditions (e.g. levels of congestion) are likely to explain at least part of this variation. In addition, regions will vary in terms of the materials used for road surface construction (affecting tyre emissions, see §2.1.1), and the kinds of geometry and gradients prevailing in that region (affecting exhaust, brake and tyre emissions, see §2.1.1), as well as the quality of road maintenance. As noted in §2.1.3, vehicle type also has a major influence on the way vehicles are driven and the emissions they produce, and so variations in the vehicle fleets typically operational will also lead to differences by geographical region.

In addition, regions differ in terms of their typical environmental conditions, such as weather and temperature. Average speeds and the frequency of deceleration and acceleration events have been seen to vary according to weather conditions (D2.1, §2.5), thus the typical prevalence of cloudy, clear, rainy or foggy conditions in a region will have an impact on inter-region variability. Particularly low and particularly high ambient temperatures have both been shown to influence levels of exhaust emissions (D2.1, §3.1.1 and §3.1.2), and so variations in the range of temperatures in different regions will lead to further inter-regional disparities. Operating temperature, partially affected by ambient temperature, also affects levels of brake-wear emissions (D2.1, §4.3.1 and §4.3.4), while temperature and humidity both influence tyre emissions (D2.1, §5.3.3).

2.2 Driving behaviour indicators and Emissions

Driving behaviour indicators can have a significant impact on vehicle exhaust and non-exhaust emissions. In D3.2, driving behaviour indicators have been reported in detail. This deliverable calculated the effects of driving behaviour on vehicle exhaust and non-exhaust emissions before and after low-emission driving training programmes based on the modelled results and driving behaviour indicators.

2.2.1 Exhaust emissions

2.2.1.1 Modelled exhaust emissions

Average NOx emission factors over various speed ranges were obtained based on the simulation results of the GT-SUITE model, and the results are illustrated in Figure 2.1. Given the fact that an acceleration rate greater than 0.9 m/s^2 is the most important indicator of driving behaviour affecting NOx emissions, the NOx emissions were calculated in this deliverable considering not only the average NOx emission factors over various speed ranges in Figure 2.1 but also the percentage of acceleration rate greater than 0.9 m/s^2. During every journey, the percentages of various speed ranges and acceleration rate greater than 0.9 m/s^2 were calculated. Afterwards, the NOx emission factor was calculated in this journey using the equations in Table 2.1.

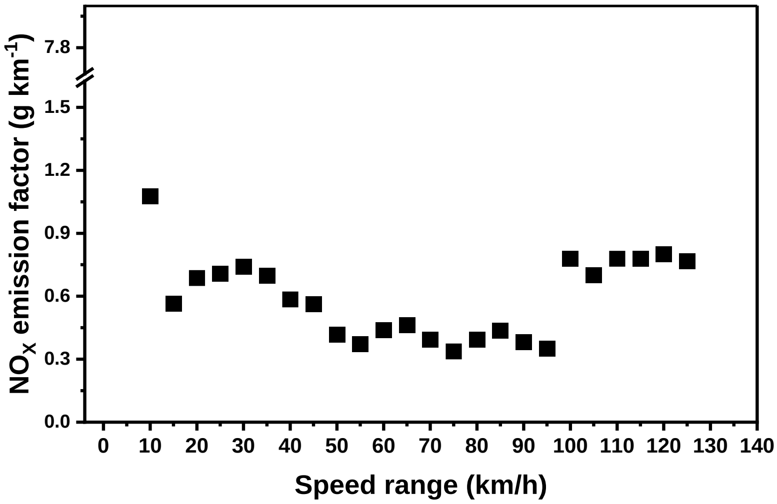


Figure 2.1: Average engine-out NOx emission factors over various speed ranges

Table 2.1: Calculation of NOx emission factor during a journey

Speed range（km/h）	*a*＞0.9 m/s² (%)	NOx (g/km)
5-10	x%	1.08 + 23.59 * (x - 0.03)
10-15	x%	0.57 + 12.37 * (x - 0.03)
15-20	x%	0.69 + 15.05* (x - 0.03)
….		
120-125	x%	0.77 + 16.80* (x - 0.03)
＞125	x%	0.79 + 17.24* (x - 0.03)

2.2.1.2 Real-world exhaust emission measurements from PEMS

To validate the modelled emission values, MODALES carried out a small measurement test of two vehicles equipped with the PEMS in Espoo (Helsinki metropolitan area, Finland) where project partner VTT is located. The relevant data collection, processing and analysis of the PEMS test are presented in Section 3.6 for integrity.

2.2.2 Brake wear emissions

The brake wear $PM_{2.5}$ and PM_{10} emissions were fitted with energy dissipated and average initial speed when braking based on the real measured results from project partner Brembo during the WLTP-Brake cycle, as shown in Figure 2.2. It can be observed that the brake wear $PM_{2.5}$ and PM_{10} emissions exhibited a higher degree of conformity with actual measured results, almost falling within a 95% or greater confidence interval. It means that filled equations with energy dissipated and average initial speed when braking are able to reasonably predict brake wear particle emissions. Similarly, (Men et al., 2022) used 1.8th power of initial speed in their calculation to predict brake wear emissions. Here, results showed a better fitting. Therefore, the brake wear emissions can be well predicted from changes in energy dissipated and vehicle speed.

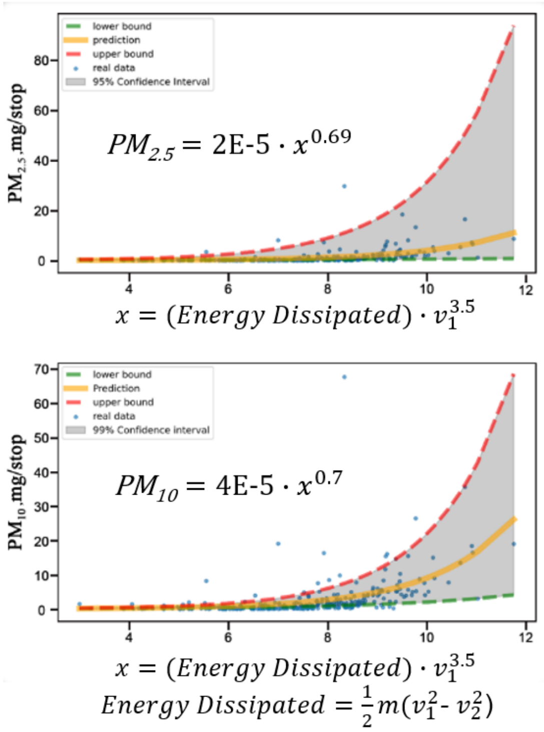


Figure 2.2: Predicted $PM_{2.5}$ and PM_{10} emissions according to measured data during the WLTP-Brake cycle

2.2.3 Tyre wear emissions

Average tyre wear rates over various speed ranges were obtained based on the simulation results of the ABEQUES commercial code, and the results are illustrated in Figure 2.2. Given the fact that vehicle speed and acceleration are the most important indicator of driving behaviour affecting tyre wear emissions, the tyre wear emissions were computed in this deliverable considering these two factors. During every journey, the percentages of various speed ranges and average acceleration were calculated. Afterwards, the emission factor of tyre wear was calculated in this journey using the equations in Table 2.3.

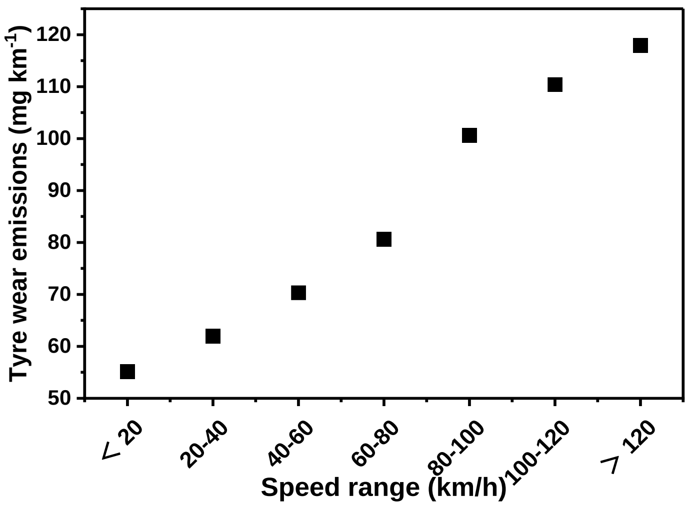


Figure 2.3: Emission factors of tyre wear over various speed ranges

Table 2.3: Calculation of emission factor from tyre wear during a journey

Speed range (km/h)	Average *a* (m/s²)	Tyre wear mass (mg/km)
＜20	x	55.11+ 272.8(x-0.2)
20-40	x	61.93 + 306.6(x-0.2)
40-60	x	70.33 + 348.1(x-0.2)
….		
100-120	x	117.9 + 583.7(x-0.2)
＞120	x	124.9 + 618.3(x-0.2)

2.2.4 Combined emissions

As vehicle emissions from three sources (i.e. powertrain, brake, and tyre) can occur at the same time while driving, it is necessary to consider an overall indicator which gives the driver realistic feedback about his/her driving profile as to optimise the total emissions. The aggregate emission (as described in Section 5.1.2 of Deliverable D5.3) combines the three emission sources and multiple air pollutants for the whole journey. Figures 2.4 and 2.5 show the relationships of journey scores with aggregate emissions and fuel consumption, respectively. As can be seen, the higher the journey score and the lower the emissions and fuel consumption. More specifically, the graphs show that an improvement of the score by 20% brings a reduction of 18.6% in fuel consumption and 23.8% in aggregate emissions.

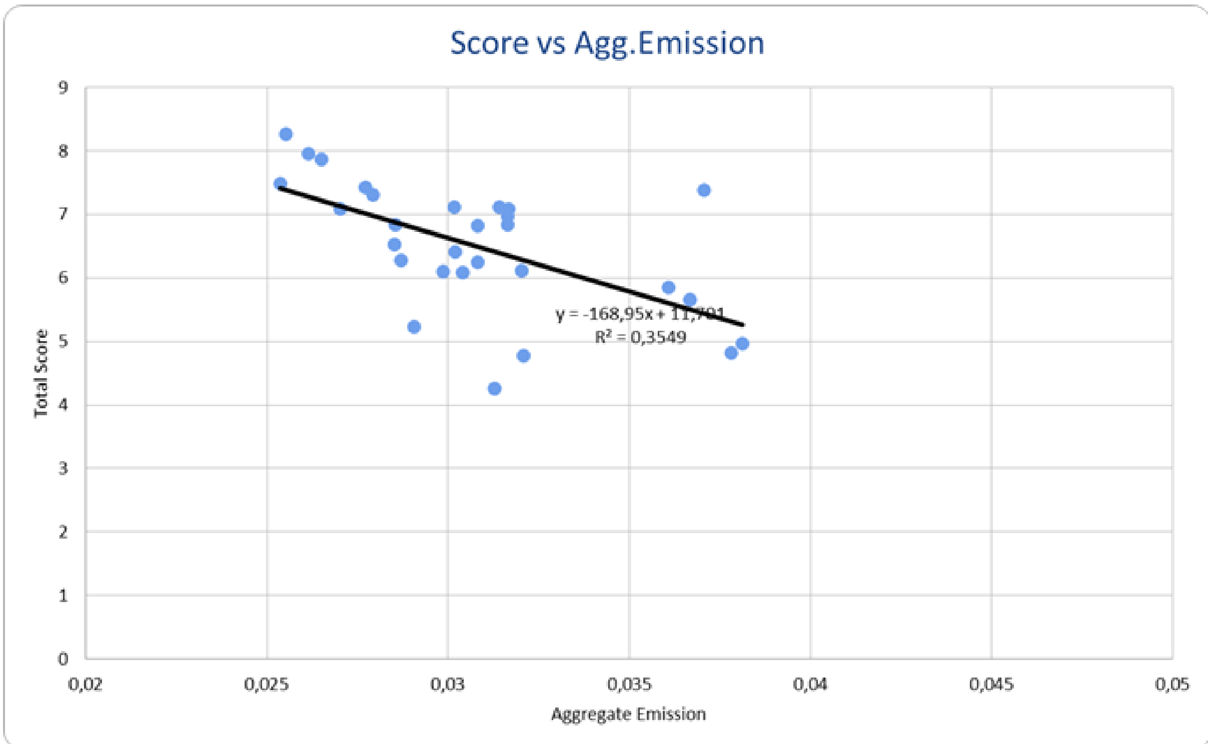


Figure 2.4: Relationship between journey score and aggregate emission

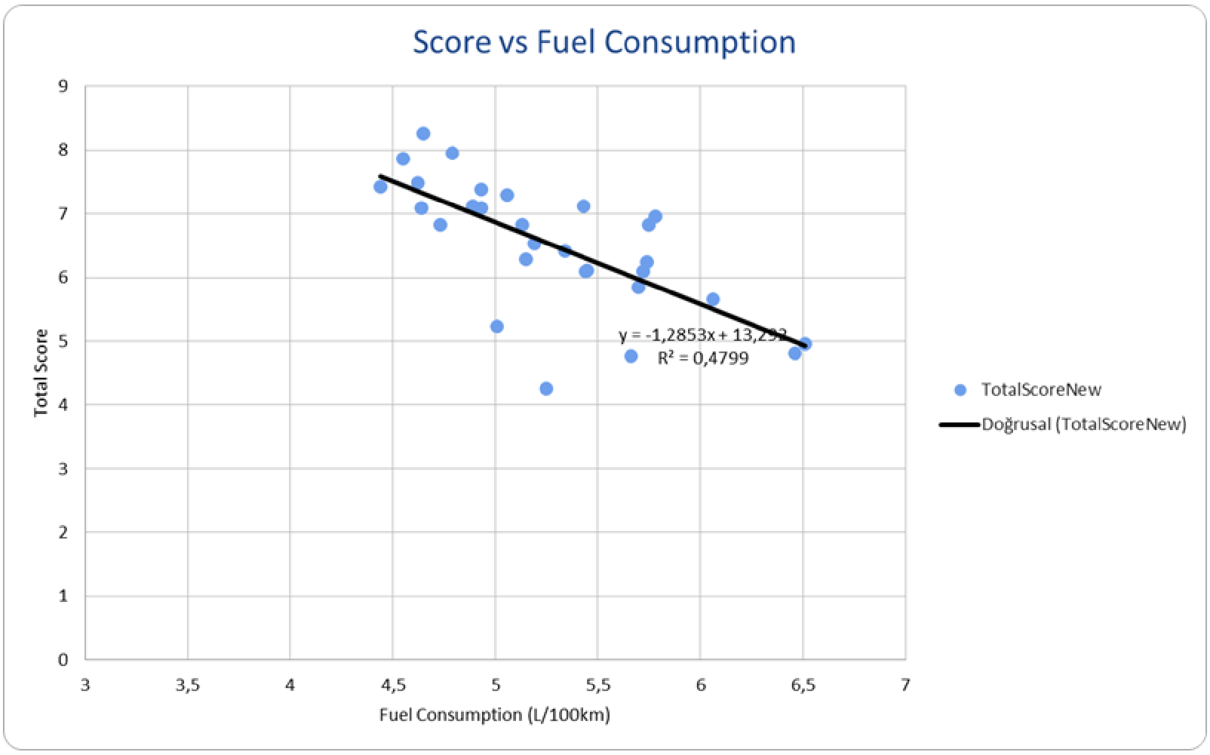


Figure 2.5: Relationship between journey score and fuel consumption

2.3 Main criteria for data selection/pre-processing

The user trial aimed to collect driver's profile data in the real driving conditions. The main way to monitor drivers' behaviour via the OBD Dongle, mobile app (MODALES App) and the web platform developed in WP5, which allowed the collection, analysis and recommendation of actions to be performed by a particular driver profile. The trials were carried out in the following sites: Leeds (UK), Helsinki (Finland), Barcelona (Spain), Istanbul (Turkey), Thessaloniki (Greece), Bergamo (Italy), and Luxembourg and Nanjing (China). The number of drivers varied from site to site (see MODALES D6.2 Trial Management[1]). In the first phase (Phase 1) the drivers used the OBD dongles and the MODALES App with no active recommendation for over 1 to 5 months. The second phase (Phase 2) lasted 1 to 2 months, which started with watching a training video and MODALES App with active recommendations. The data collected during a trip was stored on the device and frequently sent by the user and/or the mobile device itself to a central server for filtering and time series interruption checks.

Driver's behaviour is defined in terms of various journey scores, including total score, acceleration score, speed score and idle score, which are analysed to assess how the score has changed from Phase 1 to Phase 2 at different sites. The journey score has also been analysed for different types of roads, users, and vehicle types.

To measure the central tendency and spread or variability of the collected data, we used different descriptive statistics including mean, median, standard deviation and interquartile range. These

[1] https://modales-project.eu/deliverables/

statistics were compared using visual presentations (e.g. box plots and histograms) and statistical tests. In addition to visual comparison of the results in Phase 1 vs. Phase 2, different statistical tests were used. For this purpose, we used paired t-test, Wilcoxon test, analysis of variance (ANOVA) and Kruskal-Wallis test by rank, which is a non-parametric alternative to one-way ANOVA test. Analysis is mostly performed in R programming language, using its packages tidyverse, ggplot2, dplyr, lubridate, openair and lattice. Part of the analysis was also performed in MS Excel and Python.

The number of trips were higher for Phase 1 than for Phase 2, therefore, in histograms we used relative frequency, which was calculated dividing the frequency of each bar by the size of the sample. Equation 2.1 shows how relative frequency was calculated.

$$\text{Relative frequency} = (\text{frequency of each bar} / \text{size of the sample})$$

$$rf = (f / n) \qquad (2.1)$$

Where 'f' is frequency, 'rf' is relative frequency, 'n' in the number of observations in the sample for which the 'rf' is calculated.

The data was checked for both extreme values and outliers. It was realised that most of the maximum total score was linked with zero speed, therefore, negative speed, zero speed and maximum total score of 10 was not considered in the data analysis.

The following equations were used to convert total score into the total emissions, PM emissions, and fuel consumption, respectively.

$$Y = -0.0021x+0.0444 \qquad (2.2)$$

Y is the aggregated emissions and x is the total score.

$$Y = -0.3734x+7.7068 \qquad (2.3)$$

Y is the fuel consumption and x is the total score.

$$Y = -0.182x+2.8668 \qquad (2.4)$$

Where: Y is the PM emissions and x is the total score.

2.3.1 Speed data

Both an OBD Dongle and GPS were employed to track the speed of vehicles on real-world roads. The OBD data was collected every 5 seconds, while the GPS data was captured every 1 second. Afterwards, the speed information for the different road conditions was matched based on the obtained information regarding road types. To enhance the accuracy of calculating vehicle acceleration, the speed of the vehicle was determined using GPS data. This was done because the time interval for measuring vehicle speed with the OBD dongle is longer than that of the GPS.

2.3.2 Acceleration data

In this present work, the acceleration data were derived based on vehicles speed from GPS. Specifically, the acceleration was calculated by finding the difference in vehicle speed between two consecutive data points and dividing it by the corresponding time interval i.e., every 1s. Figure 2.6 presents acceleration rates from OBD and GPS data. It can be seen that change trend remained nearly identical.

This means that the acceleration results obtained using GPS data are a good reflection of the real acceleration and deceleration information on the road.

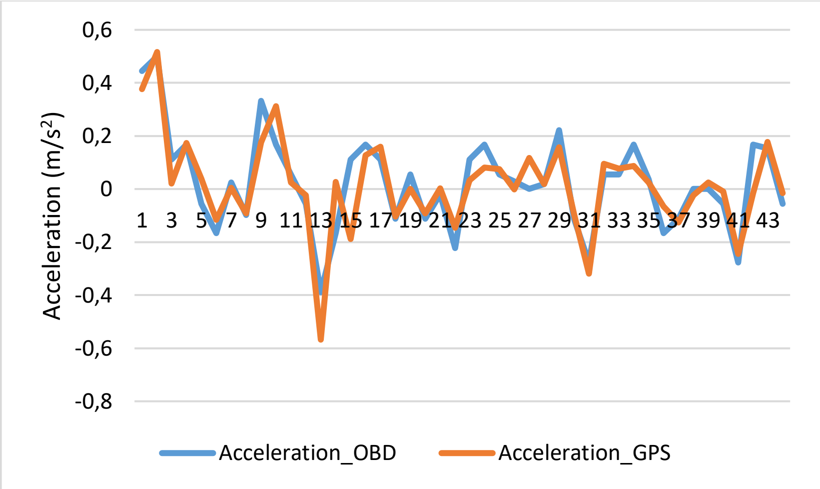


Figure 2.6: Acceleration from OBD and GPS sources

2.3.3 Selection of like-for-like journeys

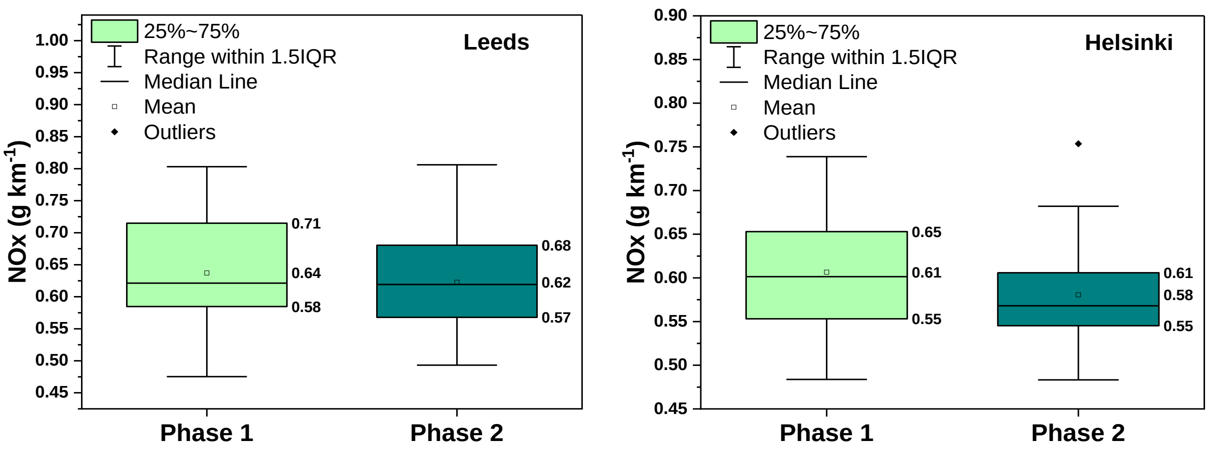
In this project data was collected at the seven sites in Europe listed in chapter 1.1. Every site recruited a different number of drivers. Several drivers at each site quitted the trial before the end, while others were still part of the trial, but they didn't collect any data in Phase 2. The drivers who didn't collect data in Phase 2, their Phase 1 data was of little use in the analysis as most of this analysis is based on Phase 1 vs. Phase 2 in different ways. When like-for-like journeys were compared, the amount of data decreased even further. In the journey score analysis, when data in Phase 1 was compared with Phase 2 considering similar road types, e.g., urban road types Phase 1 vs. urban road type Phase 2, several users didn't have data for the same route types in both phases. Although in the data cleaning process a considerable amount of data was lost, this was important to extract the true impact of the training intervention.

3 Differential influences of driving behaviour on exhaust emissions

Air pollution is a pressing environmental concern that has detrimental effects on human health and the environment. One significant contributor to air pollution is the emission of nitrogen oxides (NOx) from various sources, especially from transportation. The traffic-related NOx is mainly influenced by driving behaviour (Huang et al., 2021; Nguyen et al., 2023). Driving behaviour encompasses a wide range of factors, including speed, acceleration, deceleration, idling, and overall driving style. Different driving behaviours would have varying effects on NOx emissions due to their influence on engine operating conditions and exhaust gas temperature. It is crucial to understand the differential influences of driving behaviour on NOx emissions in order to develop effective strategies to mitigate air pollution from road vehicles. This chapter focuses on the analysis of NOx emissions from the engine out, specifically examining the influence of individual drivers, driver gender, and driver experience across different road types in seven European cities.

3.1 Overall results for exhaust emissions

The NOx emissions for individual drivers participating in the trials in seven European cities were evaluated, and the results are shown in Figure 3.1. It can be seen that the mean NOx emissions were reduced after the low-emissions driving training programmes in most cities studied. However, Thessaloniki and Istanbul did not get the expected results for NOx emissions from Phase 1 to Phase 2, which is likely to the fact that fewer participants were involved in this trial. Specifically, the mean value of NOx emissions was found to have decreased by 3.1% in Leeds following the training and use of the app. In Helsinki and Barcelona, there were reductions of 4.9% and 3.2% in NOx emissions from Phase 1 to Phase 2, respectively. During the transition from Phase 1 to Phase 2, Luxembourg and Bergamo experienced decreases of 1.6% and 3.1%, respectively. However, Thessaloniki and Istanbul showed an enhancement with regard to NOx emissions, amounting to increases of 1.5% and 6.7%, respectively. The aforementioned findings substantiate the beneficial influence of low-emission driving training programmes in diminishing NOx emissions in most cities involved.



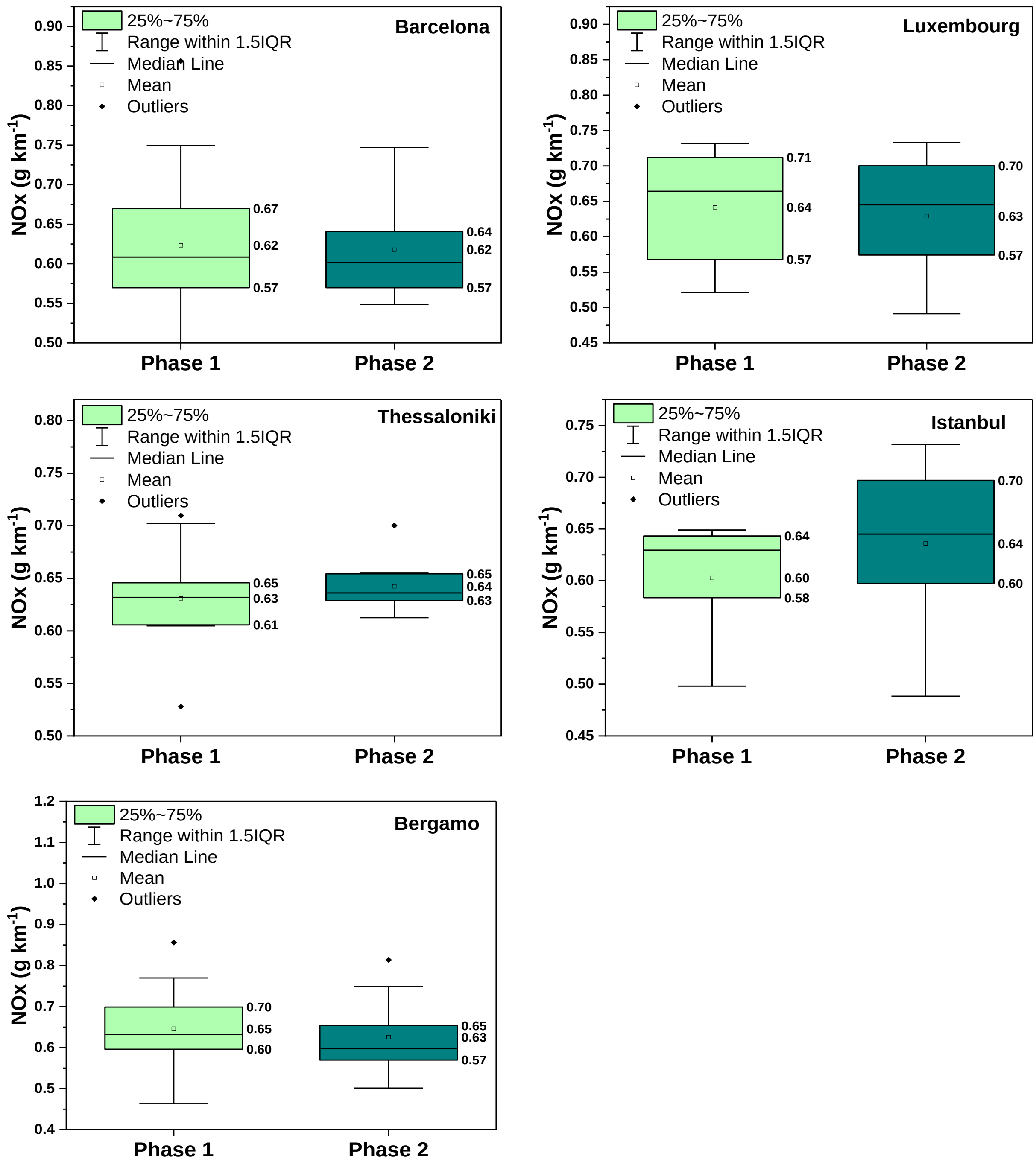


Figure 3.1: NOx emissions before and after low-emission driving training at various sites

3.2 Effect of road types

Different road types, such as urban roads, rural roads, and motorways, have distinct characteristics that can influence vehicle emissions, including NOx. Urban roads, for instance, often have frequent stops and starts, leading to increased idling and acceleration events, which can elevate NOx emissions. On the other hand, motorways typically allow for higher speed limits, which may lead to higher NOx emissions. In this section, NOx emissions on various road types will be reported in seven cities.

Figure 3.2 illustrates NOx emissions before and after low-emission driving training and the app on different types of roads in Leeds. Compared to rural roads, the NOx emissions on urban and motorway roads were relatively higher, with mean values of 0.652 g/km and 0.664 g/km, respectively, before the training video. In addition, the training and app had a positive effect on NOx emissions. Specifically, the mean values of NOx emissions reduced from 0.652 g/km to 0.643 g/km on urban roads. On rural roads, there was a reduction from 0.604 g/km to 0.585 g/km. From Phase 1 to Phase 2, a decline in the mean levels of NOx emissions on motorway roads was observed, with values decreasing from 0.664 g/km to 0.649 mg/km.

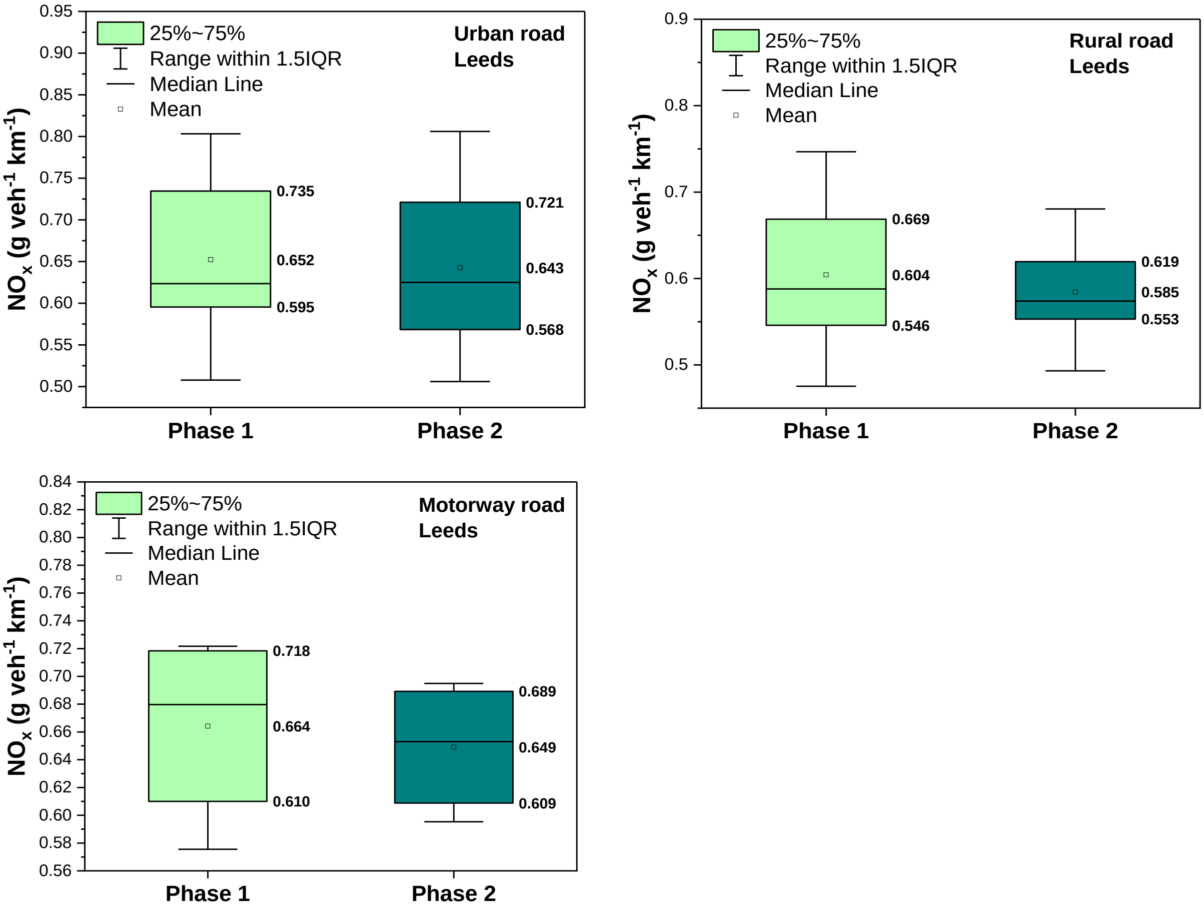


Figure 3.2: Before and after NOx emissions by different types of roads in Leeds

The results in Helsinki are shown in Figure 3.3. Similarly, in comparison to urban and motorway roads, the levels of NOx emissions were relatively lower on rural roads, which mean values of 0.571 g/km and 0.541 g/km, respectively, before and after participating in the training. Furthermore, the training and app had a positive impact on reducing NOx emissions. Specifically, on urban roads, the mean values of NOx emissions decreased from 0.598 g/km to 0.577 g/km, while on rural roads, there was a reduction from 0.571 g/km to 0.541 g/km. Moreover, a decline in the average levels of NOx emissions on motorway roads was observed during the transition from Phase 1 to Phase 2, with values decreasing from 0.640 g/km to 0.611 mg/km.

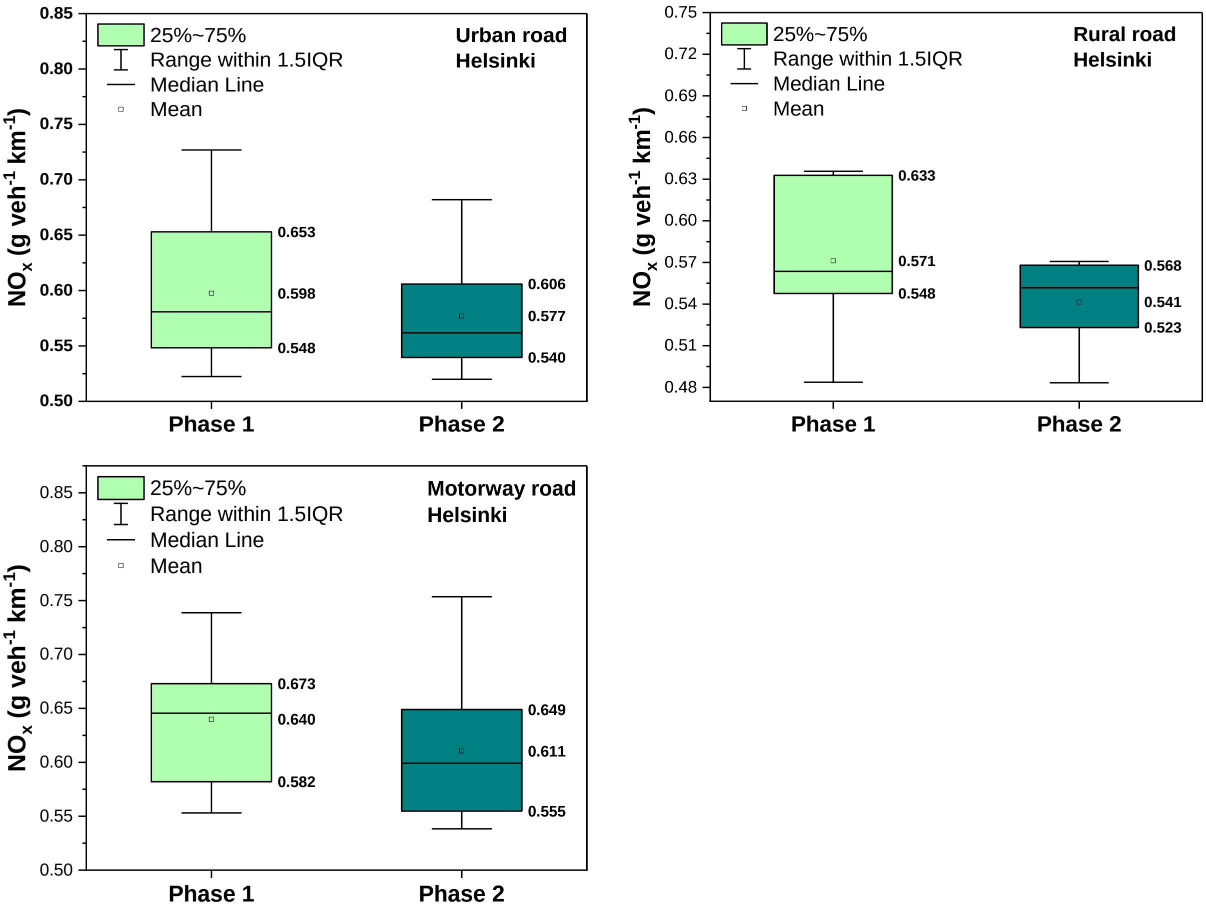


Figure 3.3: Before and after NOx emissions by road types in Helsinki

Figure 3.4 illustrates the NOx emissions before and after the training videos on different types of roads in Barcelona. It can be observed that the highest levels of emitted NOx emissions were observed on motorways, followed by urban and rural roads. This observation is likely attributed to the fact the higher speed limits on motorways would cause higher combustion temperatures in the engine cylinder, which in turn results in the generation of more NOx. Following the low-emission driving training, NOx emissions were observed to decrease across all road types. More precisely, there was a marginal reduction in the mean value of NOx emissions from 0.602 g/km to 0.598 g/km from Phase 1 to Phase 2 on rural roads. On urban and motorway roads, the corresponding mean values reduced from 0.633 g/km to 0.602 g/km as well as from 0.644 g/km to 0.630 g/km from Phase 1 to Phase 2, respectively.

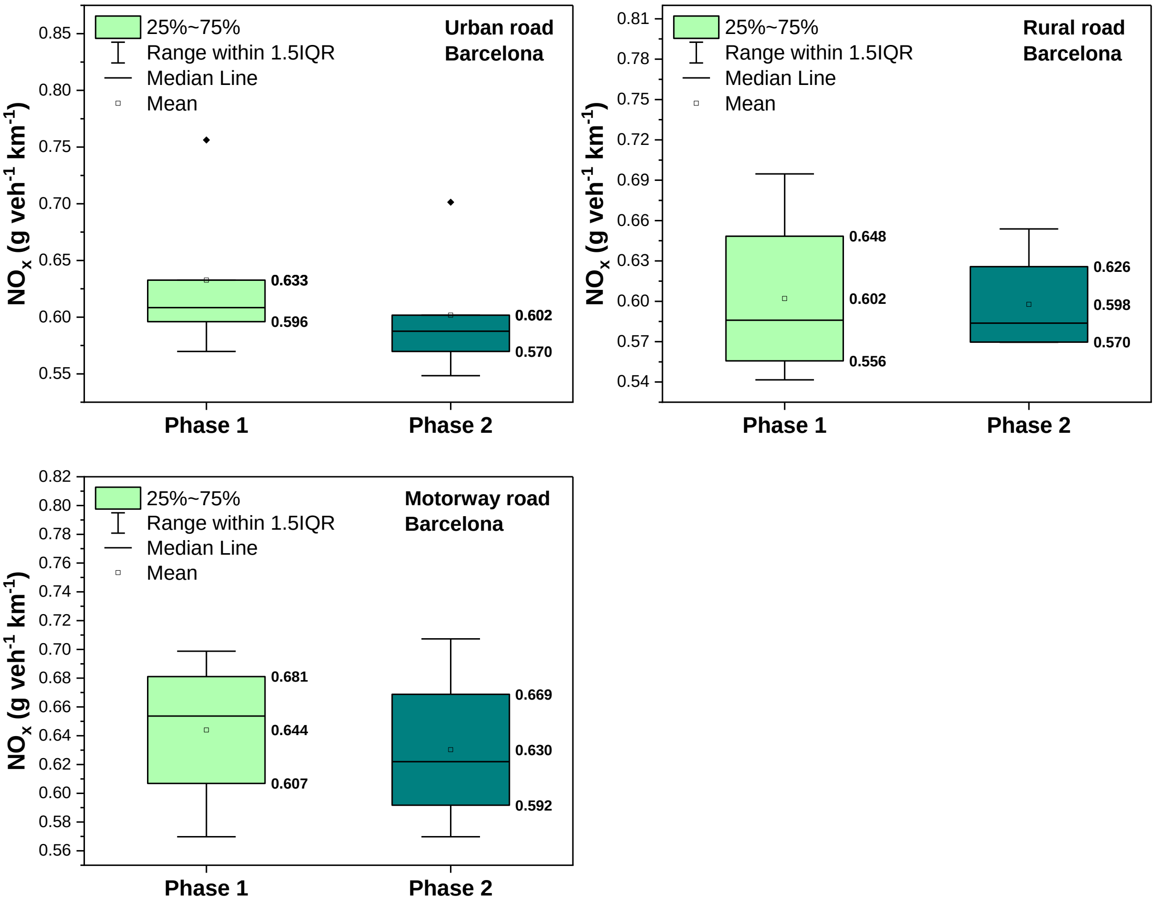
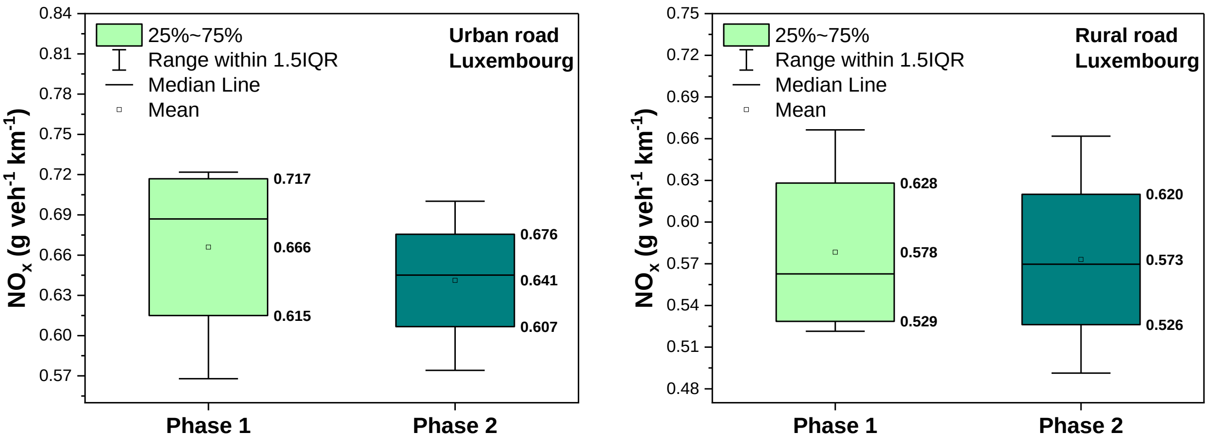


Figure 3.4: Before and after NOx emissions by road types in Barcelona

In Luxembourg, low-emission driving training had a limited effect on NOx emissions on rural and motorway roads, as evidenced by Figure 3.5. Specifically, there were reductions of 0.87% and 0.27% in mean values of NOx emissions, respectively, on rural and motorway roads from Phase 1 to Phase 2. Compared to rural roads and motorways, a higher decrease in mean values of NOx emissions was observed from Phase 1 to Phase 2 on urban roads, with a reduction of 3.8%. A similar finding was reported by (Huang et al., 2021), who found a reduction in NOx emissions via eco-driving training classes and/or on-board driver assistance devices.



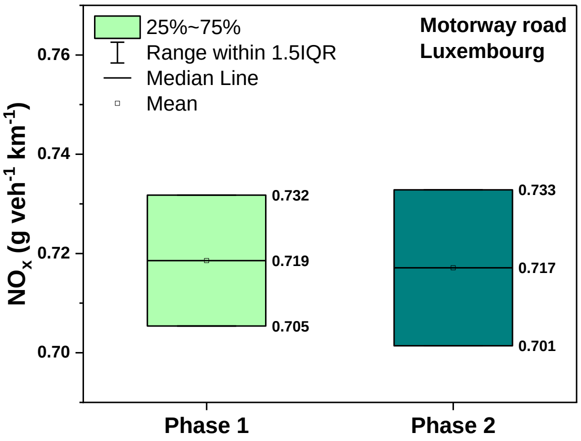


Figure 3.5: Before and after NOx emissions by road types in Luxembourg

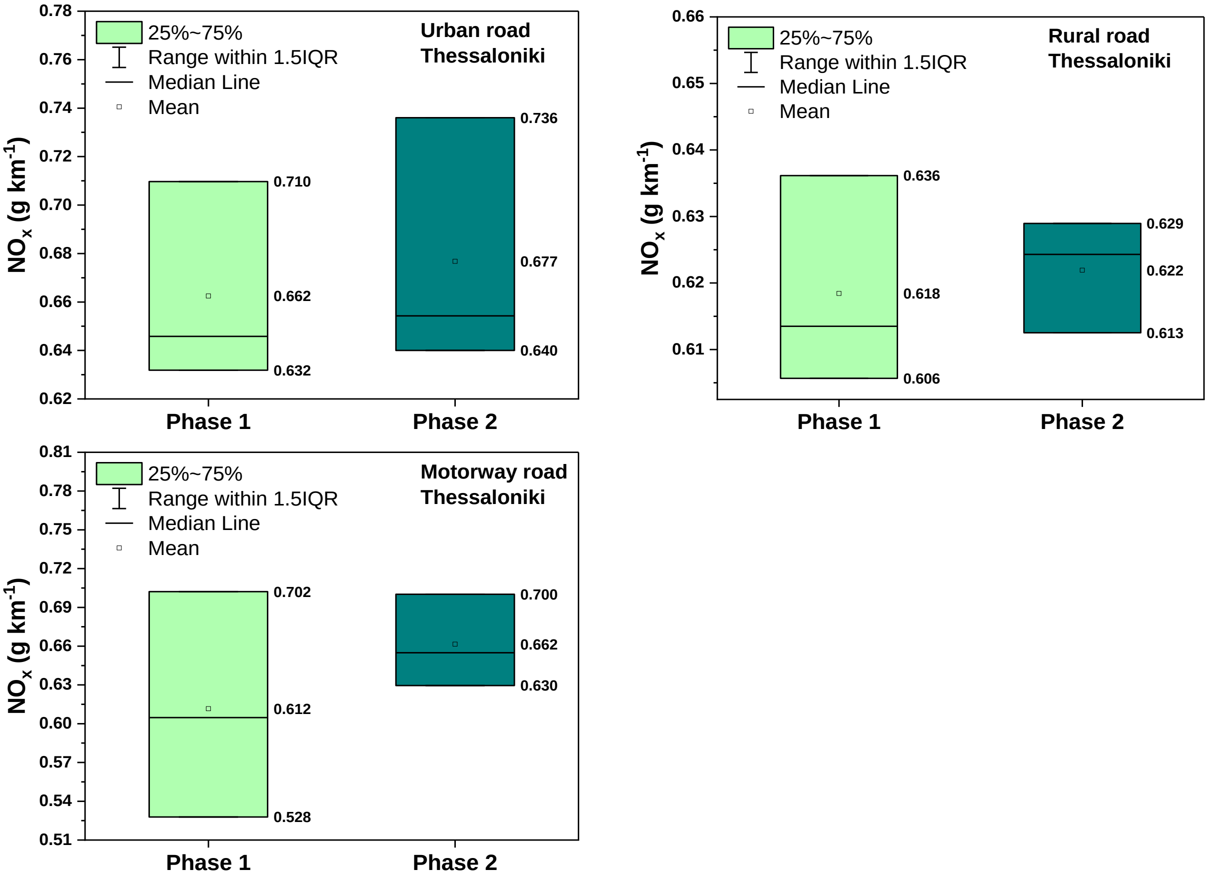


Figure 3.6: Before and after NOx emissions by road types in Thessaloniki

Unlike the results above, low-emission driving training did not promote a reduction in NOx emissions across all road types in Thessaloniki, as shown in Figure 3.6. On urban roads, the mean values of NOx emissions increased from 0.662 g/km to 0.677 g/km from Phase 1 to Phase 2. Similarly, the corresponding mean values rose from 0.618 g/km to 0.622 g/km on rural roads. On motorways, there was an increase from 0.612 g/km to 0.662 g/km after the training.

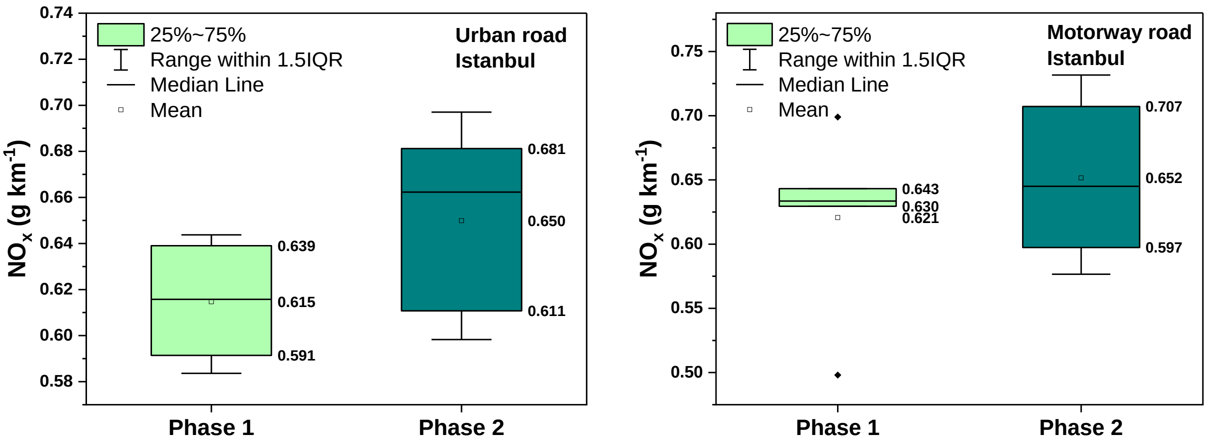


Figure 3.7: Before and after NOx emissions by road types in Istanbul

Similar to Thessaloniki, the mean values of NOx emissions showed an increased trend on urban and motorway roads following the training, as illustrated in Figure 3.7. On urban roads, the mean values of NOx emissions increased from 0.615 g/km to 0.650 g/km from Phase 1 to Phase 2, with an increase of 5.4%. On motorways, the corresponding mean values of NOx emissions demonstrated an elevation from 0.630 g/km to 0.652 g/km from Phase 1 to Phase 2, reflecting a 3.4% increment.

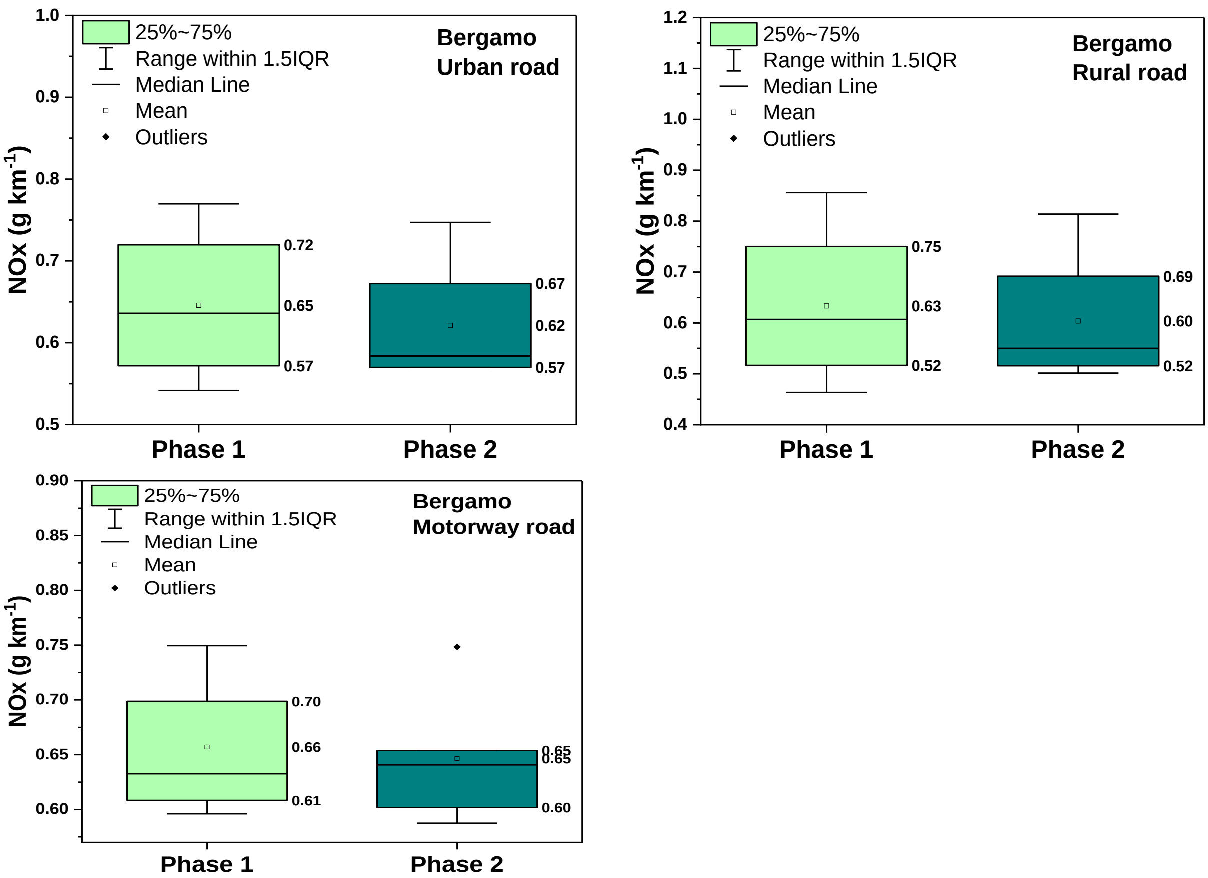


Figure 3.8: Before and after NOx emissions by road types in Bergamo

Figure 3.8 shows the NOx emissions before and after low-emission driving training on different types of roads in Bergamo. In line with the findings in most cities studied, the NOx emissions were observed to decrease following the training and app use. This implies that these programmes had a beneficial effect on mitigating NOx emissions. Specifically, the mean values of NOx emissions experienced a decrease from 0.65 g/km to 0.62 g/km from Phase 1 to Phase 2. Similarly, the corresponding mean values reduced from 0.63 g/km to 0.60 g/km on rural roads. As for motorways, there was a slight reduction from 0.66 g/km to 0.65 g/km following the training.

3.3 Effect of individual drivers

The impact of individual drivers on NOx emissions has been a subject of significant interest. Understanding the role of drivers in contributing to NOx emissions is crucial for mitigating NOx emissions and improving overall air quality. By examining the behaviours and driving patterns of individual drivers, researchers aim to gain insights into the factors that influence NOx emissions and identify potential measures to mitigate their environmental impact. This section focuses on exploring the effect of individual drivers on NOx emissions, shedding light on the importance of driver behaviour.

Figure 3.9 illustrates the NOx emissions for individual drivers before and after the driver training videos and use of the MODALES App. There were reductions for User 2, User 3, and User 4 on urban roads, whereas User 1, User 6, and User 8 did not show the expected results on urban roads from Phase 1 to Phase 2. On rural roads, reductions in NOx emissions were observed for all users except for User 3 and User 5 during the same period. On motorways, NOx emissions showed improvement for all users, except for User 5, following their move to Phase 2, after watching the video and using the app.

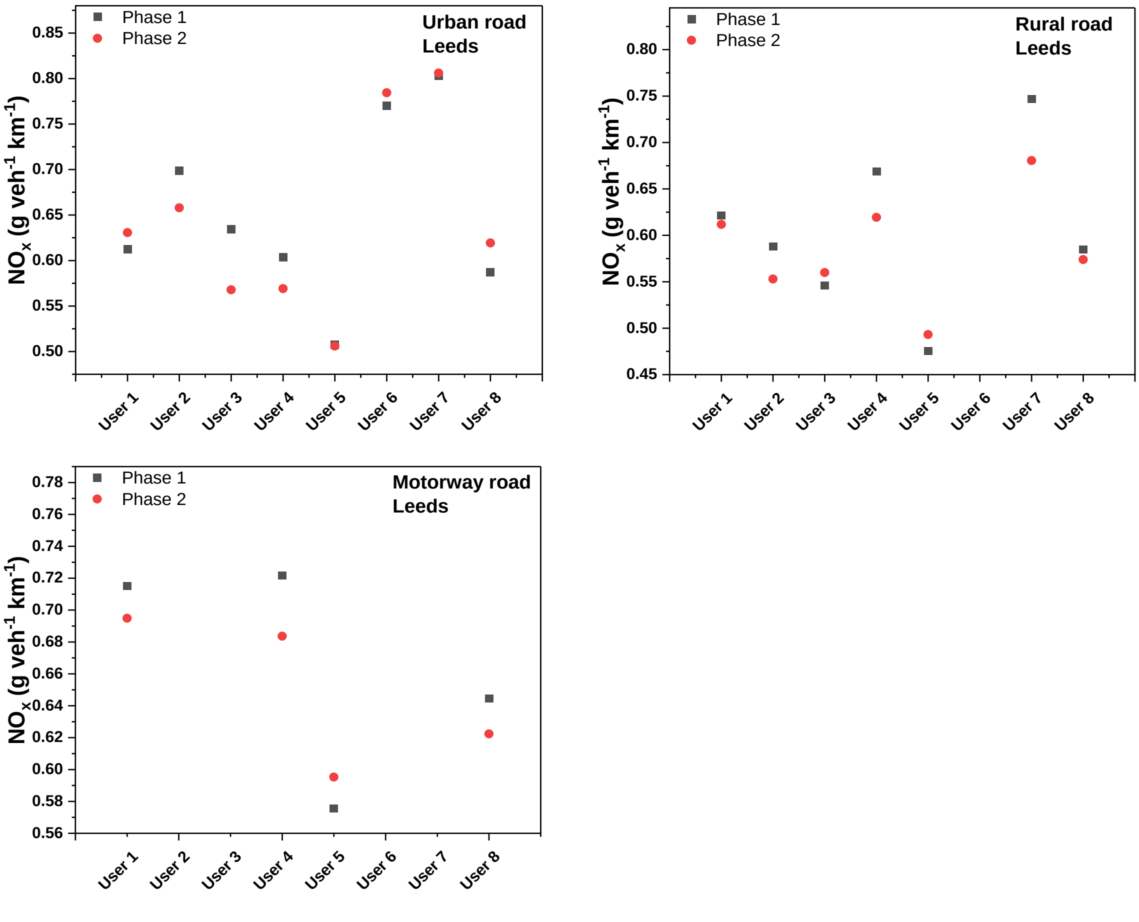


Figure 3.9: Before and after NOx emissions for individual drivers in Leeds

As shown in Figure 3.10 in Helsinki, the training and app effectively promote all users to decrease NOx emissions on urban roads. On rural motorways, the mean values of NOx emissions reduced for most users on rural roads, with the exception of User 6, from Phase 1 to Phase 2. On motorways, all users except for User 5 evidenced a reduction in NOx emissions over the same time frame.

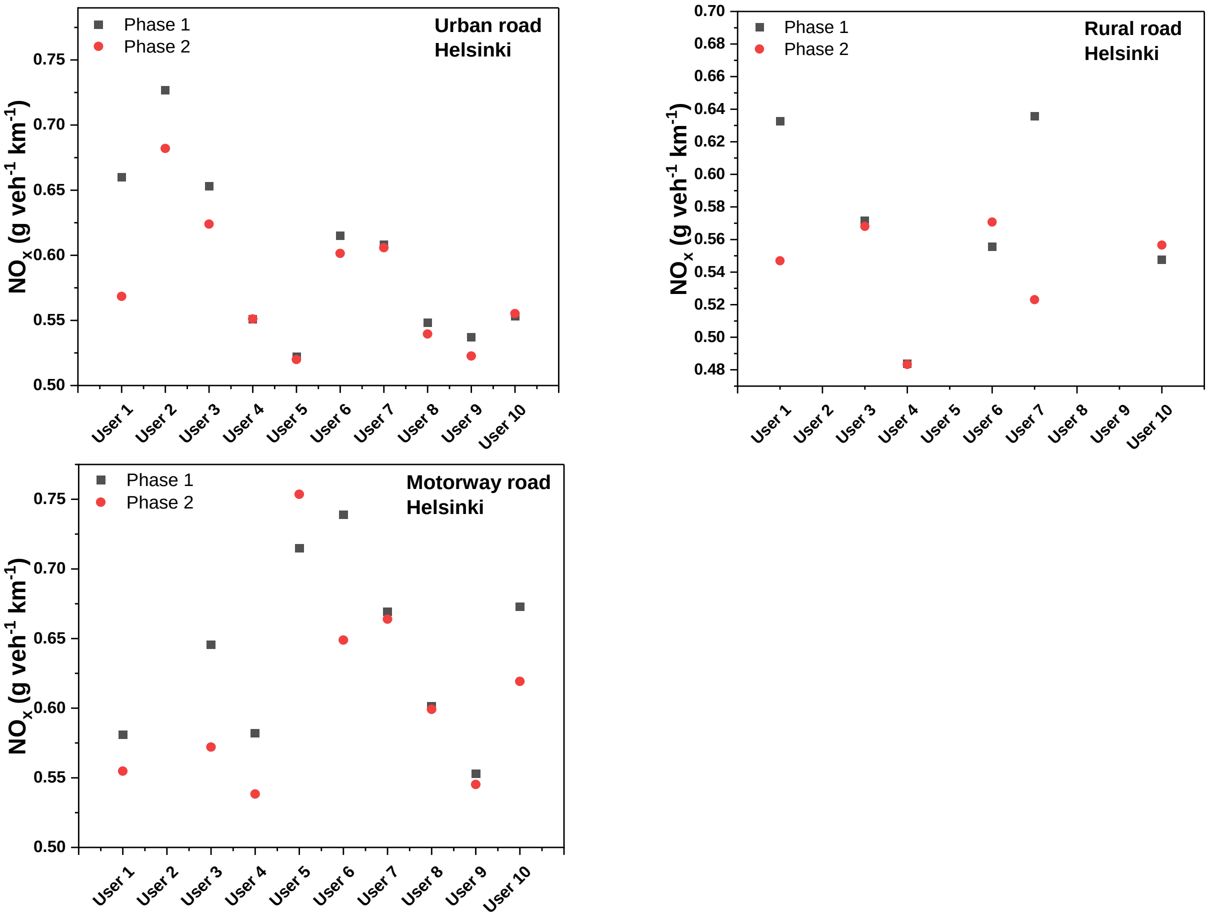
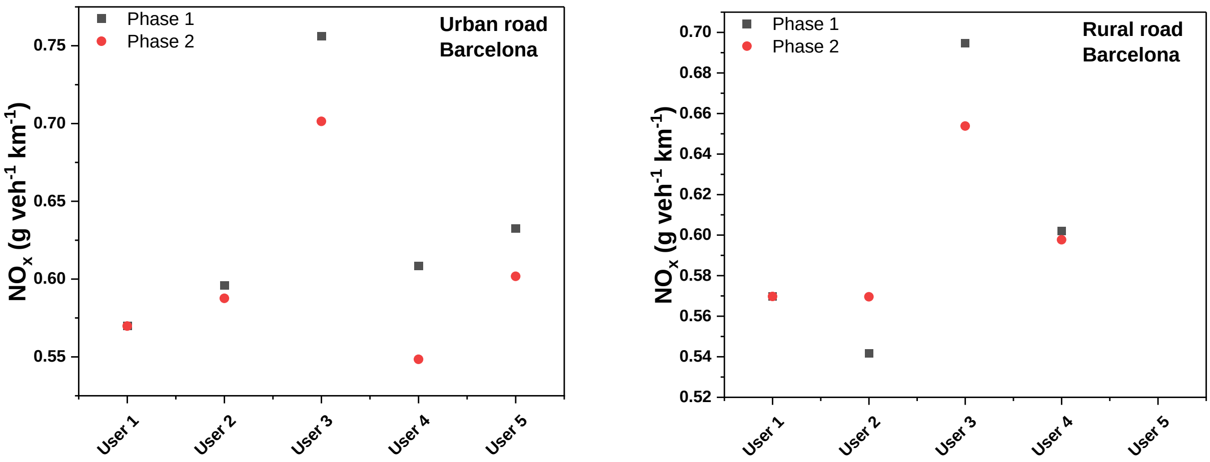


Figure 3.10: Before and after NOx emissions for individual drivers in Helsinki

Figure 3.11 illustrated NOx emissions for individual drivers before and after the low-emission training in Barcelona.



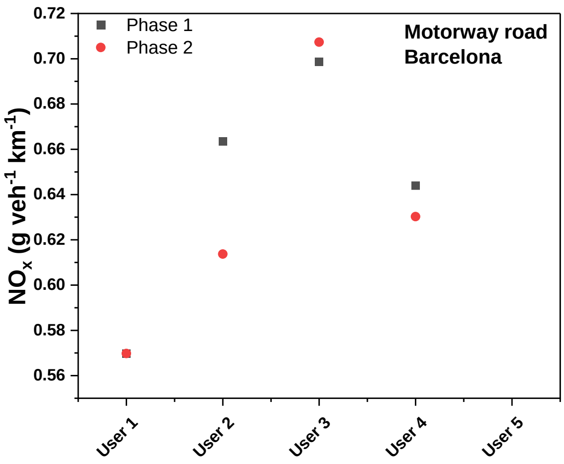
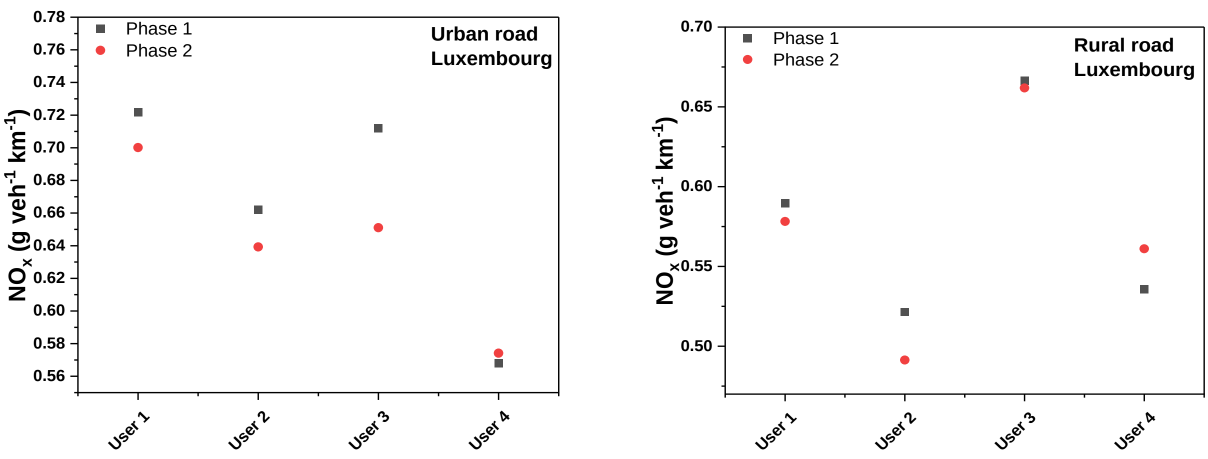


Figure 3.11: Before and after NOx emissions for individual drivers in Barcelona

It can be observed that all users demonstrated a reduction in NOx emissions from Phase 1 to Phase 2 on urban roads. On rural roads, the mean values of NOx emissions increased for only User 2 after participating in the low-emission driving training programmes, while other users showed a decreased trend. User 3 experienced an increase in the mean values of NOx emissions from Phase 1 to Phase 2, whereas other users remained almost constant or observed a decrease in the mean values of NOx emissions in the same period.

In general, there was a decrease in the mean values of NOx emissions in Luxembourg following the training and app use, as illustrated in Figure 3.12. On urban roads, the other three users experienced a reduction in NOx emissions, with the exception of User 4, from Phase 1 to Phase 2. Similarly, there was a decrease in NOx emissions on rural roads for all the users except for User 4 after the training video. However, User 1 and User 3 exhibited a contrasting trend from Phase 1 to Phase 2.



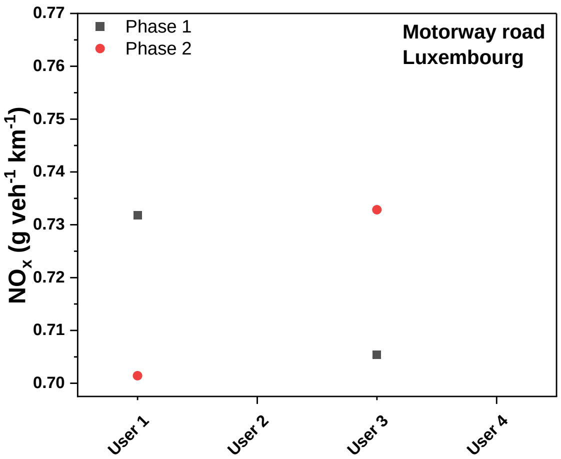


Figure 3.12: Before and after NOx emissions for individual drivers in Luxembourg

In contrast to the results above, more users experienced an increase in NOx emissions following the training across all road types, as illustrated in Figure 3.13. On urban roads, two-thirds of the users did not demonstrate an enhancement in NOx emissions from Phase 1 to Phase 2. Similarly, the mean values of NOx emissions for two-thirds of the users showed an increased trend from Phase 1 to Phase 2 on rural roads and motorways.

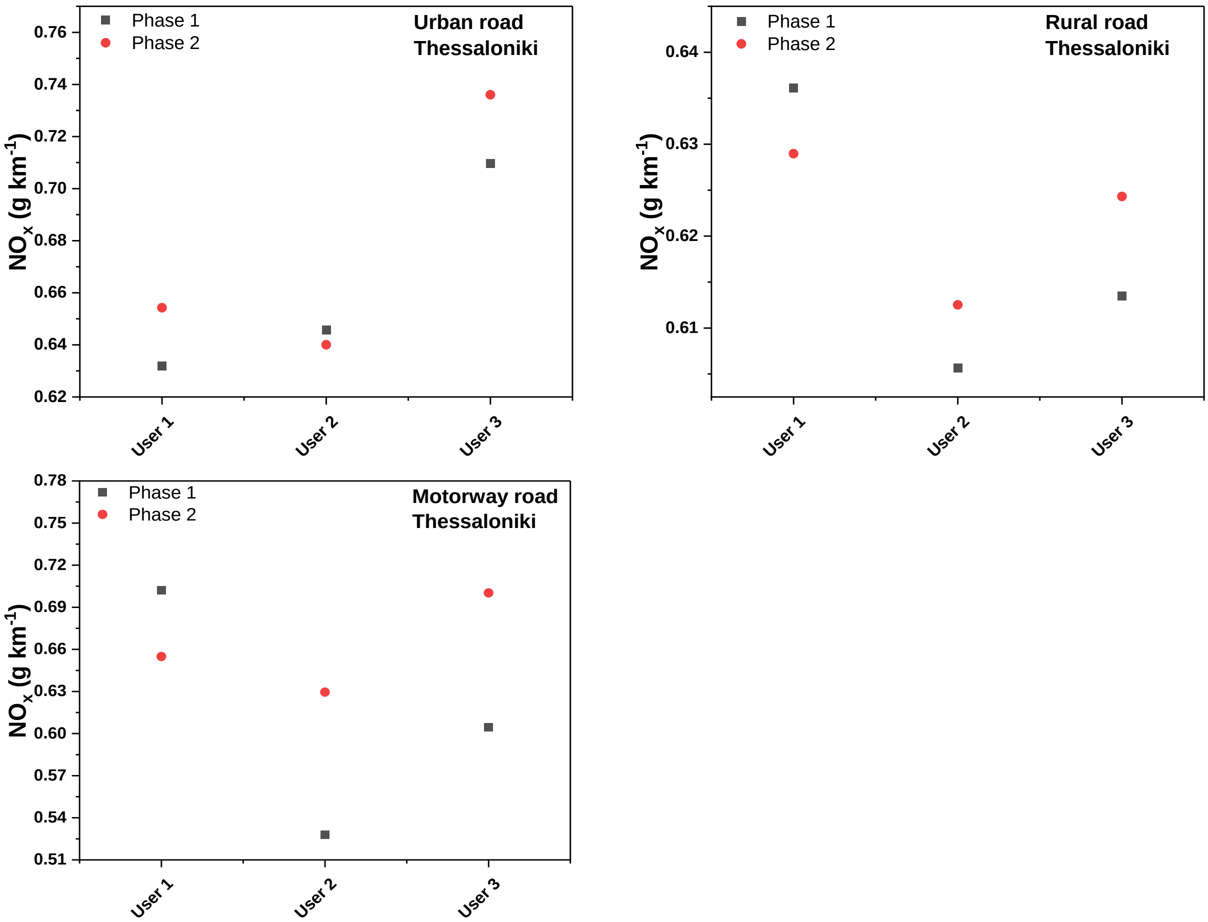


Figure 3.13: Before and after NOx emissions for individual drivers in Thessaloniki

In Istanbul, more users experienced increases in NOx emissions on urban and motorway roads after the training video, as shown in Figure 3.14. On urban roads, an increase in NOx emissions was observed for three-fifths of the users from Phase 1 to Phase 2. Similarly, three-fifths of the users showed increased mean values of NOx emissions on motorways from Phase 1 to Phase 2.

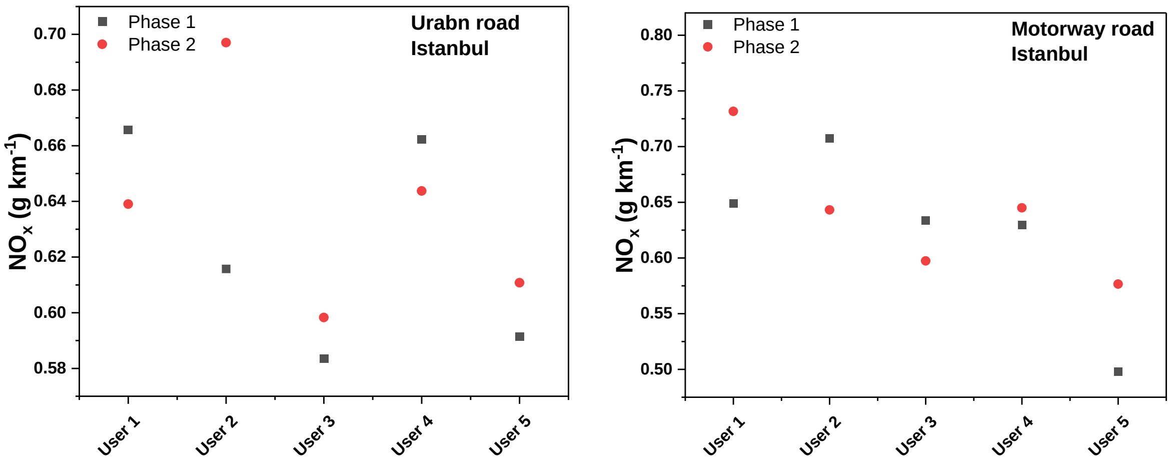


Figure 3.14: Before and after NOx emissions for individual drivers in Istanbul

3.4 Effect of gender

As concerns over environmental pollution and its impact on public health continue to rise, researchers and policymakers have been investigating various factors that contribute to harmful emissions from vehicles. Among these factors, the influence of driver characteristics, such as gender, has gained attention in recent years (Hasan Shahariar et al., 2022; Khader and Martin, 2019; Rolim et al., 2014). While the focus on reducing emissions has primarily centred on vehicle technology and fuel efficiency, understanding the potential relationship between driver gender and emissions, specifically NOx, can provide valuable insights for developing targeted mitigation strategies. In this section, the effect of driver gender on NOx emissions will be analysed.

Figure 3.15 shows NOx emissions of different gender drivers before and after the low-emission driver training. It can be observed that female drivers consistently had lower mean values of NOx emissions compared to male drivers in all the cities involved. More precisely, in Leeds during Phase 1, female drivers had NOx emissions that were 10.3% lower than male counterparts, and during Phase 2, the reduction increased to 10.7%. In Helsinki, the corresponding reductions for female drivers were 1.6% and 9.4% in Phase 1 and Phase 2, respectively, compared to male drivers. In Barcelona, the observed reductions for female drivers were 4.8% and 4.8% when compared to male drivers. In addition, during the transition from Phase 1 to Phase 2, there was a decrease in mean values of NOx emissions for both female and male drivers in Leeds. The reduction for female drivers was 3.3%, while for male drivers, it was 2.9%. In Helsinki, female drivers experienced a reduction of 4.9% in NOx emissions from Phase 1 to Phase 2, whereas male drivers experienced an increase of 3.2%. In Barcelona, there was a reduction of 1.7% for female drivers and 1.6% for male drivers from Phase 1 to Phase 2.

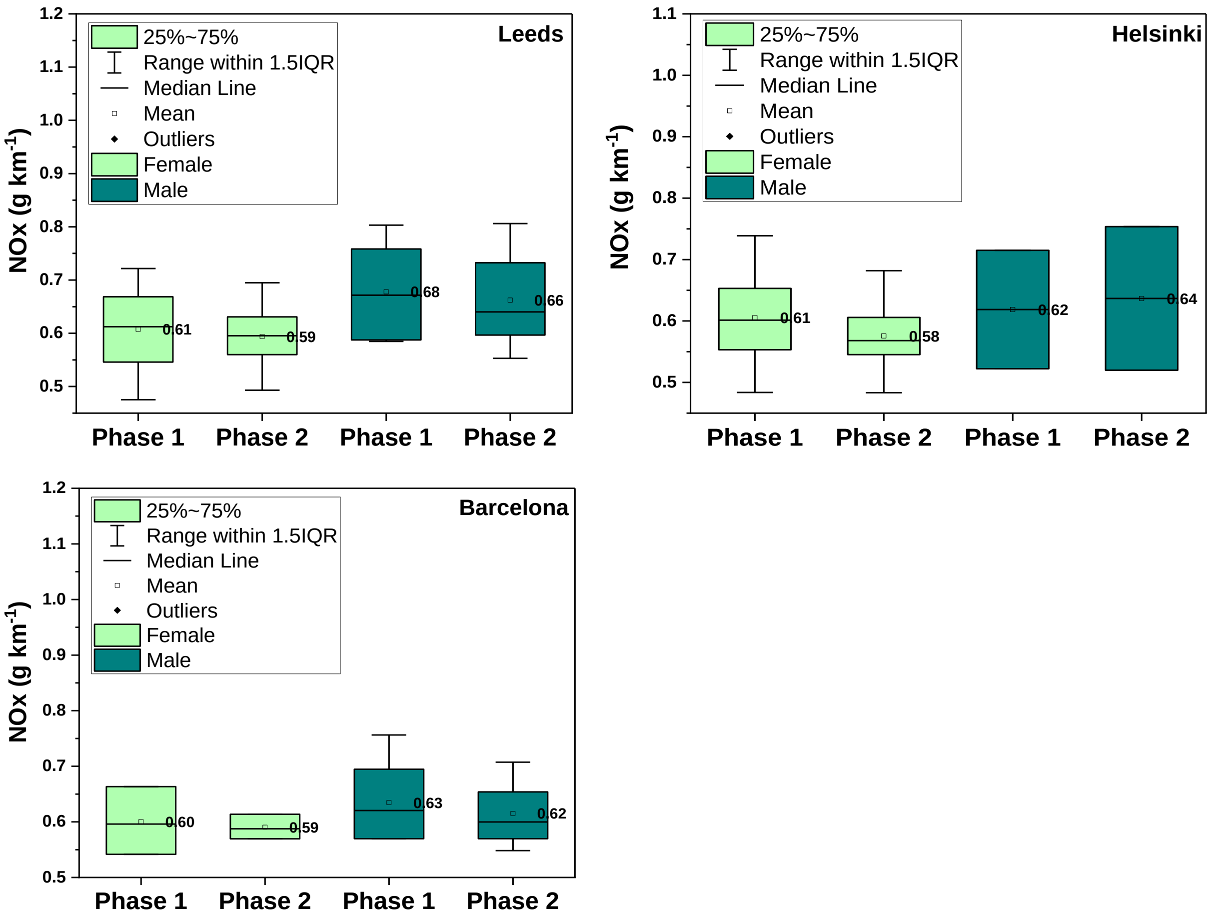


Figure 3.15: NOx emissions for individual drivers before and after low-emission driver training

3.5 Effect of experience

Nowadays, vehicle internal combustion and after-treatment technologies have been extensively studied, but the role of driver experience in NOx emissions remains relatively understudied. Driver experience includes the knowledge, skills, and habits acquired by individuals over time as they gain familiarity and proficiency in operating a vehicle. It is plausible that the experience level of a driver could impact their driving behaviours, including acceleration, deceleration, and overall vehicle control, which in turn can affect emissions. However, the specific relationship between driver experience and NOx emissions requires further investigation. Thus, this section focuses on the effect of driving experience on NOx emissions.

In order to assess the impact of driving experience on NOx emissions, the drivers were categorized into two groups: experienced drivers and novice drivers. The experienced drivers were defined as professional drivers with a minimum of 5 years of driving experience, while the novice drivers had less than 5 years of experience. Figure 3.16 shows the effects of driving experience on NOx emissions before and after watching the training video and using the app.

Overall, the mean values of NOx emissions were lower for experienced drivers compared to novice drivers, except in Thessaloniki. Furthermore, the study revealed that both experienced and novice drivers experienced reductions in NOx emissions following the training video. In Leeds, there was a reduction of 2.9% and 3.2% in NOx emissions for novice and experienced drivers, respectively, from Phase 1 to Phase 2. Similarly, in Helsinki, the mean values of NOx emissions decreased by 3.2% for novice drivers and 5.1% for experienced drivers during the same period. In Barcelona, the mean values of NOx emissions decreased by 4.3% for novice drivers and by 3.3% for experienced drivers. In Thessaloniki, a reduction of 4.8% was observed for experienced drivers from Phase 1 to Phase 2, while novice drivers experienced an increase of 6.5% in NOx emissions.

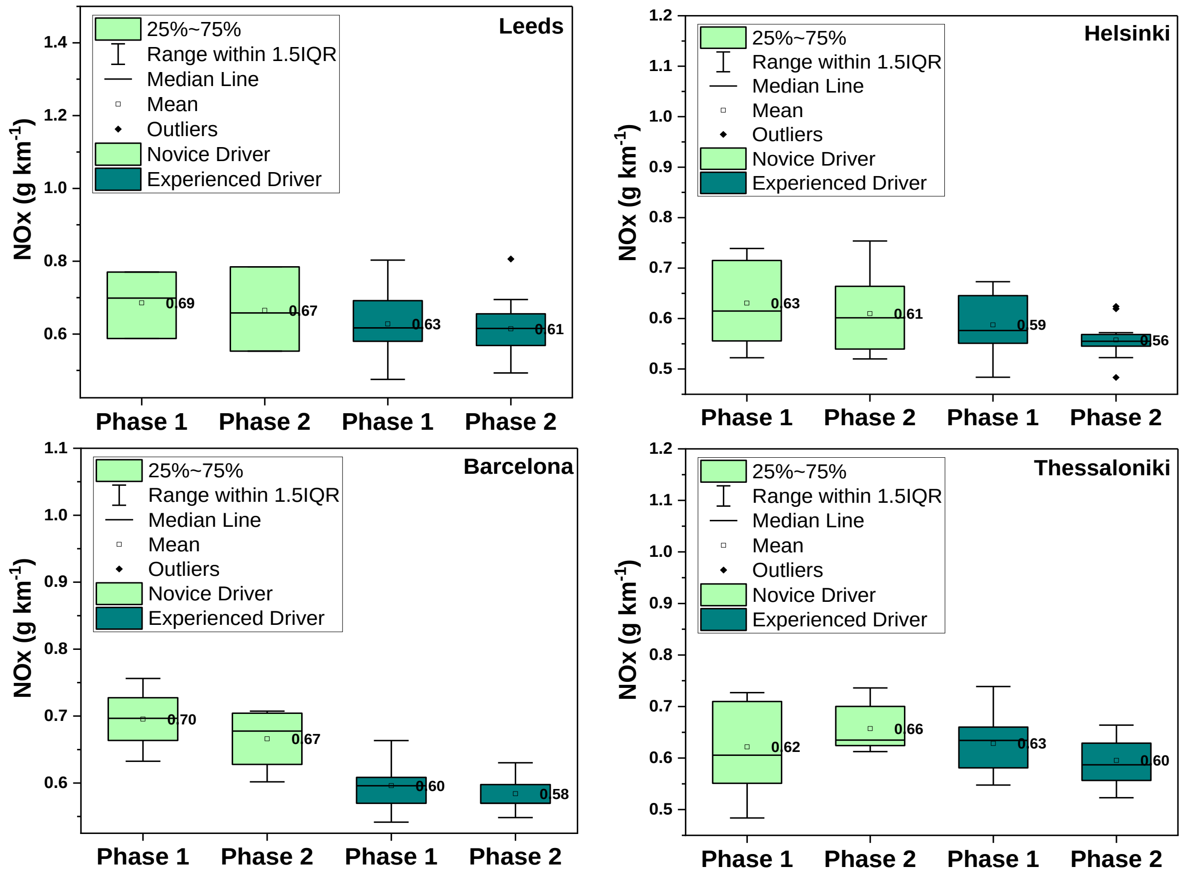


Figure 3.16: Effects of driver experience on NOx emissions before and after low-emission driver training

3.6 Differential influences of driving behaviour based on real-world emissions

The goal of this study was to validate and demonstrate the potential gains obtained in tail-pipe emissions from using the MODALES application. The net effects were measured with a portable emissions measurement system (PEMS) in real-world conditions. For this purpose, a separate PEMS-testing campaign was organised for the Helsinki trials. Two test vehicles (one petrol and one diesel vehicle) were driven by 5 test drivers each without and with the MODALES application and its recommendations activated. To ensure the highest comparability, the tests were conducted on a route specifically designed for the MODALES project. During each trip, both driving parameters and tail-pipe emissions were recorded. The results demonstrate that relatively significant gains are achievable using the MODALES-application A detailed description of the tests is provided in the MODALES Deliverable D6.2.

3.6.1 Description of the experiments

During the trial site test campaign, a more detailed, experimental study was performed for a limited set of trial site drivers in the area of Helsinki, Finland. The purpose of this experiment was to study and demonstrate the true potential of the MODALES application in real world conditions. This experimental study was conducted during the period when the trial sites were transitioning from the baseline phase to the second phase, with the MODALES application activated. The experiments were conducted with two test vehicles, one petrol and one diesel vehicle. To monitor the driving behaviour and vehicle emissions, both vehicles were equipped with a portable emission measurement system (PEMS).

3.6.2 Test driver pool

A set of seven volunteers from the Helsinki trial site were selected for this experiment. Most of the driving took place around the city of Espoo in where VTT is located, but due to its strong relation to the Helsinki region, it was referred as Helsinki. Each vehicle was operated by five drivers each. Because only seven test drivers volunteered for the experiment, three volunteers conducted tests with both vehicles. A central selection criterion for the volunteers was that the drivers were required to have sufficient time and mileage of baseline for the application to form suggestions of how to improve the user specific driving behaviour. Detailed information about the drivers are presented in Table 3.1.

Table 3.1: Break-down of the pool of test drivers

Driver ID	Gender	Age [years]	Driving experience [years]	Annual mileage
Helsinki 1	Male	58	40	> 20 000
Helsinki 2	Male	58	41	> 20 000
Helsinki 3	Male	64	46	> 20 000
Helsinki 6	Male	47	25	10 000 – 20 000
Helsinki 16	Male	40	22	10 000 – 20 000
Helsinki 26	Male	61	43	> 20 000
Helsinki 27	Male	33	15	10 000 – 20 000

3.6.3 Test protocol and test matrix

The experiments were divided into two different phases: recording the driving behaviour of the drivers' baseline behaviour and the change in behaviour with the MODALES application activated. Each driver was requested to drive the predefined MODALES PEMS route according to instructions given by the VTT MODALES project staff. The route was displayed for the drivers in a satellite navigation device, which guided the drivers throughout the complete trip. Additionally, a brief introduction of the vehicles and their attributes were given before the tests. The vehicles in question were mostly familiar to all test drivers because the same vehicles are freely available and used among VTT's staff for conducting regular business activities.

For the baseline tests, the drivers were told to drive the predefined trip two consecutive times. No instruction or training for low emission driving prior to the baseline tests were given for the drivers. The drivers were guided to record their driving with the MODALES application without the recommendations activated (Phase 1). When the baseline tests were completed, each driver would receive the MODALES training material and a short introduction on site for how to use and utilise the

MODALES-application and its active and passive recommendations. When the training was completed, the drivers were asked to activate the recommendations (Phase 2) on the MODALES application and to use the application in normal, everyday driving until the next phase of PEMS tests were conducted.

The second part of the study was aimed for recording the exact same route with the recommendations from the MODALES application activated. Before the start of the tests, the drivers were requested to analyse their history of passive recommendations from Phase 1. Additionally, the drivers were guided to follow the active recommendations displayed on their mobile phone during the PEMS tests whenever applicable. A general overview of the test matrix is shown in Table 3.2 and the different driver and vehicle combinations in Table 3.3.

Table 3.2: Test matrix for the driver, vehicle, and monitoring combinations

	Vehicle	Test configuration	No. Test drivers	No. test repetitions	Total tests
Test setup 1 (baseline)	Petrol	No driver aid applied; user driving "as usual"	5	2	10
Test setup 2 (w. MODALES app.)	Petrol	MODALES application in use	5	2	10
Test setup 3 (baseline)	Diesel	No driver aid applied; user driving "as usual"	5	2	10
Test setup 4 (w. MODALES app.)	Diesel	MODALES application in use	5	2	10

Table 3.3: Driver and vehicle matrix

Driver ID	Petrol	Diesel
Helsinki 1	x	x
Helsinki 2		x
Helsinki 3	x	
Helsinki 6		x
Helsinki 16	x	
Helsinki 26	x	x
Helsinki 27	x	x

3.6.4 Test vehicles

The test vehicles used in the experiments were VTT's in-house vehicles dedicated for internal purposes. The vehicles are generally familiar to most of the staff, including the test drivers because the vehicles are available for all VTT personnel if necessary. The reason for choosing these test vehicles for the tests was simple: the vehicles had previous history with PEMS-testing, which in turn was in favour for practical reasons (regarding configuring and installing the PEMS-device) and the drivers had previous understanding of the vehicle behaviour. Furthermore, the vehicles represent relatively well the typical vehicles present possessed by Finnish road users. Both vehicles were from the same brand and model. The first vehicle was equipped with a petrol engine combined with a 6-speed manual transmission. The latter vehicle was a diesel model equipped with an automatic 7-speed DSG transmission. The vehicles with the PEMS devices installed are illustrated in Figure 3.17 and Figure 3.18. A more detailed list of the vehicle configuration is presented in Table 3.4.

Figure 3.17: Skoda Octavia Petrol (test vehicle #1) with the PEMS device installed

Figure 3.18: Skoda Octavia Diesel (test vehicle #2) with the PEMS device installed

Table 3.4: The main specifications of the test vehicles

Test vehicle #	1	2
Make	Skoda	Skoda
Model	Octavia	Octavia
Model year	2017	2019
Fuel type	Petrol	Diesel
Engine size [dm^3]	1.498	1.598
Induction	Turbo	Turbo
Power [kW]	110	85
Transmission type	Manual 6-speed	Automatic (DSG 7-speed)
Mass [kg]	1470	1556
Emission class	Euro 6C	Euro 6d_temp
EATS	TWC	EGR + DOC + SCR + DPF

3.6.5 Test route

The test route implemented for the experiments was a tailor-made route consisting of different driving conditions, such as urban, rural and motorway sections. The route started from VTT's vehicle laboratory, circulated around Espoo region, and returned to the starting point. The first and last section (ca. 4.5 km) were the same route but driven in opposite directions. This route is the same as that which was initially implemented in the emissions measurement work described in MODALES D3.1. The route chosen for this experiment is a relatively diverse yet representative for typical road usage, including several junctions, traffic lights and bus stops. It should be noted that all such road conditions together with the momentary traffic conditions may potentially affect the driving consistency between trips. The total length of the route was ca. 31 km, with an estimated average trip time (by the navigator) of ca. 45 - 50 minutes depending on traffic conditions. The speed limits over the route differed from 40/50 km/h for most of the streets to short sections of 20 km/h in the very beginning and at the end, with a few short sections (2.4 km in total) of 30 km/h. The rural route sections of some 2.8 km had speed limit of 60 km/h. The motorway section (2.5 km) had 100 km/h speed limit, and the dual carriageway type of ring-road section (3.5 km) had speed limit of 80 km/h. An illustrative map of the route including the corresponding sections speed limits are shown in Figure 3.19.

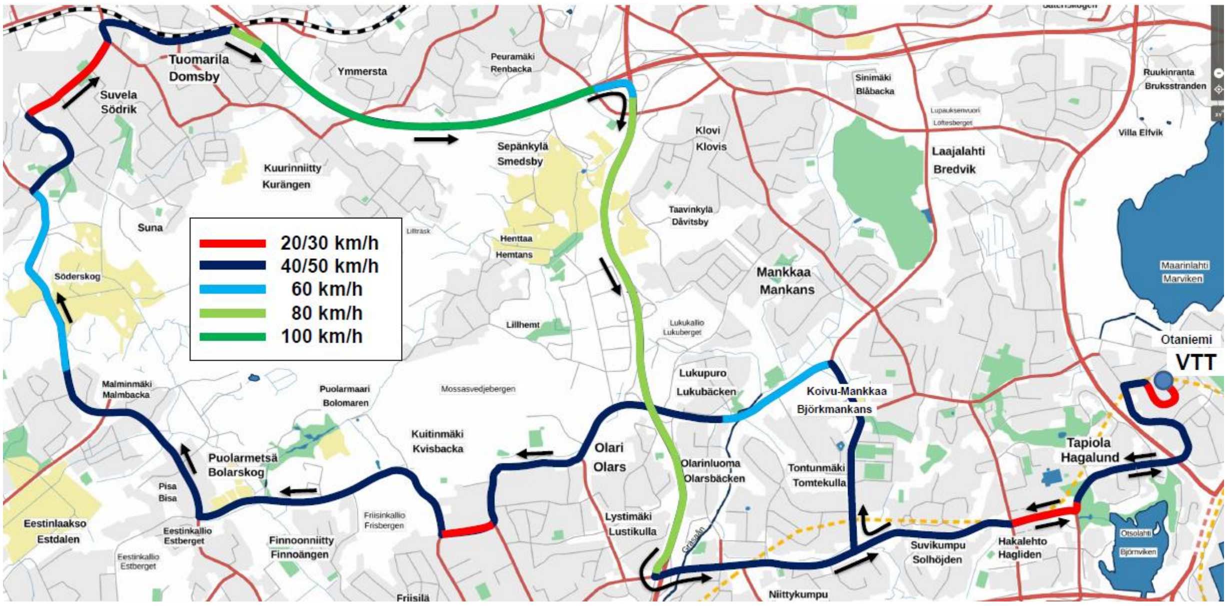


Figure 3.19: The preselected test route used for the PEMS tests

3.6.6 Test equipment and data collection

To record the essential data of each trip, a PEMS device (AVL M.O.V.E.) was installed in both test vehicles. The PEMS device can record the ambient conditions, exhaust emissions, driving parameters and GPS position. The post processing was performed using a dedicated PEMS data software (AVL Concerto). The output file contains both instantaneous (emissions/s) and cumulative (emissions/test, emissions/km) emissions values. Essential driving parameters were recorded by PEMS from vehicle OBD II port. The vehicles speed (km/h) was recorded by the PEMS device either based on the vehicle OBD-data or from the change in GPS position. From the vehicle speed data, concerto provides with additional information, such as acceleration (m/s^2) and v*a positive, or va_pos (m^2/s^3), a parameter describing the (positive) vehicle acceleration in relation to current driving speed by multiplying the acceleration and the driving speed. However, the v*a positive does not account for deceleration, which in turn should be accounted for by other means. Main parameters recorded are listed following:

Parameters collected during the experiments:

From ECU/OBD:

- Driving speed (km/h)
- Engine speed (rpm)
- Power (kW)
- Engine torque (Nm or %)
- Engine work (kWh)
- Coolant temperature (°C)

From PEMS:

- Exhaust emissions: CO, CO_2, NO, NO_2, O_2, PN (particulate number)
- Exhaust mass flow (kg/h)
- Exhaust temperature (°C)
- GPS position (long. lat. alt), vehicle speed (km/h) and distance travelled (km)

From MODALES application

- Passive recommendations

Simultaneously for each trip, the MODALES application was activated before the start of the test. The mobile MODALES application was not connected to the OBD-port, because the data collection would conflict with the PEMS recording. The mobile phones containing the MODALES application was positioned in the centre of the vehicle console, well within the line of sight of the driver but such that it would minimise the distraction of the overall driving view (Figure 3.20). For the baseline tests, MODALES app was left in Phase 1 mode such that no driving recommendation would be present during the driving event. For the second phase, the MODALES recommendations were activated, displaying the trip scoring from each test (Figure 3.21).

The net effect and gains obtained from using the MODALES application were analysed based on both momentary, total trip and average values of all data collected. For calculating the net results, the two consecutive tests for each driver/vehicle configuration were accounted for. If any OBD or vehicle related faults or abnormal behaviour occurred, the data of this output was discarded from the analysis. This includes discarding of trips with DPF-regeneration, which was expected to take place somewhat randomly yet repeatedly for the diesel vehicle.

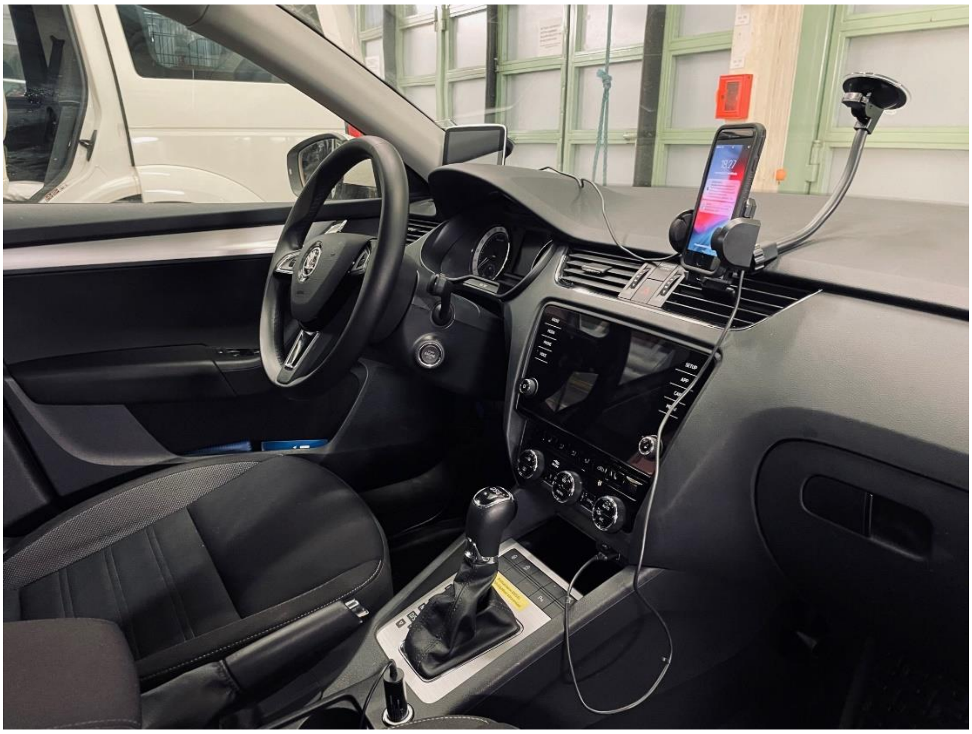


Figure 3.20: Mobile phone and the satellite navigation device positions in the vehicle cabin

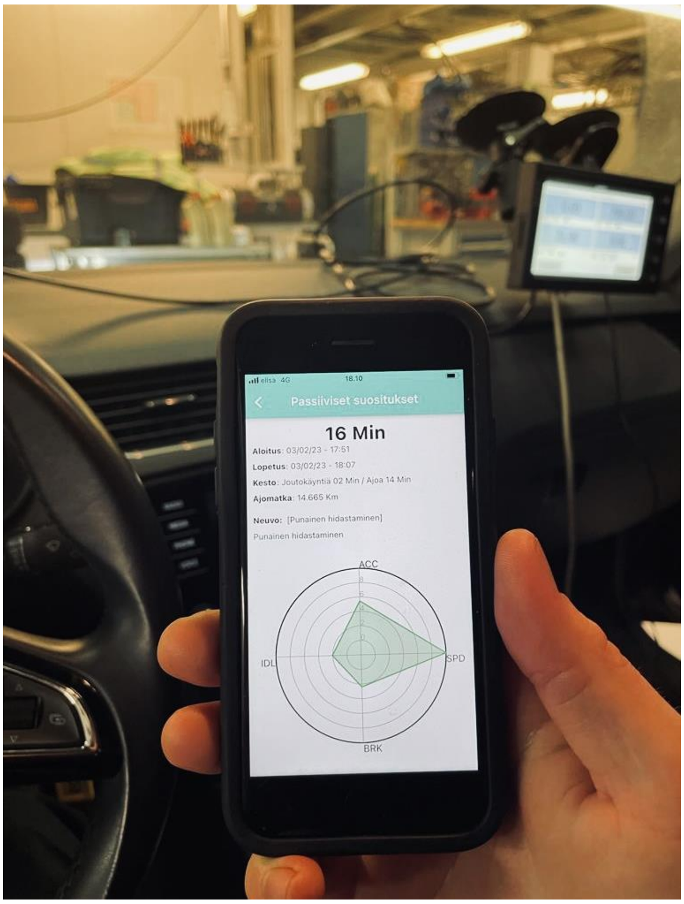


Figure 3.21: An example of passive recommendations for trip scoring

3.6.7 Validation and quality assurance

The validity and quality of each result was assured by implementing an integrated validation scheme provided by the PEMS supplier. This includes daily pre-check calibrations using standard gas mixtures with known concentrations, as well as post-checks. Possible analyser drifts were measured, and datasets were corrected according to the deviation between the pre- and post- tests. Additionally, momentary ambient conditions were recorded by the PEMS device, and the data was used to normalise the results. The tests were prepared and supervised and data post-processed by experienced professionals that regularly work with specifically this PEMS- device.

3.6.8 Execution of the PEMS-tests

The PEMS tests for this work were conducted in February 2023. February is typically one of the coldest months, temperatures below -20 °C being not uncommon. However, due to a milder winter, the average ambient temperatures were generally above or around 0 °C, thus conditions were seen suitable for PEMS testing. The lowest allowed ambient temperature (lower boundary condition) for the PEMS device is -10 °C, but extended conditions for Euro 6 vehicles reach down to -7 °C. All conducted tests fulfilled these boundary conditions but ranged between + 1.2 °C to + 7.7 °C for the petrol vehicle and between - 4.6 °C to + 4.3 °C for the diesel vehicle. The average trip temperatures are shown for the petrol vehicle in Table 3.5 and for the diesel vehicle in Table 3.6.

Table 3.5: Average trip temperature of PEMS test campaign with the Petrol vehicle

Petrol vehicle	Baseline		w. MODALES app	
Driver ID	Date	Average ambient temperature [°C]	Date	Average ambient temperature [°C]
Helsinki 1	9.2.2023	3.0	14.2.2023	5.0
Helsinki 3	13.2.2023	7.1	14.2.2023	3.7
Helsinki 16	10.2.2023	2.2	15.2.2023	2.0
Helsinki 26	10.2.2023	1.9	15.2.2023	1.2
Helsinki 27	9.2.2023	2.9	13.2.2023	7.7

Table 3.6: Average trip temperature of PEMS test campaign with the Petrol vehicle

Diesel vehicle	Baseline		w. MODALES app	
Driver ID	Date	Average ambient temperature [°C]	Date	Average ambient temperature [°C]
Helsinki 1	21.2.2023	-4.6	1.3.2023	2.7
Helsinki 2	24.2.2023	-1.4	28.2.2023	2.7
Helsinki 6	23.2.2023	-1.7	28.2.2023	4.3
Helsinki 26	23.2.2023	-2.4	24.2.2023	-0.1
Helsinki 27	27.2.2023	2.0	1.3.2023	5.6

3.6.9 The user level influence of the MODALES application on an aggregated level

This chapter describes the general, average results obtained from the test campaign on an aggregated level. The results are presented as average values over the total trip per vehicle and driver based on predominant test phase. All momentary data from these tests are broken down as time resolved, second-by-second data in chapters 2.6.9 and 2.6.10.

The recorded values of main driving parameters for each driver/vehicle configuration are shown in Table 3.7. The results represent average values of typically two successful trips and are separately presented for each car and each driver combination (baseline + driving with MODALES application), as well as an average of all driver/car combinations. In case any data was discarded, the average values only account for one test, which is marked separately in the table with thick borderlines. The AVG column describes an average value of all drivers for the specific vehicle and test phase.

The principle behind the colour indicators were defined as follows:

Baseline results: All baseline values are displayed are neutral results, no colour indication applied.

Tests with MODALES application activated: If the average value for the corresponding parameter of the driver in question is higher than its baseline result, the cell is marked with red, and if the average value is lower than for baseline, the result is indicated in green. Additionally, average results accounting for the results calculated all drivers (for one vehicle and test phase) higher than for the baseline result are indicated in red and vice versa.

Overall, some naturalistic variation in driver-to-driver behaviour was found for all driving parameters. The variation between test to test occurred typically due to changes in traffic conditions, such as driving time, traffic flow etc. Interestingly, the average trip time, distance and average speed for the total test pool was noted to be virtually unchanged between tests conducted for the baseline and with the MODALES recommendations activated. However, the impact on certain driving parameters, such as average engine speed and engine torque were more evident for the petrol vehicle when using the MODALES application, which was not the case for the diesel vehicle. The main reason for this is that the drivers are practically unable to influence the selected gear with vehicles equipped with an automatic transmission, meanwhile with manual transmissions, the selected gear is mostly determined by the momentary vehicle speed and required engine response. Interestingly, the decrease in average engine speed applied for all test drivers with the petrol car throughout the spectrum.

It should still be noted that still after activating the recommendations, relatively large variation between driver to driver was found, suggesting that the preference of gear selection and driver feeling is rather large between the test drivers. Equally, most gain in terms of engine power, torque and work was obtained with the MODALES application certain drivers, albeit the overall difference or gain in terms of average values remain relatively low. Generally, drivers 1, 2, 3 and 16 improved their driving style simultaneously engine power and torque, resulting in decreased engine work/trip. Meanwhile, Helsinki 27 seemed to increase the average power, torque and work over the tests with MODALES recommendations activated. One connecting parameter that was found improving for both test vehicles and all drivers was “v*a positive”, which decreased from baseline over to the Phase 2 for all drivers. This means that less aggressive accelerations were generally adapted for all test drivers over the tests, suggesting that the driving was becoming smoother. Based on these results, a conclusion may be withdrawn that the trial members seemed to adapt their driving behaviour more with the vehicle with a manual transmission, albeit less aggressive driving was noted with both vehicles.

Table 3.7: Average results for driving parameters per driver and test configuration

#SPILL!		Test drivers							AVG
Trip Duratior	Configuration	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	h
Petrol	Baseline	0.79	o	0.79	o	0.82	0.86	0.85	0.82
Petrol	w. MODALES-app	**0.83**	**o**	**0.79**	**o**	**0.80**	**0.91**	**0.80**	**0.82**
Diesel	Baseline	0.80	0.89	o	0.81	o	0.86	0.83	0.84
Diesel	w. MODALES-app	**0.83**	**0.86**	**o**	**0.78**	**o**	**0.89**	**0.86**	**0.84**
Trip Distance		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	km
Petrol	Baseline	31.2	o	31.2	o	31.2	31.4	31.3	31.25
Petrol	w. MODALES-app	**31.3**	**o**	**31.2**	**o**	**31.3**	**31.2**	**31.3**	**31.26**
Diesel	Baseline	31.1	31.3	o	31.3	o	31.2	31.1	31.21
Diesel	w. MODALES-app	**31.2**	**31.3**	**o**	**31.3**	**o**	**31.1**	**31.1**	**31.21**
Avg. Speed		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	km/h
Petrol	Baseline	40	o	40	o	38	37	37	38.1
Petrol	w. MODALES-app	**38**	**o**	**39**	**o**	**39**	**34**	**39**	**38.0**
Diesel	Baseline	39	35	o	39	o	36	37	37.4
Diesel	w. MODALES-app	**38**	**37**	**o**	**40**	**o**	**35**	**36**	**37.2**
Avg. Engine speed		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	rpm
Petrol	Baseline	1399	o	1652	o	n/a	1419	1356	1457
Petrol	w. MODALES-app	**1212**	**o**	**1596**	**o**	1367	**1349**	**1341**	**1373**
Diesel	Baseline	1350	n/a	o	1369	o	1352	1302	1343
Diesel	w. MODALES-app	**1308**	1346	**o**	**1381**	**o**	**1342**	**1329**	**1341**
Avg. Engine Power		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	kW
Petrol	Baseline	9.2	o	10.8	o	9.2	8.8	9.1	9.4
Petrol	w. MODALES-app	**7.9**	**o**	**10.2**	**o**	**9.1**	**8.1**	**9.8**	**9.0**
Diesel	Baseline	18.3	n/a	o	18.8	o	17.6	17.2	18.0
Diesel	w. MODALES-app	**17.7**	17.8	**o**	**19.5**	**o**	**17.5**	**17.0**	**17.9**
Avg. Engine Torque		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	Nm
Petrol	Baseline	62	o	62	o	64	59	63	61.9
Petrol	w. MODALES-app	**61**	**o**	**60**	**o**	**63**	**56**	**68**	**61.7**
Diesel	Baseline	115	n/a	o	125	o	119	110	117.3
Diesel	w. MODALES-app	**115**	120.5	**o**	**129**	**o**	**119**	**115**	**119.8**
Trip Work		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	kWh
Petrol	Baseline	7.3	o	8.5	o	7.5	7.6	7.7	7.7
Petrol	w. MODALES-app	**6.5**	**o**	**8.1**	**o**	**7.3**	**7.6**	**7.7**	**7.4**
Diesel	Baseline	14.6	n/a	o	15.2	o	15.1	14.3	14.8
Diesel	w. MODALES-app	**14.6**	15.2	**o**	**15.2**	**o**	**15.5**	**14.6**	**15.0**
va_pos		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	m^2/s^3
Petrol	Baseline	1.5	o	1.7	o	1.5	1.3	1.6	1.5
Petrol	w. MODALES-app	**1.3**	**o**	**1.6**	**o**	**1.5**	**1.2**	**1.5**	**1.4**
Diesel	Baseline	1.3	1.1	o	1.2	o	1.2	1.6	1.3
Diesel	w. MODALES-app	**1.1**	**1.1**	**o**	**1.1**	**o**	**1.1**	**1.2**	**1.1**

o	Driver did not drvie this car
n/a	Result not available due to malfunctions
	Result for the driver, one trip with regeneration event omitted

Table 3.8: Relative change in driving parameters per driver and test configuration between baseline and test performed with MODALES-recommendations activated

TEST DRIVERS

Trip Duratior	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	5 %		1 %		-3 %	5 %	-7 %	0 %
Diesel	4 %	-4 %		-4 %		3 %	3 %	1 %
Avg	4 %	-4 %	1 %	-4 %	-3 %	4 %	-2 %	0 %

Trip Distanc	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	0 %		0 %		0 %	-1 %	0 %	0 %
Diesel	0 %	0 %		0 %		0 %	0 %	0 %
Avg	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %

Avg. Speed	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-5 %		-1 %		3 %	-6 %	7 %	0 %
Diesel	-3 %	4 %		4 %		-3 %	-3 %	-1 %
Avg	-4 %	4 %	-1 %	4 %	3 %	-5 %	2 %	0 %

Avg. Engine	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-13 %		-1 %		3 %	-6 %	7 %	-6 %
Diesel	-3 %	n/a		1 %		-1 %	2 %	0 %
Avg	-8 %	n/a	-1 %	1 %	3 %	-3 %	5 %	-3 %

Avg. Engine	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-14 %		-5 %		-1 %	-8 %	8 %	-4 %
Diesel	-4 %	n/a		3 %		0 %	-1 %	-1 %
Avg	-9 %	n/a	-5 %	3 %	-1 %	-4 %	4 %	-2 %

Avg. Engine	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-1 %		-4 %		-1 %	-4 %	8 %	0 %
Diesel	0 %	n/a		3 %		0 %	5 %	2 %
Avg	0 %	n/a	-4 %	3 %	-1 %	-2 %	6 %	1 %

Trip Work	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-11 %		-5 %		-3 %	0 %	0 %	-4 %
Diesel	0 %	n/a		0 %		3 %	2 %	2 %
Avg	-6 %	n/a	-5 %	0 %	-3 %	2 %	1 %	-1 %

va_pos	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	AVG
Petrol	-17 %		-2 %		-3 %	-7 %	-7 %	-7 %
Diesel	-14 %	-5 %		-15 %		-8 %	-24 %	-14 %
Avg	-15 %	-5 %	-2 %	-15 %	-3 %	-7 %	-15 %	-10 %

Table 3.9 describes average emission results from all tests per driver, Table 3.10 describes the deviation between each drivers emission result and the total average for the corresponding test pool/driver/phase configuration and Table 3.11 the relative effect obtained between the baseline tests and tests conducted with the MODALES recommendations activated. For comparison, Table 3.9

includes an additional column indicated as "TA", which describes the type approval values for each emission component.

Table 3.9: Average results for tailpipe emissions per driver and test configuration

		TEST DRIVERS							AVG	TA
CO_2 [g/km]	Configuration	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	g/km	g/km
Petrol	Baseline	123	o	128	o	119	118	129	123	115 (143*)
Petrol	w. MODALES-app	117	o	126	o	121	120	119	120	115 (143*)
Diesel	Baseline	130	126	o	127	o	127	125	127	105 (141*)
Diesel	w. MODALES-app	117	115	o	117	o	123	118	118	105 (141*)
CO [mg/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	mg/km	mg/km
Petrol	Baseline	6.0	o	3.3	o	28.0	3.7	15.5	11.3	221
Petrol	w. MODALES-app	7.8	o	10.2	o	8.9	5.2	10.4	8.5	221
Diesel	Baseline	27.0	0.2	o	0.0	o	0.1	9.0	7.3	35.4
Diesel	w. MODALES-app	0.0	0.2	o	0.1	o	0.0	0.0	0.1	35.4
NOx [mg/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	mg/km	mg/km
Petrol	Baseline	8.9	o	8.5	o	7.2	7.0	9.1	8.1	34.1
Petrol	w. MODALES-app	10.4	o	7.0	o	7.9	8.0	7.7	8.2	34.1
Diesel	Baseline	33.4	14.3	o	18.6	o	22.5	31.6	24.1	29.2
Diesel	w. MODALES-app	14.1	15.9	o	12.8	o	11.1	9.5	12.7	29.2
PN_{23} [#/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	#/km	#/km
Petrol	Baseline	3.8E+10	o	4.9E+10	o	1.1E+11	3.0E+10	6.6E+10	5.9E+10	1.1E+11
Petrol	w. MODALES-app	3.1E+10	o	3.2E+10	o	5.9E+10	1.9E+10	3.0E+10	3.4E+10	1.1E+11
Diesel	Baseline	7.2E+08	7.0E+08	o	7.7E+08	o	7.2E+08	6.7E+08	7.2E+08	2.0E+09
Diesel	w. MODALES-app	7.0E+08	7.0E+08	o	7.0E+08	o	7.4E+08	6.9E+08	7.0E+08	2.0E+09

o — Driver did not drvie this car
n/a — Result not available due to malfunctions
(boxed cell) — Result for the driver, one trip with regeneration event omitted
*announced value according to the WLTP protocol, for petrol estimated

Correspondingly found for driving parameters, relatively strong driver-to-driver variation for average exhaust emissions occurred. For example, the variation in CO_2 between driver to driver was found larger than for the diesel vehicle (Table 3.9). During baseline tests, the variation in CO_2 was ca. +/- 4.5% compared to the test pool average value with the petrol vehicle, meanwhile corresponding variation for the diesel vehicle was ranging between -1.6% to 2.4%, as shown in Table 3.10. With the MODALES recommendations activated, the variation between driver to driver decreased for both vehicles. Interestingly, no improvements in terms of CO_2 emissions were seen for the petrol vehicle with drivers which produced least CO_2. In all other cases, improvements were achieved. Most net gain in CO_2 (i.e. fuel consumption) was achieved with the diesel vehicle, which improved on average with ca. 7 %, meanwhile the net gain with the petrol vehicle was ca. 2%, seen in Table 3.11.

The net change in CO emissions were generally found low for most of the drivers, despite similar, great variation occurred (Table 3.9, Table 3.10 and Table 3.11). The improvements on a driver level with the petrol vehicle were somewhat random, despite some gains in over the total test pool average were achieved. It should be noted that for certain drivers. e.g. Helsinki 3 and Helsinki 6, great relative negative changes we seen, which can be explained by the fact that the absolute values for the baseline tests were found low to begin with. Overall, changes in absolute values that are considered very low to begin with in the baseline tests should be critically analysed in terms of relative gains/losses. For the diesel vehicle, a relatively greater impact was seen, and the CO emissions were reduced with the MODALES recommendations activated close to zero. The CO emissions recorded with both vehicles are however generally very low, which raises questions of its significance.

Table 3.10: Deviation between each driver's emission result and the total average for the corresponding test pool/driver/phase configuration

		TEST DRIVERS						
CO_2 [g/km	Configuration	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27
Petrol	Baseline	-0.1 %	o	3.7 %	o	-3.6 %	-4.5 %	4.4 %
Petrol	w. MODALES-app	-3.0 %	**o**	4.4 %	**o**	0.5 %	-0.5 %	-1.5 %
Diesel	Baseline	2.4 %	-0.6 %	o	-0.3 %	o	0.1 %	-1.6 %
Diesel	w. MODALES-app	-0.8 %	-2.2 %	**o**	-1.0 %	**o**	4.2 %	-0.2 %
CO [mg/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27
Petrol	Baseline	-47 %	o	-71 %	o	148 %	-67 %	37 %
Petrol	w. MODALES-app	-8 %	**o**	19 %	**o**	4 %	-39 %	23 %
Diesel	Baseline	271 %	-97 %	o	-99 %	o	-98 %	23 %
Diesel	w. MODALES-app	-87 %	219 %	**o**	67 %	**o**	-100 %	-99 %
NOx [mg/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27
Petrol	Baseline	9 %	o	4 %	o	-11 %	-14 %	12 %
Petrol	w. MODALES-app	27 %	**o**	-15 %	**o**	-4 %	-2 %	-6 %
Diesel	Baseline	39 %	-41 %	o	-23 %	o	-7 %	31 %
Diesel	w. MODALES-app	11 %	26 %	**o**	1 %	**o**	-13 %	-25 %
PN [#/km]		Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27
Petrol	Baseline	-35 %	o	-16 %	o	87 %	-49 %	13 %
Petrol	w. MODALES-app	-9 %	**o**	-8 %	**o**	72 %	-44 %	-12 %
Diesel	Baseline	0 %	-3 %	o	8 %	o	1 %	-6 %
Diesel	w. MODALES-app	-1 %	-1 %	**o**	0 %	**o**	4 %	-2 %

The change in exhaust pollutants were however mostly concluded positive with two exceptions (Table 3.9): the average NO_x results recorded from all drivers with petrol vehicle remain virtually equal between baseline tests, meanwhile significant change in PN_{23} emissions occurred. For the diesel vehicle, the effect was found opposite. This phenomenon can be explained by comparing the engine after treatment systems (EATS) applied for given test vehicles. The petrol vehicle was equipped with a three-way catalyst (TWC), but no particulate filter. Typically, in order to maintain a high emission conversion rate with the TWC, petrol vehicles are calibrated to operate to its most efficient exhaust matrix, i.e., close to stoichiometric conditions ($\lambda = 1$). Furthermore, the exhaust gas temperatures on petrol vehicles are typically by nature sufficiently high to maintain the light-off temperatures in most driving conditions. However, as the vehicle lacks a particulate filter, the particulate emissions are passed by through the exhaust system untreated.

On contrary, the diesel vehicle was equipped with a selective catalytic reduction system (SCR) and a diesel particulate filter (DPF). The efficiency of SCR systems in diesel vehicles are more dependent of the response of the urea-additive injection, catalyst sizing and its light-off temperature. Therefore, NOx emissions in diesel vehicles are often more sensitive to both driving parameters, predominant conditions and engine/EATS calibration and configuration. However, due to the DPF, the PN_{23} emissions recordings for the diesel vehicle were low during both the baseline tests and tests with MODALES recommendations activated. This phenomenon applied for any absolute values (Table 3.9), driver to driver variation (Table 3.10) and the relative gains (Table 3.11) throughout the results obtained with the diesel vehicle.

Table 3.11: Relative change in tailpipe emissions per driver and test configuration between baseline and test performed with MODALES recommendations activated

CO_2 [%]	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	%
Petrol	-5 %		-2 %		2 %	2 %	-8 %	-2 %
Diesel	-10 %	-9 %		-8 %		-3 %	-6 %	-7 %
Avg	-8 %	-9 %	-2 %	-8 %	2 %	-1 %	-7 %	-5 %

CO [%]	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	
Petrol	31 %		206 %		-68 %	41 %	-33 %	-25 %
Diesel	-100 %	-100 %		109 %		-100 %	-100 %	-99 %
Avg	-34 %	-100 %	206 %	109 %	-68 %	-29 %	-66 %	-62 %

NOx [%]	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	
Petrol	17 %		-18 %		10 %	15 %	-15 %	1 %
Diesel	-58 %	11 %		-31 %		-51 %	-70 %	-47 %
Avg	-20 %	11 %	-18 %	-31 %	10 %	-18 %	-43 %	-23 %

PN [%]	Helsinki 1	Helsinki 2	Helsinki 3	Helsinki 6	Helsinki 16	Helsinki 26	Helsinki 27	
Petrol	-18 %		-36 %		-46 %	-35 %	-54 %	-41 %
Diesel	-3 %	0 %		-9 %		2 %	3 %	-2 %
Avg	-10 %	0 %	-36 %	-9 %	-46 %	-17 %	-26 %	-22 %

The linear correlation between CO_2 and other exhaust emissions (CO, NO_x and PN) per driver were found relatively low as shown in Table 3.12. Greatest relation between local exhaust pollutants and CO_2 emissions were overall concluded for the petrol vehicle and NOx emissions. However, by analysing average absolute values shown in Table 3.8, only minor improvements related to CO_2 was achieved, and thus no change in average NOx emissions for the petrol vehicle was noted (as also described in the previous paragraph). Additionally, a somewhat strong correlation between CO_2 emissions and PN was seen for the diesel vehicle with the MODALES recommendations activated, which was not noted for the baseline tests. These findings suggest that the relation between "eco driving" and exhaust pollutants may vary case by case, depending on the fuel type, vehicle and the vehicles engine and EATS technology. The relatively low sample count, no statistically reliable support between eco driving and low emissions driving from the data may be concluded.

Table 3.12: Correlation between CO_2 emissions and measured

Vehicle	Configuration	CO	NO_x	PN
Petrol	Baseline	0.05	0.78	0.01
Petrol	w. MODALES-app	0.13	0.62	0.02
Diesel	Baseline	0.53	0.13	0.12
Diesel	w. MODALES-app	0.40	0.35	0.78

The average total emissions data from each tested vehicle, test pool and test phase may be summarized per emission type as shown for CO_2 in Figure 3.22, for CO in Figure 3.23, for NOx in Figure 3.24 and for PN_{23} in Figure 3.25. In each figure, the TA-values (declared by manufacturer based on either NEDC/WLTP-procedure) are presented for a comparison with the average baseline results and for the test conducted with the MODALES-recommendations activated. The error bars included in the average results represents the variation between the greatest and lowest results recorded from the driver pool.

Figure 3.22 shows that net gains from implementing MODALES recommendations for CO_2 were found to be more meaningful for the diesel vehicle. The average CO_2 emissions decreased from 127 g/km to 118 g/km. For the petrol vehicle, the effect was less evident especially as drivers with lowest baseline-values did not manage to improve CO_2 emissions at all. The CO emissions were in terms of absolute values very low for both vehicles as seen in Figure 3.23.

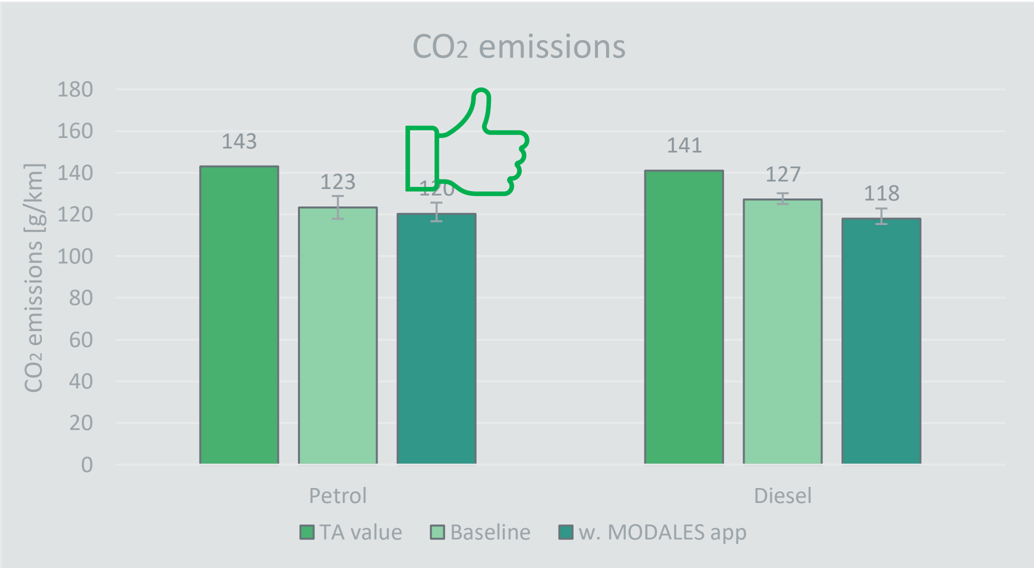


Figure 3.22: Average CO_2 results from baseline and with MODALES application activated compared to the type-approval values

The high TA value declared by the manufacturer for the petrol vehicle (221 mg/km) may be in this case misleading because the TA-process includes a cold start, which typically is the dominant phase for CO production. Because all tests were initiated with a pre-warmed engine, no CO promoting conditions did take place in the measurements described in this document. Nevertheless, the results indicate that with the MODALES recommendations, minor improvements with the petrol vehicle may be achieved, meanwhile for the diesel vehicle, the CO emissions were reduced to virtually zero. The NOx emissions for the petrol vehicle were in terms of absolute values generally very low, yet no gains on average were achieved over the total driver pool. Meanwhile for the diesel vehicle, NOx emissions were in this case practically reduced by half (~47%). On the opposite, both TA-based and recorded PN_{23} emissions for the diesel vehicle were very low to begin with. The declared TA-value below $2*10^9$ #/km compared to type approval limit is $6*10^{11}$ #/km, correspondingly ca. $7*10^8$ #/km for both baseline tests and tests with the MODALES recommendations followed.

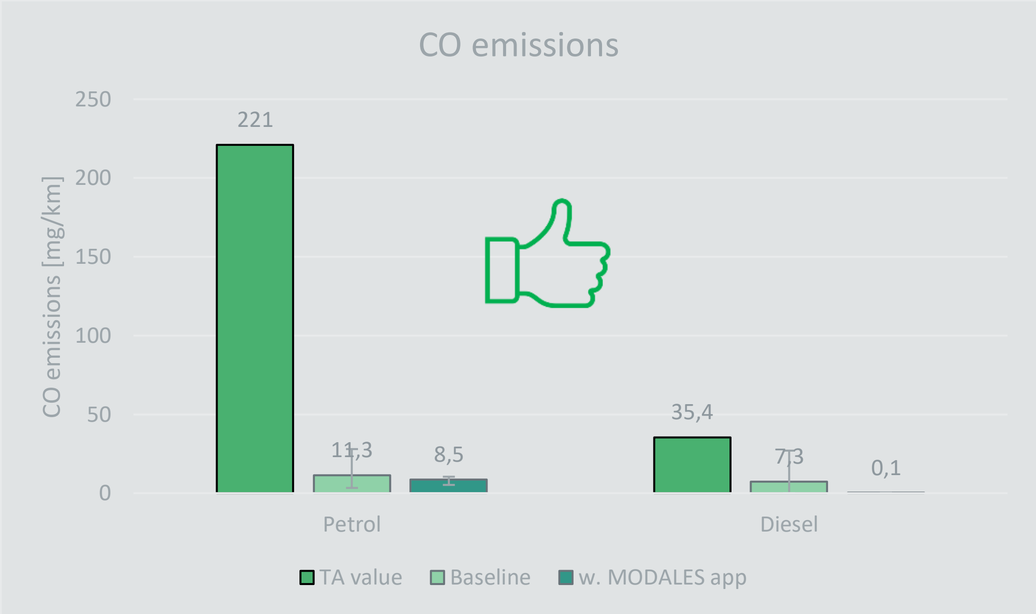


Figure 3.23: Average CO results from baseline and with MODALES application activated compared to the type-approval values

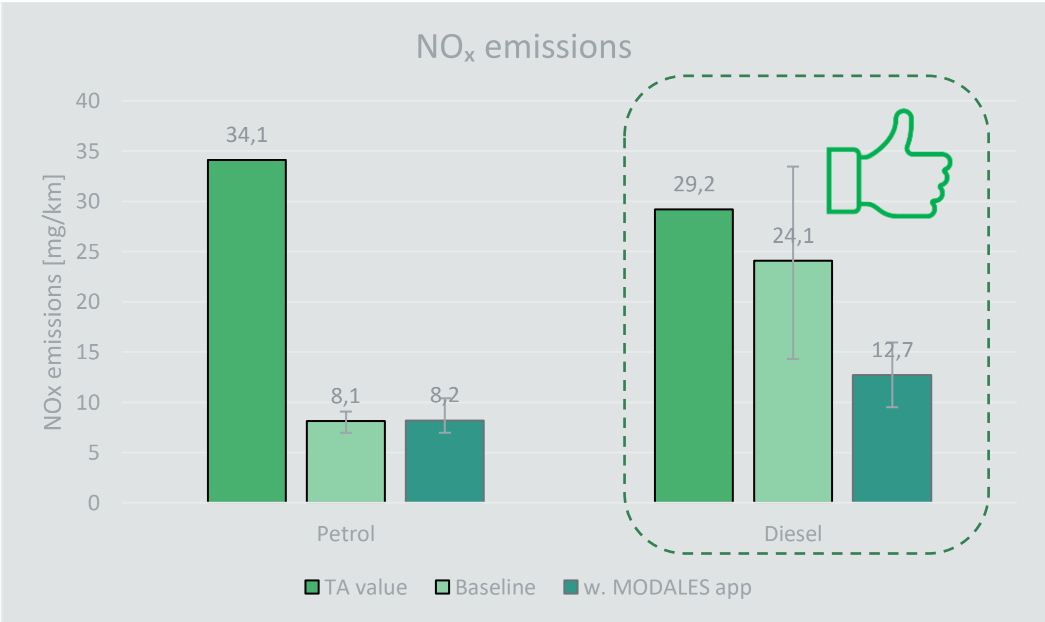


Figure 3.24: Average NOx results from baseline and with MODALES application activated compared to the type-approval values

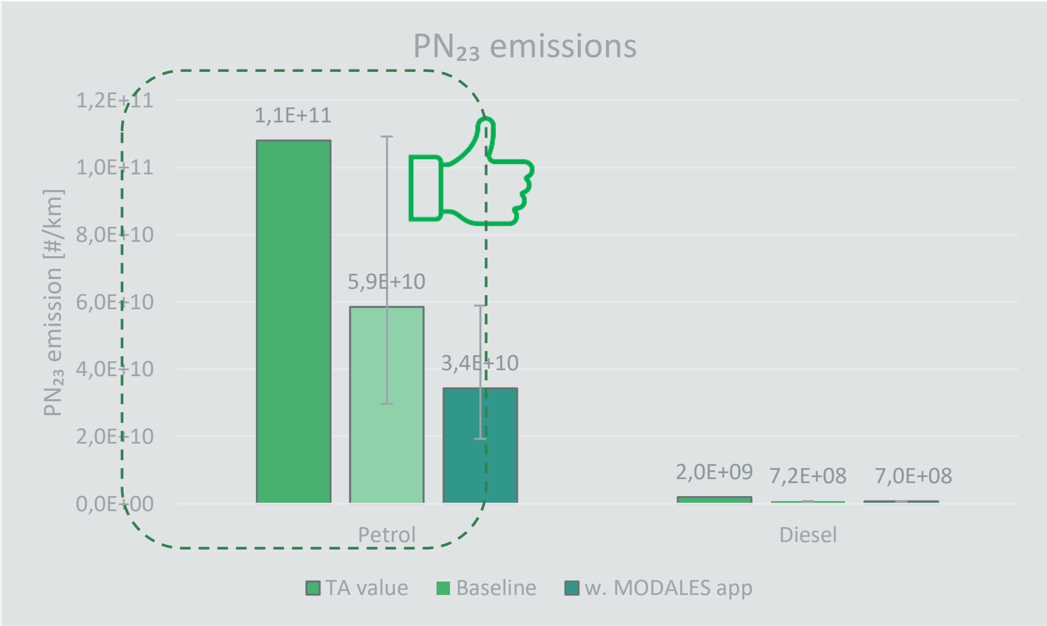


Figure 3.25: Average PN results from baseline and with MODALES application activated compared to the type-approval values

3.6.10 Analysis of the test results on a time-resolved level

This chapter describes the analysis of the test results on a time-resolved level. The time-resolved data is based on second-by-second data recorded by the PEMS device. To assure objective comparability, all individual tests were broken down to momentary data with respect to travelled distance throughout each test. This method allowed to analyse the results in more detail and enabled examination of the emissions response caused by the driver behaviour in different route sections and driving conditions. Furthermore, the time resolved results enabled to compare the change in actual, in situ driving behaviour between baseline (Phase 1) driving and driving with MODALES recommendations activated (Phase 2) for each individual driver.

3.6.10.1 Breakdown of momentary emissions – Petrol vehicle

The graphs presented in this chapter addresses solely recordings obtained with the petrol vehicle. This chapter contains all key findings and some examples of data related to driving behaviour with corresponding traces of tail-pipe emissions for certain drivers which represents most evidently main effect of the usage of the MODALES application and its recommendations.

Figure 3.26 illustrates the driving speed of each driver compared with the route speed throughout the test route. Deviation in vehicle speed traces between each driver were observed but were expected to be caused by differences in driving behaviour but also due to natural variation in traffic conditions, such as traffic lights, predominant traffic flow and other parameters that drivers are typically unable to influence. Because none of these factors could accurately be monitored, no clear connection between the driving speed and usage of MODALES application could be drawn.

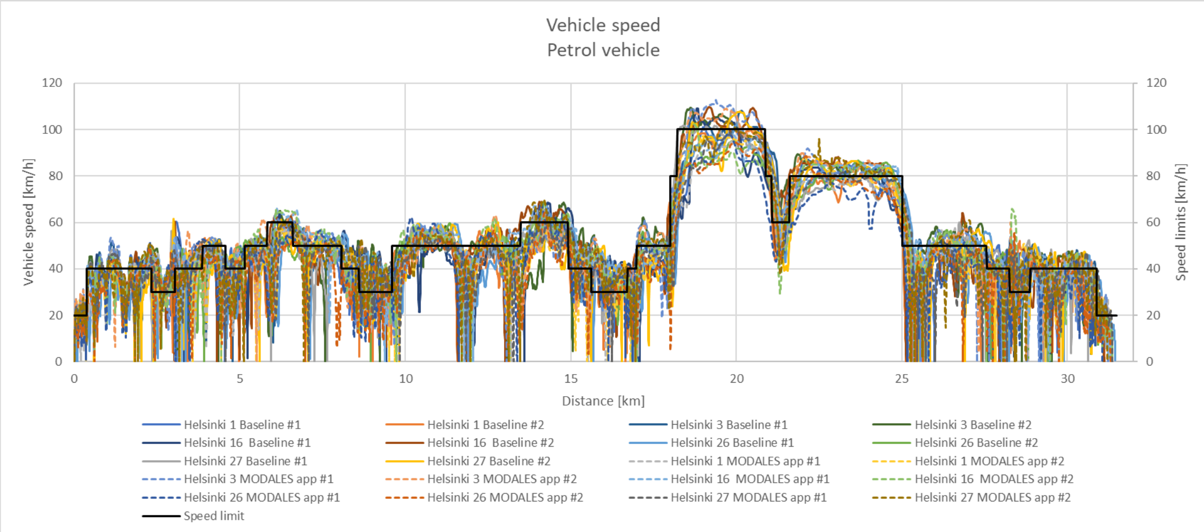


Figure 3.26: Momentary driving speed for each driver together with the speed limit profile of the MODALES test route

The instantaneous CO_2 emission data obtained for all drivers with the petrol vehicle are shown in Figure 3.27. The corresponding cumulative values are illustrated in Figure 3.28. The differences in the CO_2 trends between the results from the baseline tests and tests conducted with the MODALES recommendation activated were found minor, yet typically in favour of the cases where the MODALES recommendations were followed.

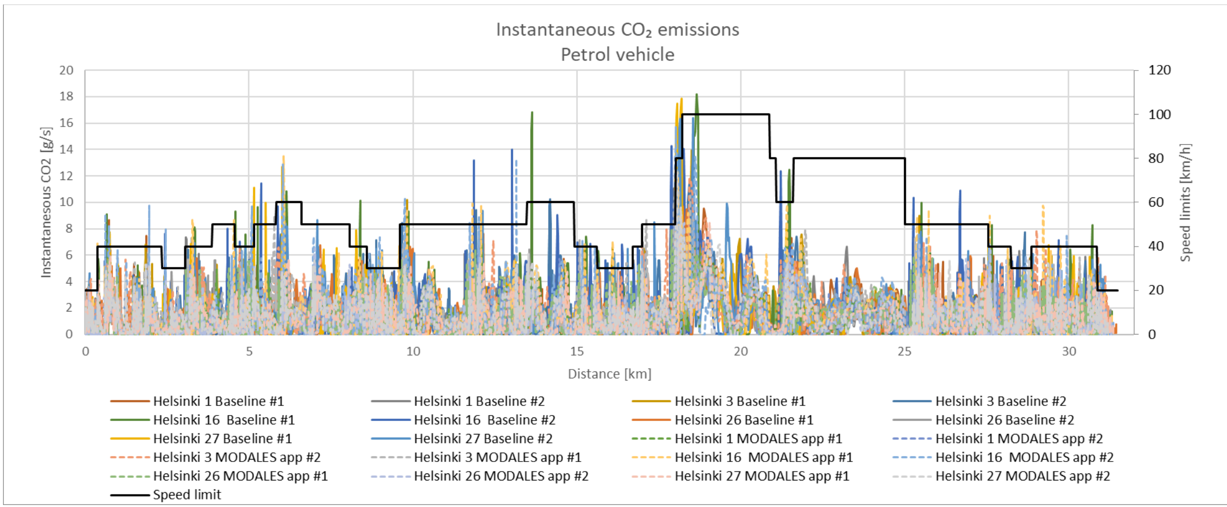


Figure 3.27: Momentary CO_2 emission data obtained with petrol vehicle and all drivers

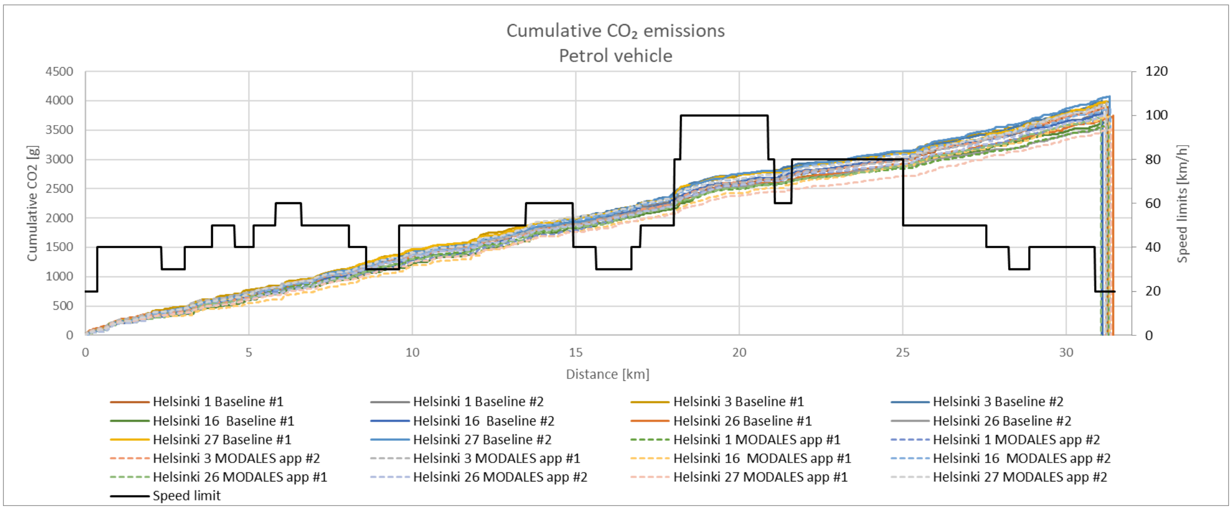


Figure 3.28: Cumulative CO_2 emissions for the petrol vehicle and all drivers

The momentary NOx emissions recorded for the petrol vehicle conducted by all test drivers are illustrated in Figure 3.29. Despite the petrol vehicle producing very low NOx emissions, randomly occurring sudden yet rapid peaks in NOx emissions were seen for both baseline tests and test within the tests conducted with the MODALES recommendations activated. No clear correlation nor any significant change in NOx behaviour could be identified from the instantaneous NOx emissions. To further evaluate the effect of driving behaviour (baseline vs MODALES application) on NOx emissions with the petrol vehicle, the results were analysed and compared as cumulative NOx emissions as shown in Figure 3.30. The traces of cumulative NOx emissions recorded from the baseline tests and for the results obtained with the MODALES recommendations followed were found generally overlapping such that no clear effect of improvements nor disadvantages from the MODALES-recommendations could be found.

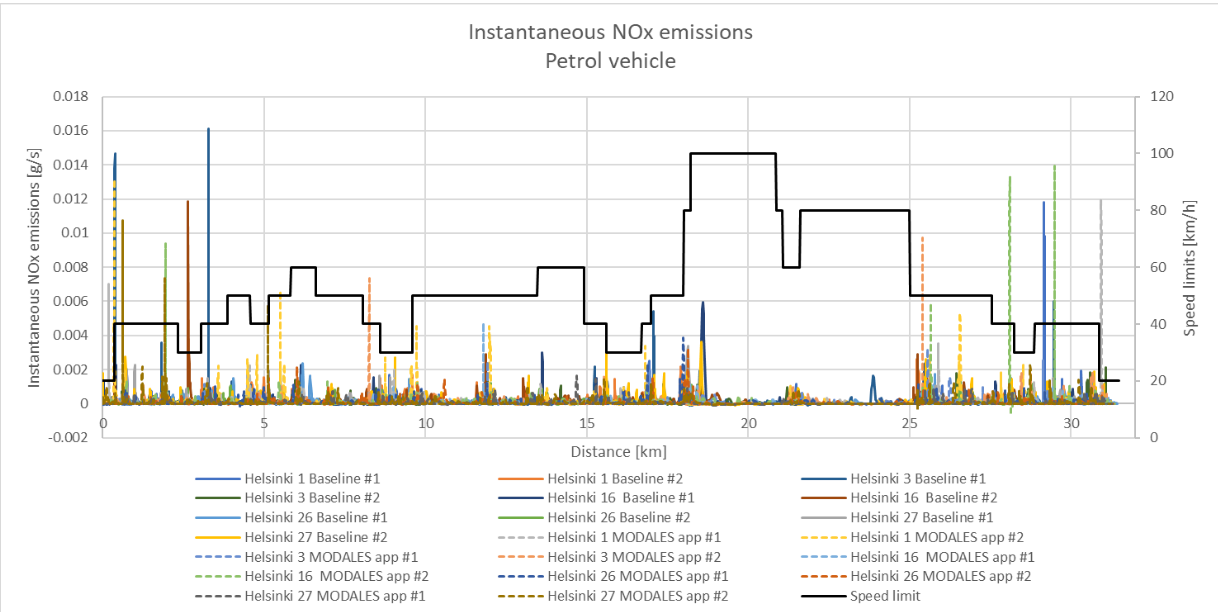


Figure 3.29: Instantaneous NOx emissions for each driver together with the speed limit profile of the MODALES test route

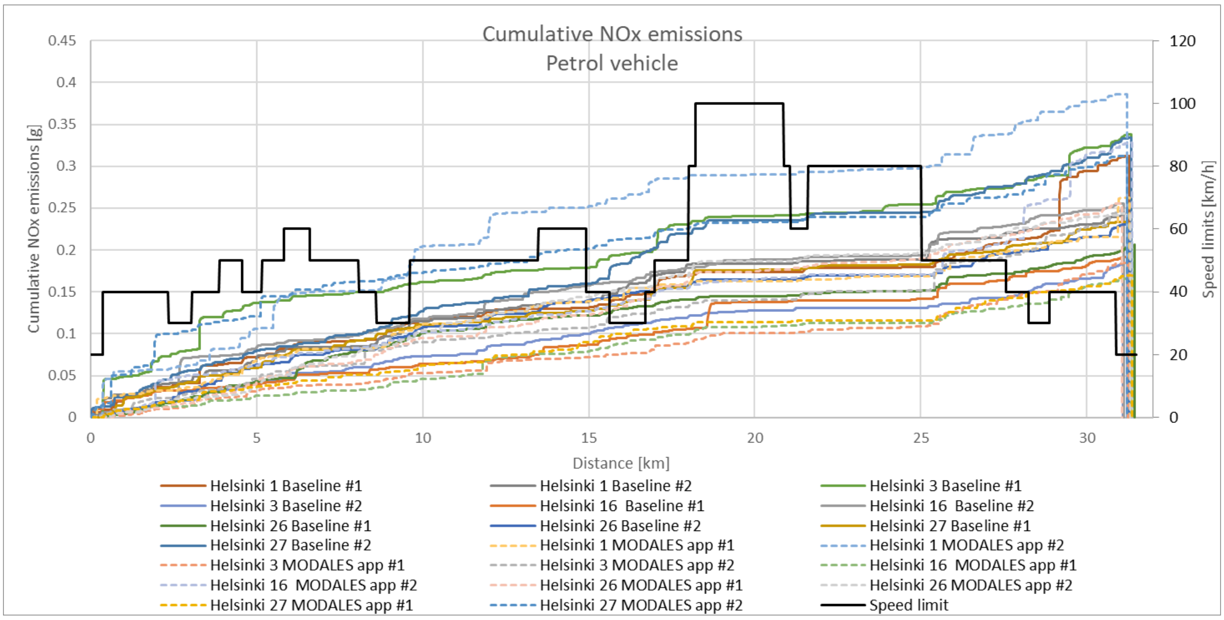


Figure 3.30: Cumulative NOx emissions for each driver together with the speed limit profile of the MODALES test route

Figure 3.31 illustrates the momentary PN_{23} emissions recorded from all drivers. Opposite to the conclusions made from NOx recordings, the PN traces included more distinguishable, high-emitting events for road sections where most of the PN emissions were emitted (indicated as green dotted lines in Figure 3.31). Based on instantaneous data, most of the high emitting peaks occurred during or within road sections where junctions, traffic lights or intersections were present in combination of a rapid increase in the speed limit. Similarly, the traces of cumulative PN emissions shown in Figure 3.32 indicate that the PN emissions increase as steps throughout the complete trip during sections where there is an increase in speed limit. The cumulative PN emission increase throughout each trip typically relatively mildly, yet the slope was found overall somewhat milder for the cases with the MODALES recommendations followed. However, the most evident and significant increase in PN-emissions take place in the area where the intersection from the urban area connects to the high-speed motorway-section (marked in Figure 3.32 in red). In this area, the speed limit increase from 50 km/h to 80km/h and then to 100 km/h virtually instantly.

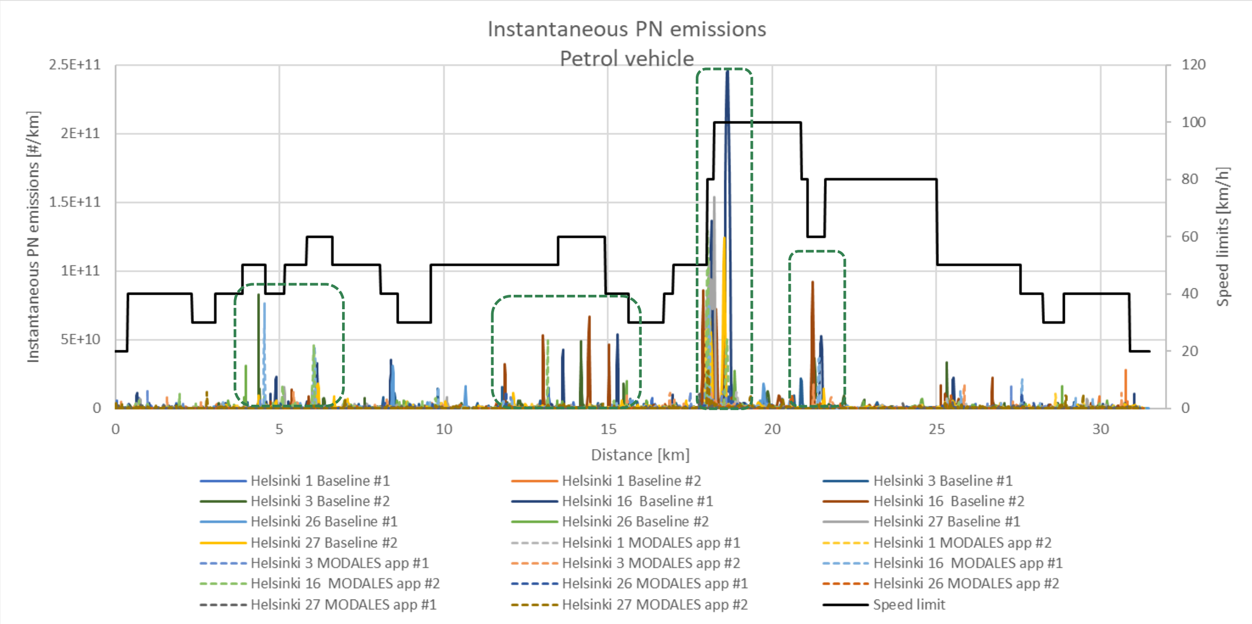


Figure 3.31: Instantaneous PN_{23} emissions of the petrol vehicle for each driver together with the speed limit profile of the MODALES test route

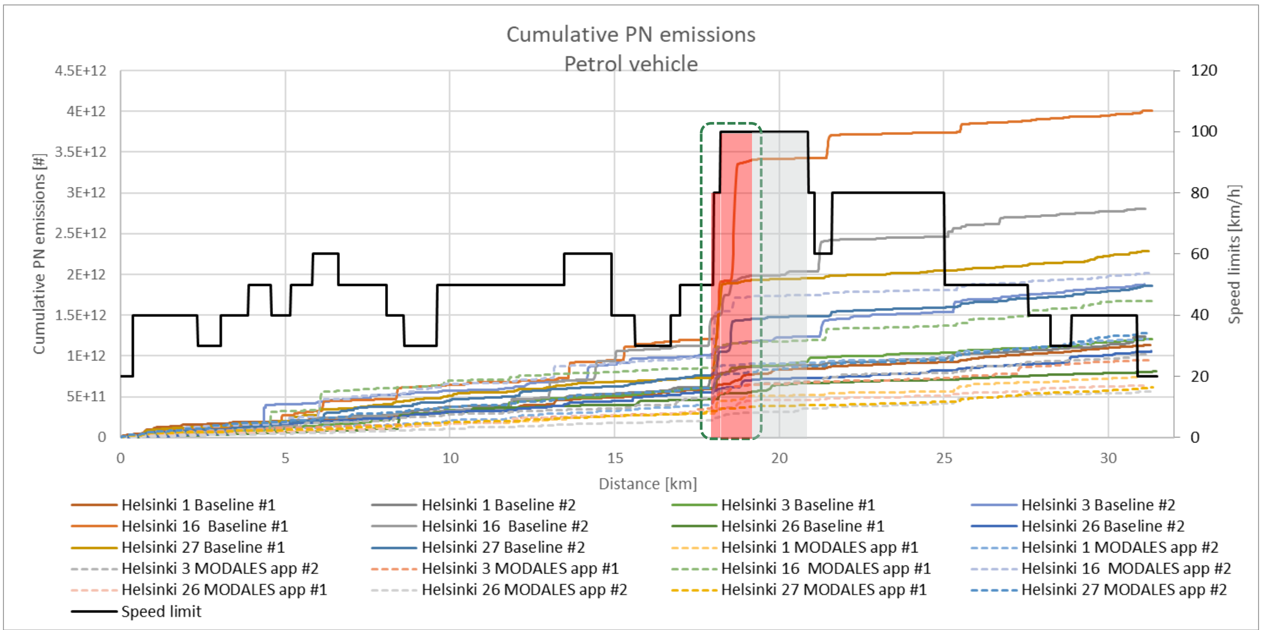


Figure 3.32: Cumulative PN_{23} emissions of the petrol vehicle for each driver together with the speed limit profile of the MODALES test route

By further examining the junction entering the motorway, highest fractions of PN-emissions were generally generated during the baseline tests, meanwhile the corresponding peaks were typically milder when using the MODALES recommendations (as shown in Figure 3.33). When the data was further analysed, a relation between PN-emissions and instantaneous engine power was found. Examples of usage of engine power are shown Helsinki 16 in Figure 3.34 and for Helsinki 27 in Figure 3.35. The graphs include one example for a baseline test and a corresponding example for tests conducted with the MODALES recommendations followed. Prior to the junction, the usage of power is relatively comparable between baseline and when using the MODALES recommendations. However, this was not the case when accelerating from the urban area to the motorway, as both drivers accelerate, and thus utilize significantly more power during the baseline tests. This yet again is reflected to the driving parameter va_pos, shown in Figure 3.36, explaining the positive trajectory found as a commonly connected, yet improved parameter as described in the previous chapter (2.6.9).

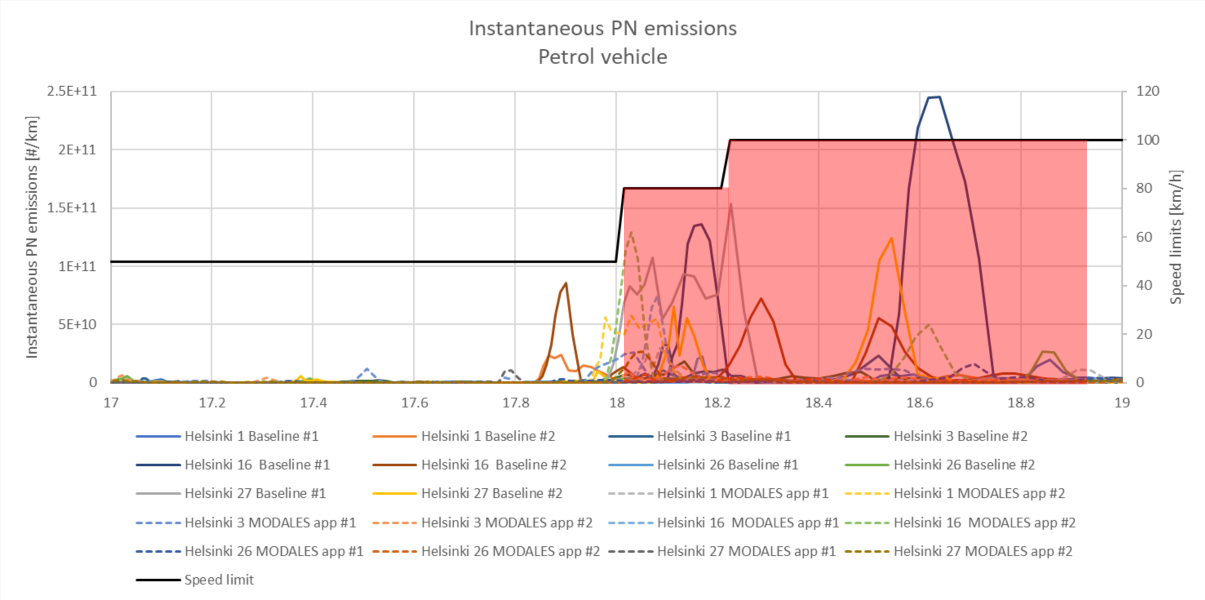


Figure 3.33: Instantaneous PN_{23} emissions of the petrol vehicle around the junction from an unrban area to a motorway section

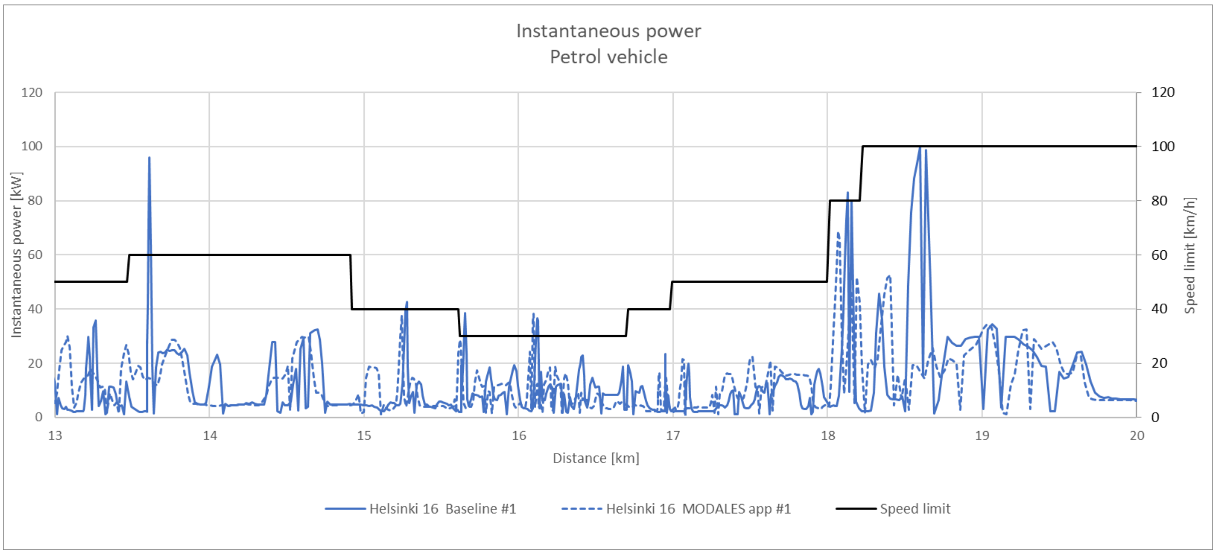


Figure 3.34: Instantaneous engine power of the petrol vehicle for a baseline test and a test with MODALES recommendations activated for driver: Helsinki 16

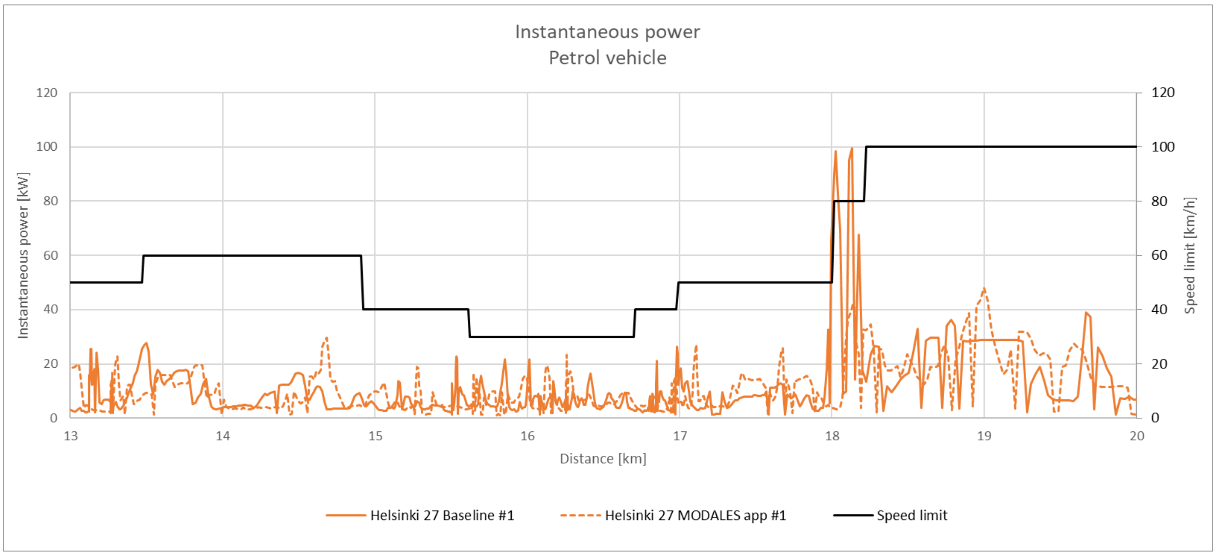


Figure 3.35: Instantaneous engine power of the petrol vehicle for Helsinki 27 compared over a baseline test and a test with MODALES recommendations activated

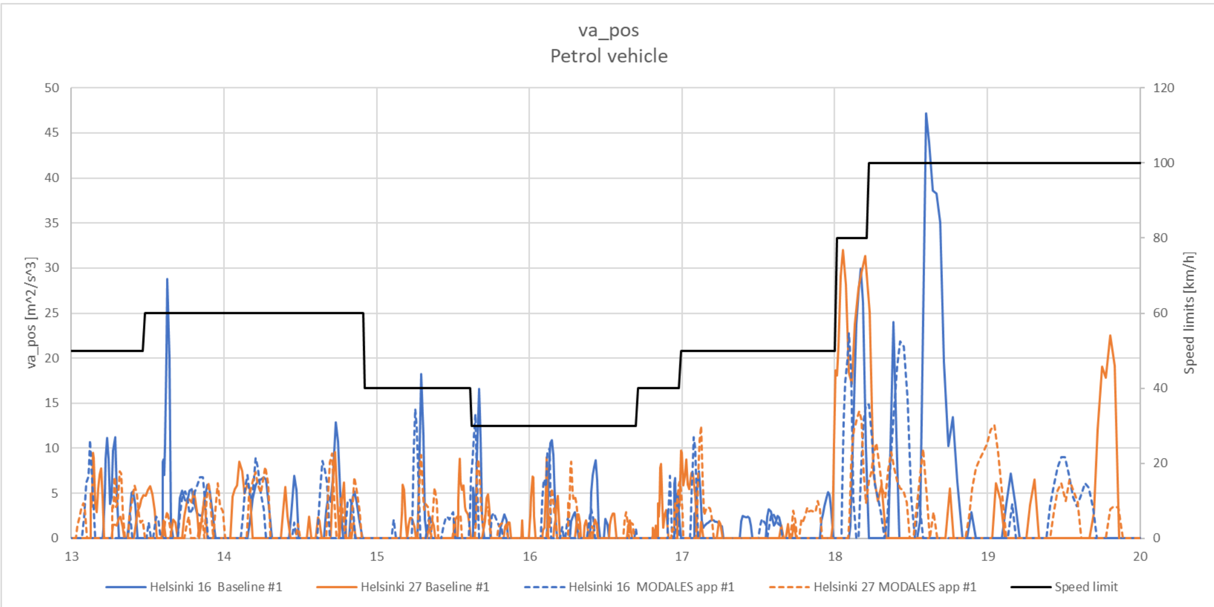


Figure 3.36: v*a positive- values compared for the petrol vehicle compared with two drivers: Helsinki 16 and Helsinki 27, baseline vs with MODALES recommendations activated

3.6.10.2 Breakdown of momentary emissions – Diesel vehicle

An identical, second-by-second based analysis was performed for the diesel vehicle as described for the petrol vehicle in the previous chapter. The driving speeds for each test with the diesel vehicle is shown in Figure 3.37. The vehicle speed traces were relatively like the petrol tests, and thus no abnormal deviations or inconsistencies were noted.

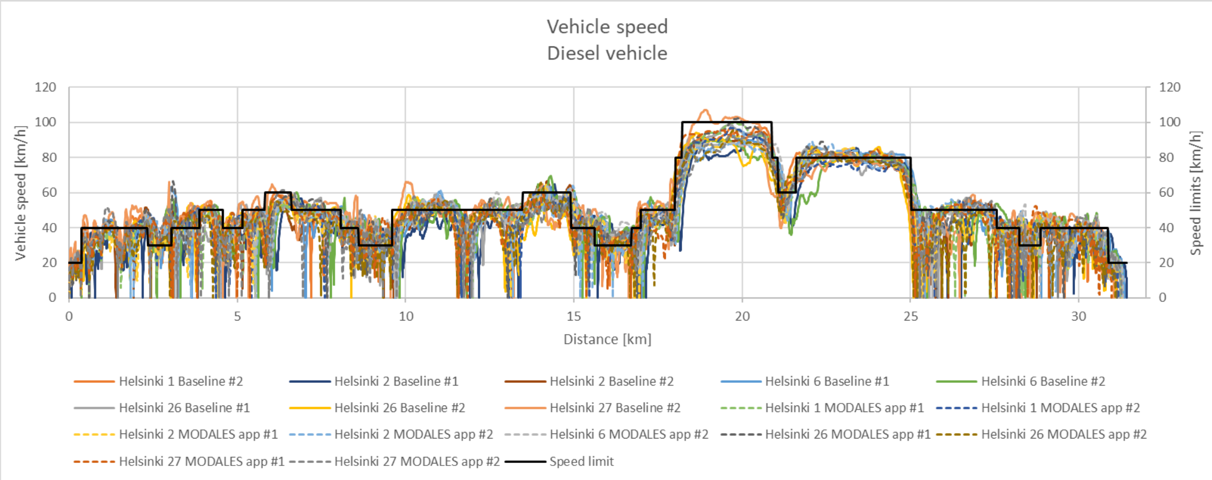


Figure 3.37: Momentary driving speed for the diesel vehicle and for each driver together with the speed limit profile of the MODALES test route

The instantaneous CO_2 emission data obtained for all drivers with the diesel vehicle are presented in Figure 3.38 with the corresponding cumulative values are illustrated in Figure 3.39. Contrary to the petrol vehicle, a more distinguishable change in CO_2 emissions could be noted between the baseline tests and the results recorded with the MODALES recommendations activated. The cumulative trends are more distinctively split between baseline tests and for the Phase 2 tests. This was also noted in the average results described in chapter 2.6.9, because all drivers managed to improve their average CO_2 results by following the MODALES recommendations.

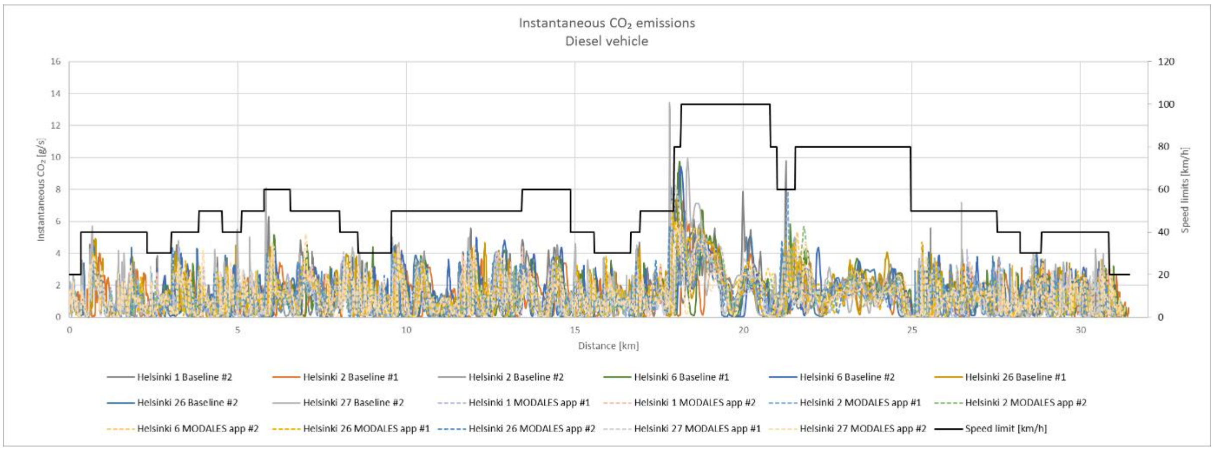


Figure 3.38: Momentary CO_2 emission data obtained with diesel vehicle and all drivers

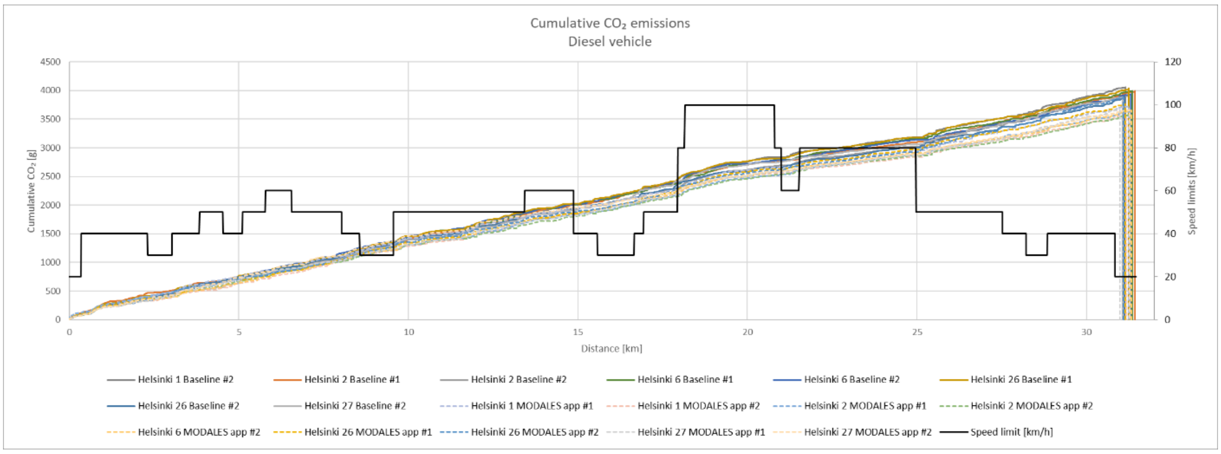


Figure 3.39: Cumulative CO_2 emissions for the diesel vehicle and all drivers

Contrary to the petrol vehicle, the exhaust PN_{23} emissions caused by the diesel car were remarkably lower yet producing arbitrary peaks throughout the trips both during the baseline test and for tests where the MODALES recommendations were followed (Figure 3.40). No clear benefits or penalties regarding PN emissions could be distinguished for the diesel vehicle from using the MODALES recommendations. However, similarly to the patterns found with PN emissions for the petrol vehicle, certain road sections that caused concentrated emission peaks could be distinguished for the diesel vehicles NOx emissions. This applies especially for the road section with the junction entering the motorway caused most of the local emissions, as indicated as dotted lines in Figure 3.41. The NOx emissions were comparably largest during the acceleration events through the junction entering the motorway and caused typically most rapid increase in the momentary NOx data.

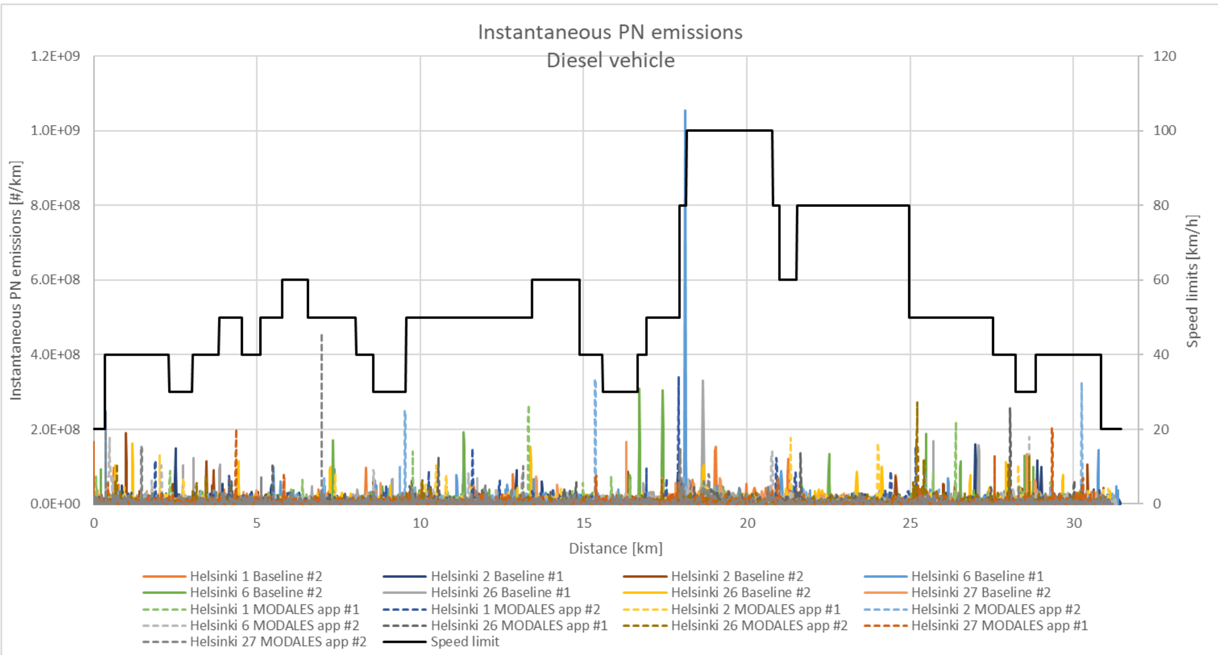


Figure 3.40: Instantaneous PN_{23} emissions for the diesel vehicle and all drivers displayed together with the speed limit profile of the MODALES test route

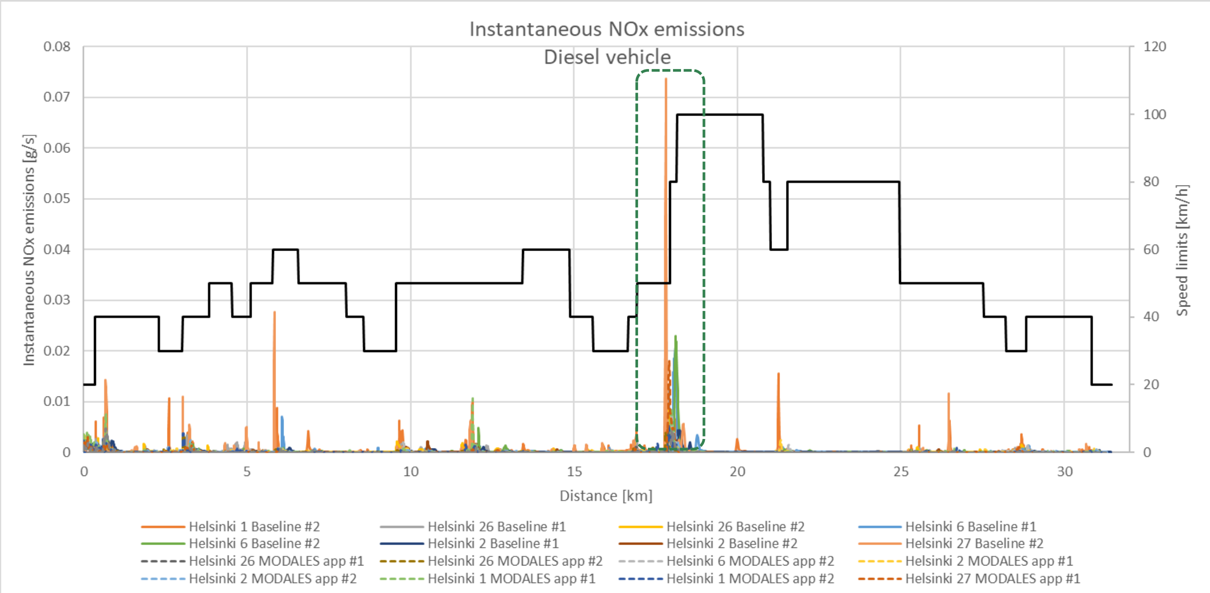


Figure 3.41: Instantaneous NOx emissions for the diesel vehicle and all drivers displayed together with the speed limit profile of the MODALES test route

The traces of cumulative the NOx emissions recorded for the diesel vehicle are portrayed in Figure 3.42. The cumulative NOx emissions were found stacked in two overlapping groups: lowest values were generally achieved with by using the MODALES recommendations, followed by the results obtained from the baseline tests. The most aggressive NOx profiles were found for Helsinki 27 baseline tests, which were separated from results obtained from any driver. Yet, all cumulative trends indicated that the most significant increase occurred during accelerations, especially in the region of the junction connecting to the motorway section as highlighted with dotted lines in Figure 3.42.

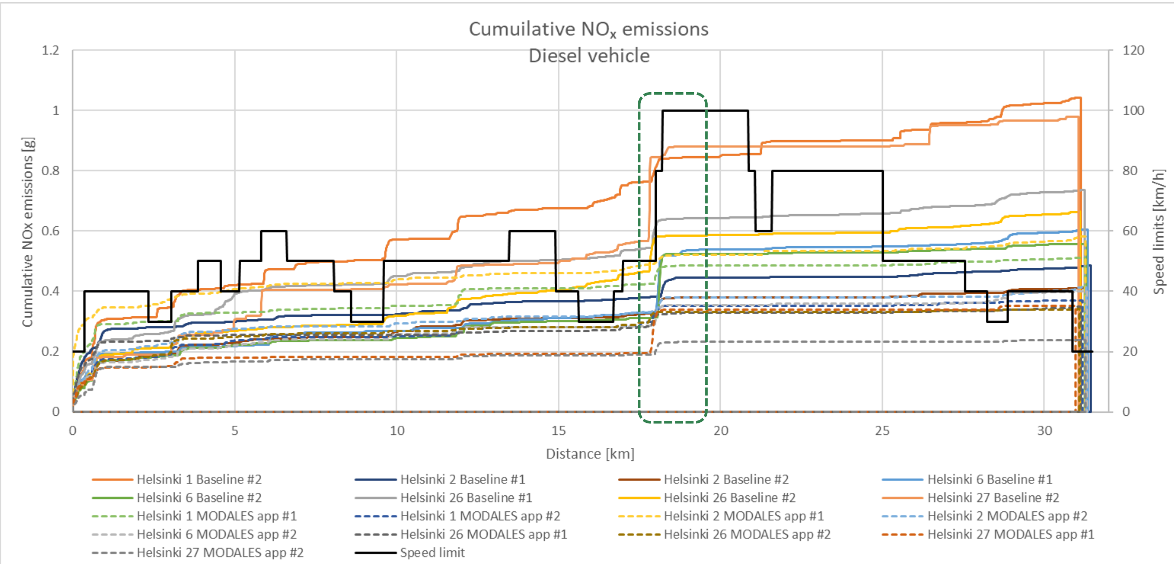


Figure 3.42: Cumulative NOx emissions for the diesel vehicle

By further studying the momentary NOx emissions produced during trips in the junction from urban to motorway, the NOx profiles were significantly milder for the cases where the drivers followed the MODALES recommendations. As an example, the peak NOx emissions in the were over 3 times higher for Helsinki 16 baseline tests compared to Phase 2 tests as shown in Figure 3.43. The main reason behind this phenomenon is, similarly to the petrol vehicle, usage of engine power, illustrated in Figure 3.44. Despite the overall engine power is somewhat similar, the usage of engine power was with the MODALES recommendations activated less aggressive, more smooth, resulting in less sharp peaks. Correspondingly this reflected directly to a lower v*a positive value as shown in Figure 3.45.

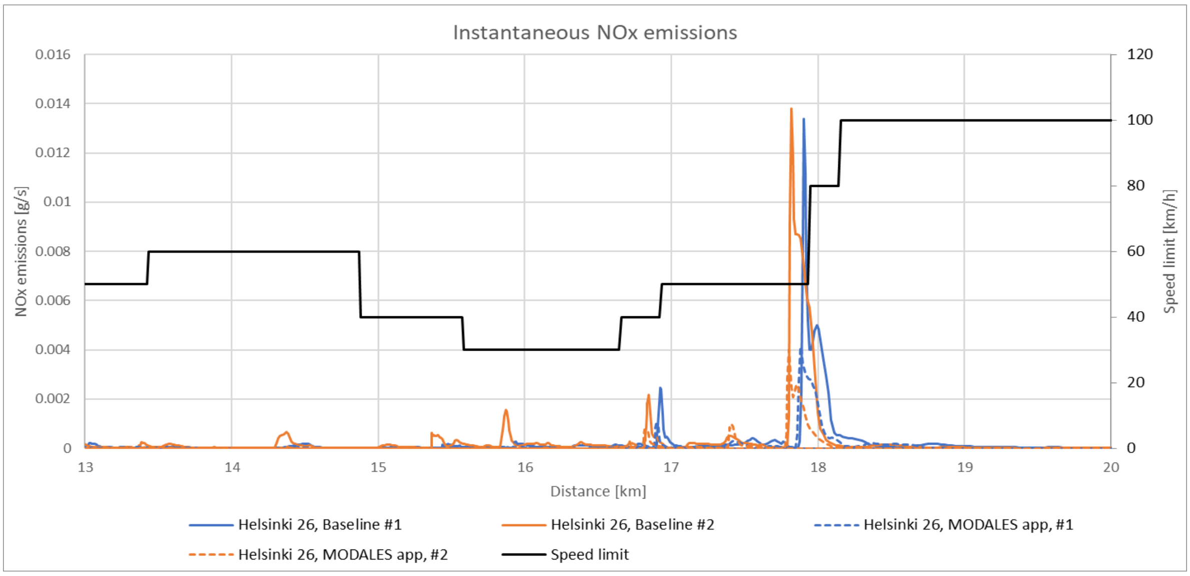


Figure 3.43: Instantaneous NOx emissions for Helsinki 16 (Phase 1 and Phase 2) before and over the junction entering the motorway section. The junction starts just before 17 km of the total trip.

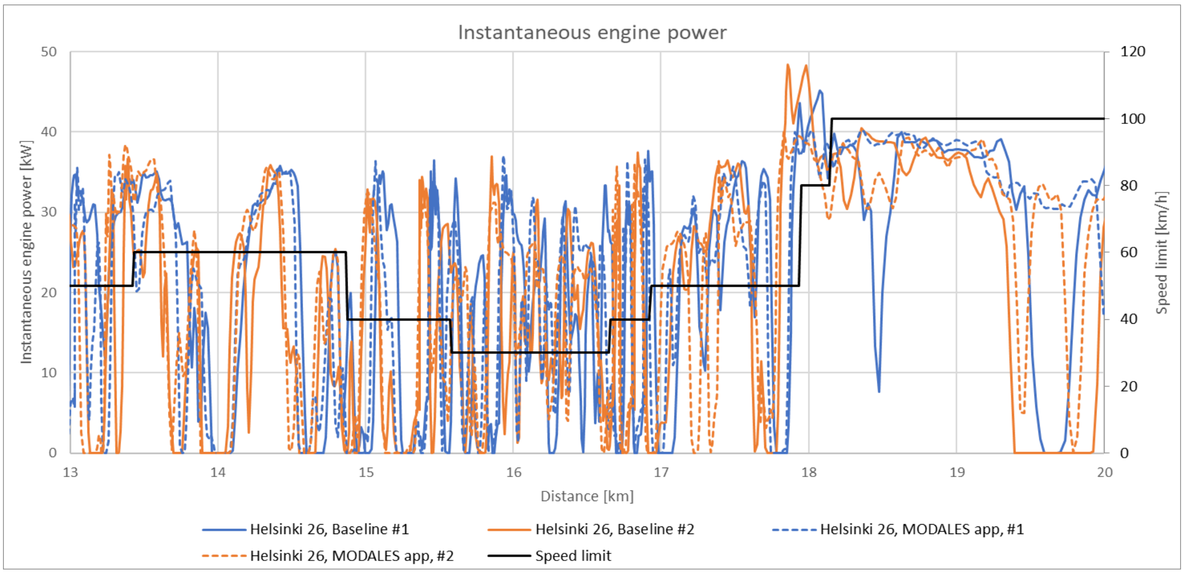


Figure 3.44: Instantaneous engine power for driver Helsinki 26, baseline vs. utilisation of the MODALES recommendations

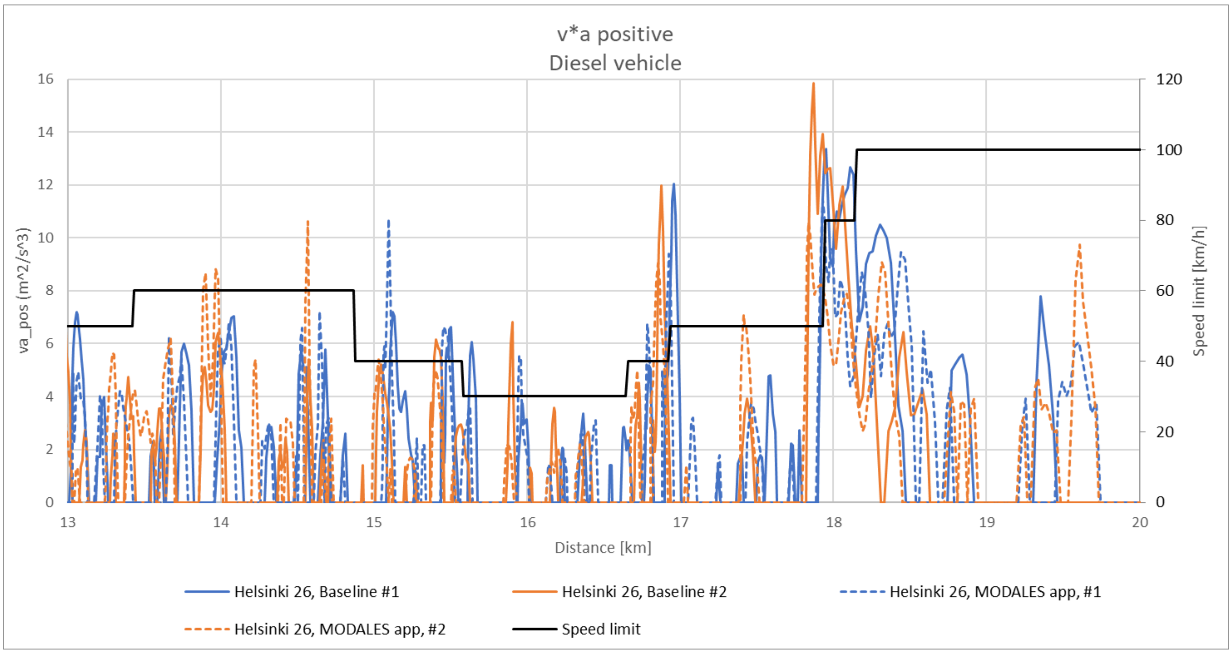


Figure 3.45: An example of recorded v*a positive- values from four tests of one driver conducted with the diesel vehicle: Helsinki 26, baseline vs with MODALES recommendations activated

3.6.11 Data validity and common uncertainties

Because the data obtained from the PEMS tests were conducted in real world conditions, some factors potentially contributing with uncertainties could not be completely controlled. First, the effect of varying conditions such as predominant traffic flow and ambient temperatures may potentially influence the bias the results for single drivers. Secondly, the limited samples of the PEMS tests (two tests per driver/car and phase, i.e. 10 tests per configuration and 40 tests in total) may be somewhat insufficient from a statistical point of view.

Because the aim of this study was solely to experimentally evaluate and validate the net effects from using the MODALES application, no emphasis related to psychological effects was accounted for in this study. Because of this, the absolute net gains from the usage of the MODALES application and its recommendations can be concluded without considering the fact that the drivers were aware of the monitoring or that changes in driving behaviour may be influenced by the uncontrolled conditions. The results presented in this chapter should therefore be treated solely as indicative trends, not as absolute values. The conclusions withdrawn from the tests are in any case proof of certain main phenomenon and could be used as validation for the trial site monitoring.

3.6.12 Summary and conclusions from the PEMS tests

The experimentally produced results presented in this chapter indicated that by using the MODALES application, evident benefits in terms of both exhaust emissions and thus in fuel economy may be obtained. Yet, the results point out that the magnitude of effect is depends on a how well an individual driver performs to begin with. Well performing drivers have less potential for improvements, while drivers producing more emissions have a greater gap to improve. Another factor found affecting the achievable gain is how well the driver may be able to adopt and apply the recommendation provided by the MODALES application. Because of these factors, relatively great driver-to-driver variation was seen, and most gains were typically obtained for drivers with most emitting baseline behaviour and vice versa.

The dominant factor for the improvements obtained in terms of tail-pipe emissions were because the MODALES application promotes driving smoothness, which results in less aggressive accelerations and fluctuating driving events. This decreased the usage of engine power especially during the most rapid accelerations, hence suppressing the peaks in exhaust pollutants. Despite the driver behaviour was smoother, no significant gains nor penalties in trip time or average speed over the total driver test pool was found. Due to the differences in powertrain, fuel type and EATS, the net gains obtained for the two test vehicles were found different. Because the petrol vehicle was equipped with a TWC but lacked a GPF, the net effect on NOx emissions were virtually non-existent, simultaneously as a reduction on 45% in PN emissions were achieved. Correspondingly, due to the EATS of the diesel vehicle, including SCR and a DPF, gains obtained in PN emissions were found insignificant, meanwhile an average NOx reduction of 47% was noted. Both vehicles produced very small CO emissions to begin with, but despite that, improvements were generally observed. The impact on fuel CO_2 (and fuel economy) was between -8% to +2% for the petrol vehicle, with an average gain of ca. 2%. The corresponding gains for the diesel vehicle were between -2% to –+10%, with and average improvement of ca. 7% over the total driver test pool.

The results described above should be considered as proof of concept which successfully validates the benefits and potential gained from the MODALES application. Because the MODALES application was experimentally tested with only two vehicles and a limited number of test drivers, the results should be considered indicative. The net effect may vary case by case depending on driver, vehicle and the predominant circumstances.

3.7 Summary for exhaust emissions

In this chapter, the differential influences of driving behaviour, such as road types, individual drivers, driver gender, and driving experience, were evaluated on NOx emissions in seven European cities. The main conclusions can be summarised as follows:

- Low-emission driving training programmes have shown the potential to contribute to reductions in mean values of NOx emissions in most of the seven European cities evaluated, with Thessaloniki and Istanbul being exceptions.
- Individual drivers displayed variations in their impact on NOx emissions. Nevertheless, the training proved to be effective in reducing NOx emissions for the majority of participants across all road types.
- The low-emission driving training and app successfully decreased NOx emissions for both female and male drivers. However, female drivers experienced more significant reductions compared to their male counterparts.
- Most novice and experienced drivers experienced a reduction in NOx emissions after participating in the low-emission driving training.

4 Differential influences of driving behaviour on brake wear emissions

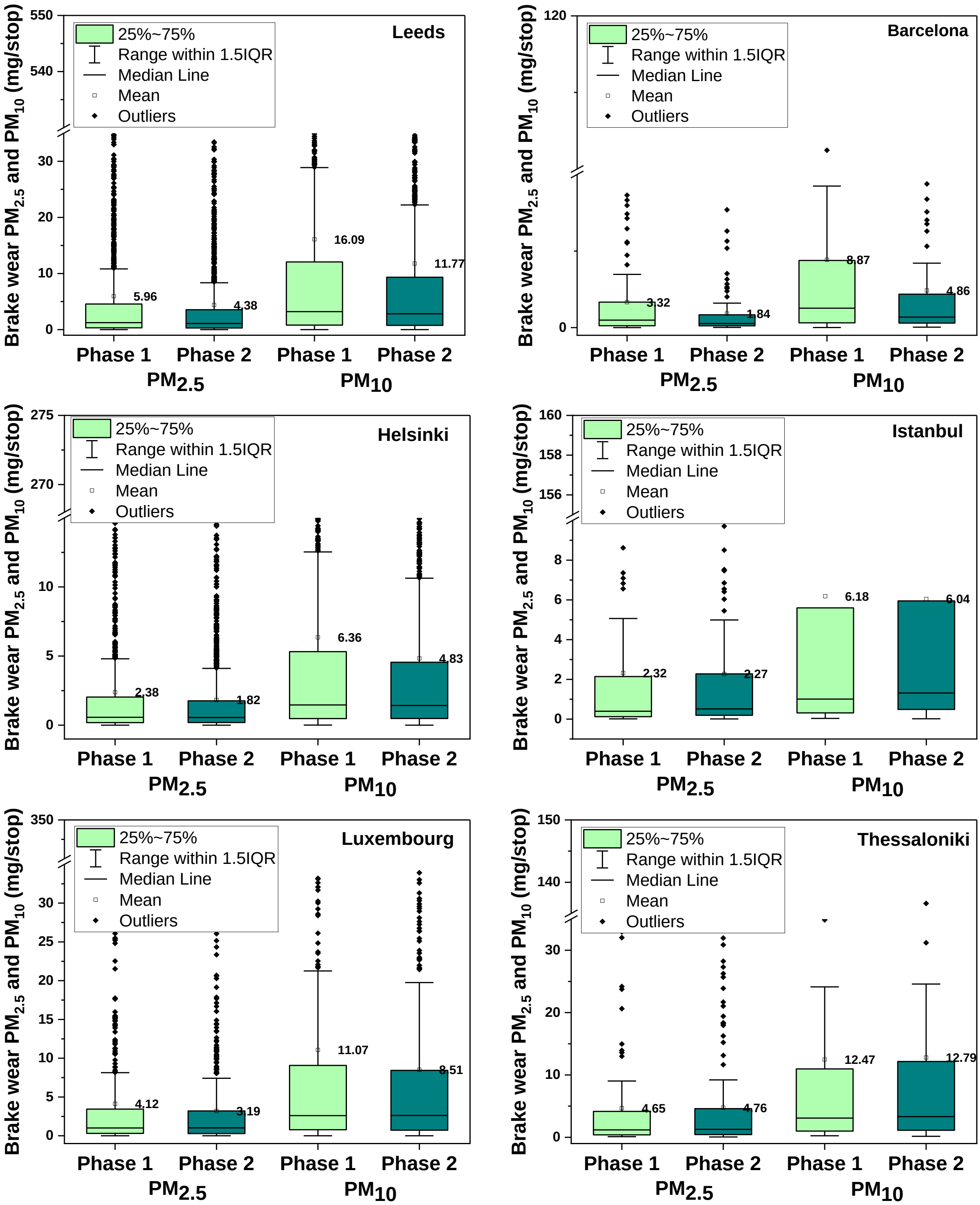
Brake wear emissions have gained significant attention in recent years as a major contributor to air pollution (Liu et al., 2022b; Straffelini and Gialanella, 2021). Brake wear emissions, composed of PM and toxic metals, are released into the atmosphere during vehicle operation and can have adverse effects on both the environment and public health (Gasser et al., 2009; Gerlofs-Nijland et al., 2019). This chapter aims to explore deeper into the specific influences of driving behaviour, taking into account various factors such as road types, individual drivers, driver gender, and driver experience.

One crucial aspect is the impact of road types on brake wear emissions. Different road conditions, such as urban, rural, and motorway roads, impose distinct demands on the braking system, potentially leading to variations in brake wear emissions. By examining the differential influences of driving behaviour on brake wear emissions across different road types, we aim to provide insights into effective driving strategies tailored to specific driving environments. Moreover, how individual drivers can contribute to variations in brake wear emissions was evaluated. Understanding these differential influences allows us to identify specific areas where driver education and awareness programmes can be implemented to effectively reduce brake wear emissions. Finally, the influence of driver gender and experience on brake wear emissions was assessed, which can provide insights into the importance of driver training and the potential for reducing emissions through improved driver education.

4.1 Overall results for brake wear emissions

The box figure in this present work illustrates the comparison of brake wear $PM_{2.5}$ and PM_{10} emissions before and after low-emission driver training at various sites. In the box figure, each box represents the distribution of data for a specific site. The boxes typically span from the lower quartile (Q1) to the upper quartile (Q3) of the data, suggesting the range within which most of the data points fall. The horizontal line inside the box represents the median emission level and a square symbol is used to represent the mean emission level for each site. The changes in brake wear $PM_{2.5}$ and PM_{10} emissions were assessed by comparing the median and mean emission levels before and after the training and use of the app.

It can be seen from Figure 5.1 that there was a general declining trend in brake wear $PM_{2.5}$ and PM_{10} among the seven cities located in various countries across Europe. On average, emissions levels decreased after the training and app usage, demonstrating their positive impact on reducing brake wear emissions in these cities, except for Thessaloniki. In Leeds, the mean values of brake wear $PM_{2.5}$ and PM_{10} were reduced by 26.5% and 26.8%, respectively. Helsinki witnessed reductions of 23.5% and 24.1% for brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. Barcelona experienced substantial improvements with reductions of 44.6% and 45.2% in brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. Luxembourg showcased decreases of 22.6% and 23.1% in brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. Istanbul, on the other hand, exhibited slight reductions of 2.2% and 23.1% in brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. Meanwhile, Bergamo demonstrated noteworthy improvements with reductions of 30.1% and 30.3% in brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. However, there was a slight increase of 2.4% and 2.6% observed in the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. Among the studied cities, it can be concluded that Barcelona exhibited the most significant improvements in brake wear $PM_{2.5}$ and PM_{10} emissions, decreasing 44.6% and 45.2% in brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. It means that the implementation of low-emission driver training contributes to a more sustainable and healthier environment.



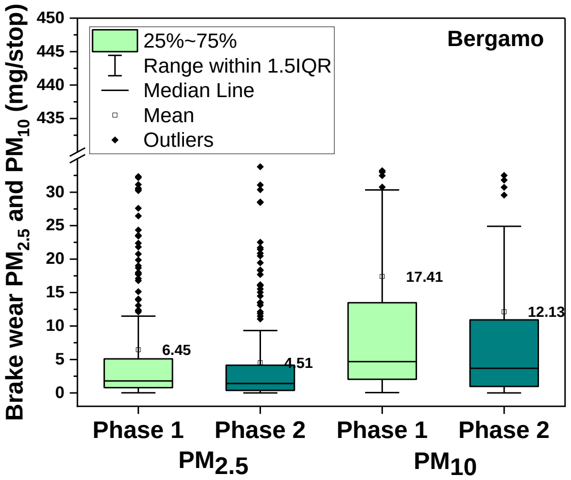


Figure 4.1: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by trial sites.

4.2 Effect of road types

The impact of different road types on braking can vary significantly, leading to variations in brake wear emissions. Generally, urban roads have frequent intersections, traffic signals, and lower speed limits. The start-stop nature of city driving often requires more frequent braking, resulting in increased brake wear emissions. In addition, traffic congestion on urban roads may result in extended idling and frequent deceleration, which contributes to brake wear. Compared to urban areas, rural roads typically have lower traffic volumes and fewer intersections. Consequently, the frequency of braking events on rural roads is likely to be lower, potentially leading to reduced brake wear emissions. On motorway roads, there are higher speeds and fewer traffic stops. The reduced frequency of braking events may cause lower brake wear emissions. However, higher speeds can also lead to more intense braking when necessary, which in this case may increase brake wear emissions, especially ultrafine particles (zum Hagen et al., 2019).

Figure 4.2 shows brake wear $PM_{2.5}$ and PM_{10} emissions before and after low-emission driving training on different types of roads in Leeds. It can be seen that mean values of $PM_{2.5}$ and PM_{10} per stop on motorways in Leeds were the largest, followed by rural and urban roads. This observation may be ascribed to the fact that motorways often have higher average speeds compared to urban and rural roads, which resulted in more intense braking when necessary and thus contributed to increased brake wear emissions per stop (Mathissen et al., 2018). On urban roads in Leeds, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions reduced from 1.30 mg/stop and 3.41 mg/stop to 1.05 mg/stop and 2.74 mg/stop, respectively, after the implementation of the training. On rural roads in Leeds, the corresponding mean values lowered from 6.61 mg/stop and 14.57 mg/stop to 6.04 mg/stop and 13.35 mg/stop, respectively. On motorways, the corresponding mean values lowered from 18.25 mg/stop and 49.62 mg/stop to 10.68 mg/stop and 28.80 mg/stop, respectively.

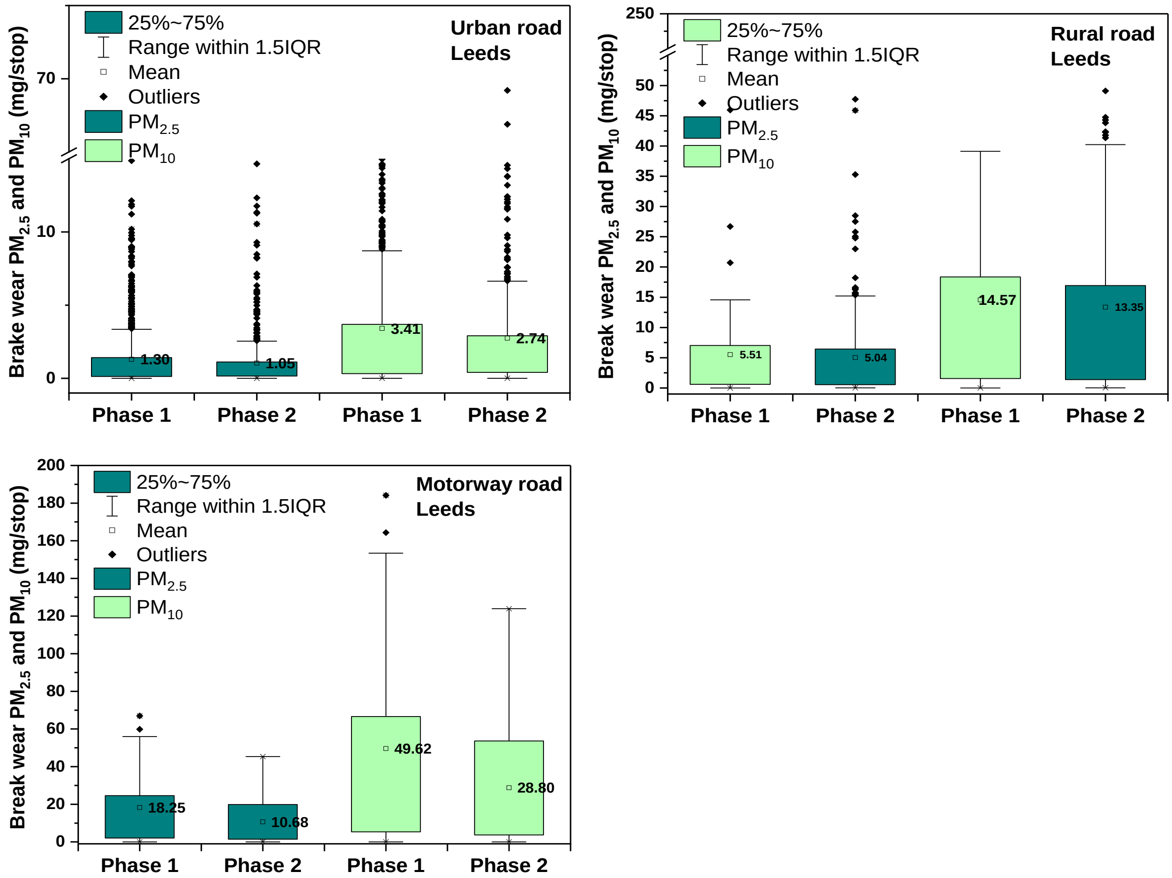
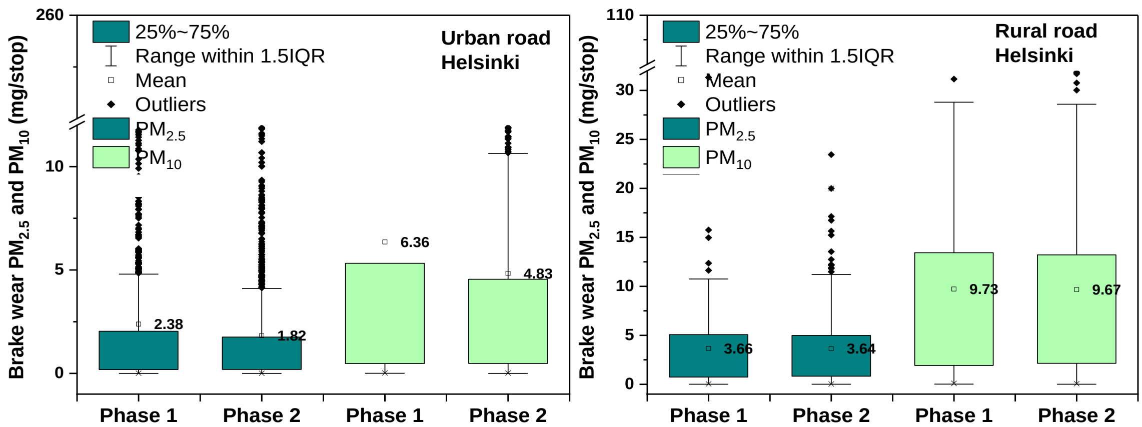


Figure 4.2: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Leeds.

Similarly, the emitted $PM_{2.5}$ and PM_{10} from brake wear per stop on motorway roads were the largest in Helsinki, followed by rural and urban roads, as evidenced by Figure 4.3. Following the low-emission driver training, significant reductions in brake wear $PM_{2.5}$ and PM_{10} emissions were observed on all types of roads in Helsinki. Specifically, the mean values of $PM_{2.5}$ emissions decreased from 2.38 mg/stop to 1.82 mg/stop, while the mean values of PM_{10} emissions decreased from 6.36 mg/stop to 4.83 mg/stop. On rural roads, the mean values of $PM_{2.5}$ and PM_{10} emissions declined slightly from 3.66 mg/stop to 3.64 mg/stop and from 9.73 mg/stop to 9.67 mg/stop, respectively. On motorways, the mean values of $PM_{2.5}$ and PM_{10} emissions reduced from 8.23 mg/stop to 4.08 mg/stop and from 22.18 mg/stop to 10.89 mg/stop, respectively.



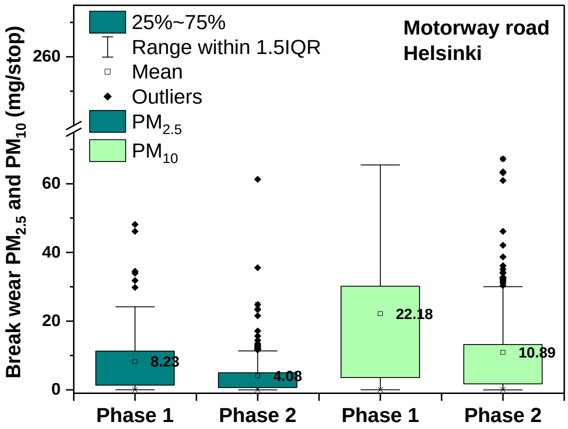


Figure 4.3: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Helsinki

In contrast to Leeds and Helsinki, from Figure 4.4, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions in Barcelona increased from 0.72 mg/stop to 0.94 mg/stop and 1.86 mg/stop to 2.47 mg/stop on urban roads, as well as from 1.44 mg/stop to 2.21 mg/stop and 3.76 mg/stop to 5.80 mg/stop on rural roads, after the training. However, the corresponding mean values on motorways reduced from 4.38 mg/stop to 2.39 mg/stop and 11.67 mg/stop to 8.32 mg/stop, respectively. Meanwhile, motorways in Helsinki exhibited the highest levels of emitted $PM_{2.5}$ and PM_{10} from brake wear per stop, with rural and urban roads following in decreasing order.

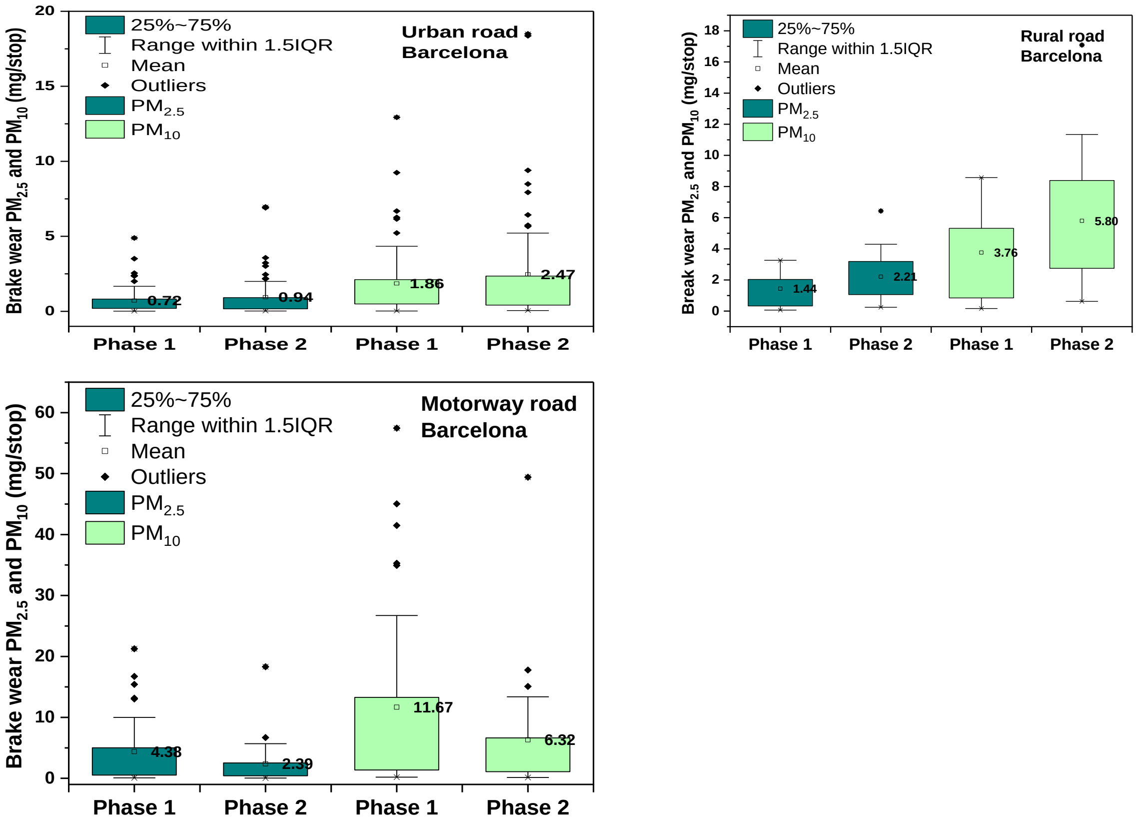


Figure 4.4: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Barcelona

In Luxembourg, regardless of brake wear $PM_{2.5}$ and PM_{10} emissions, motorways showed higher levels of emissions from brake wear per stop, compared to lower levels on rural and urban roads, as shown in Figure 4.5. Following the low-emission driver training, there was a decrease in brake wear emissions across all road types. More precisely, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions were reduced from 1.55 mg/stop to 0.99 mg/stop and 4.49 mg/stop to 2.58 mg/stop on urban roads, from 6.13 mg/stop to 5.56 mg/stop and 16.44 mg/stop to 14.86 mg/stop on rural roads, and from 10.52 mg/stop to 10.13 mg/stop and 25.58mg/stop to 27.23 mg/stop on motorways.

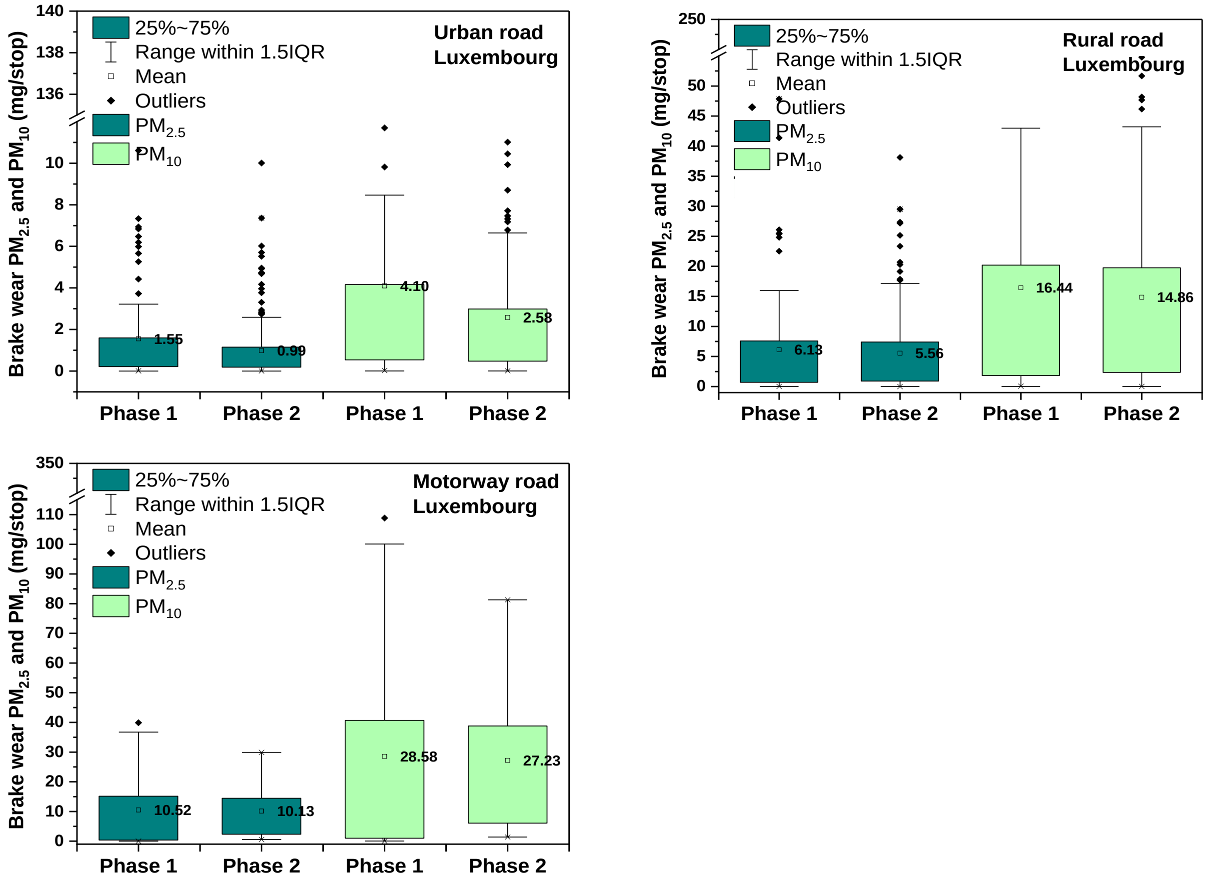


Figure 4.5: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Luxembourg

In Thessaloniki, slight reductions were observed from Figure 4.6 in the emitted $PM_{2.5}$ and PM_{10} emissions from brake wear across all road types. On urban roads, the mean values of $PM_{2.5}$ and PM_{10} decreased from 1.64 mg/stop to 1.61 mg/stop and 4.34 mg/stop to 4.24 mg/stop, respectively. On rural roads, the mean values of $PM_{2.5}$ and PM_{10} were observed from 6.13 mg/stop to 5.56 mg/stop and from 16.44 mg/stop to 14.86 mg/stop, respectively. On motorways, a decrease in mean values of $PM_{2.5}$ and PM_{10} was observed, with $PM_{2.5}$ emissions reducing from 6.13 mg/stop to 5.56 mg/stop, and PM_{10} emissions reducing from 16.44 mg/stop to 14.86 mg/stop.

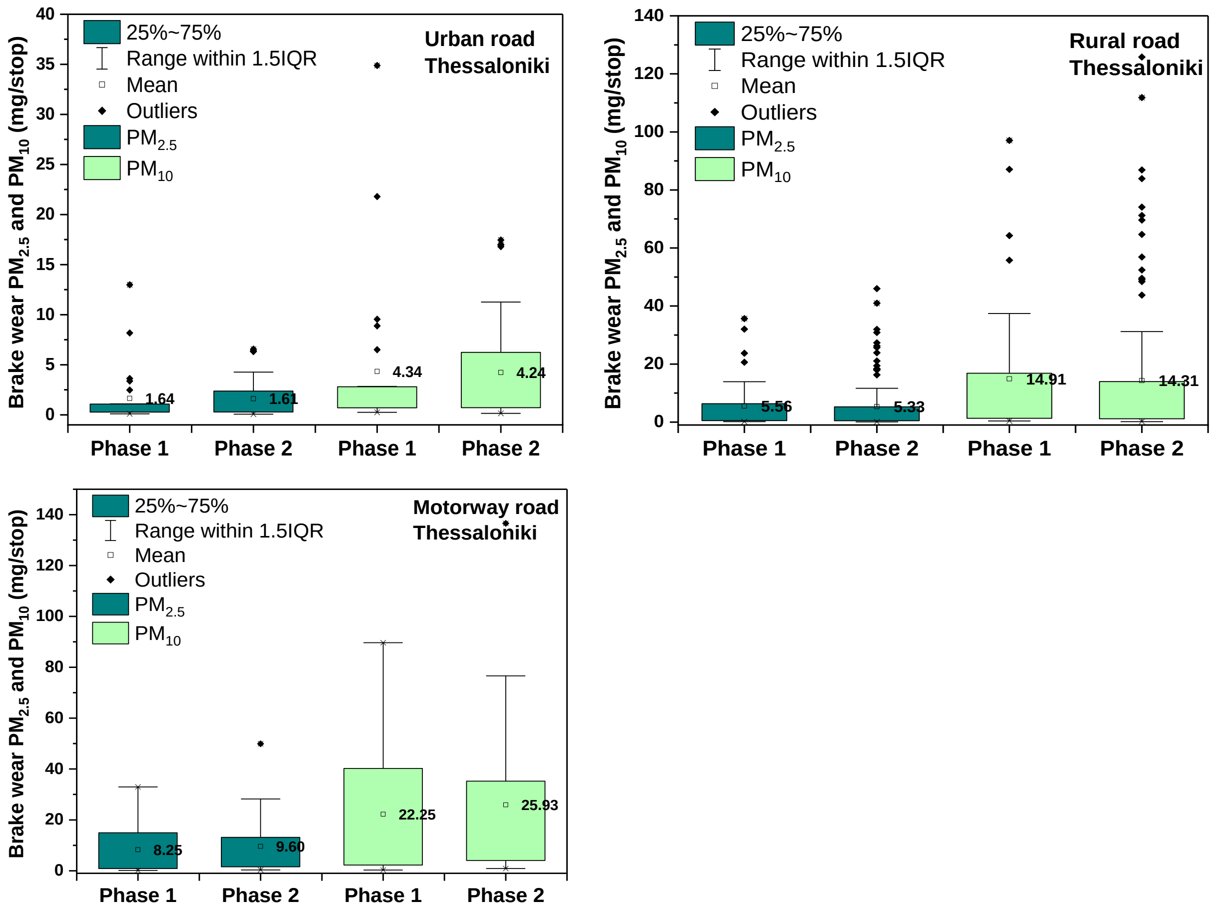


Figure 4.6: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Thessaloniki

Figure 4.7 presents $PM_{2.5}$ and PM_{10} emissions from brake wear before and after low-emission driver training on different types of roads in Istanbul. It can be observed that compared to other cities, $PM_{2.5}$ and PM_{10} emissions from brake wear were only available on urban roads and motorways due to no records of recruited participants on rural roads. Similarly, brake wear emissions decreased following the training. Specifically, the mean values regarding $PM_{2.5}$ and PM_{10} emissions from brake wear were reduced from 12.34 mg/stop to 2.31 mg/stop and from 6.25 mg/stop to 6.14 mg/stop, respectively, on urban roads. On motorways, corresponding $PM_{2.5}$ and PM_{10} mean values decreased from 2.11 mg/stop to 1.67 mg/stop and from 5.55 mg/stop to 4.67 mg/stop. In addition, unlike other cities, the brake wear emissions from motorways were lower than those from urban roads.

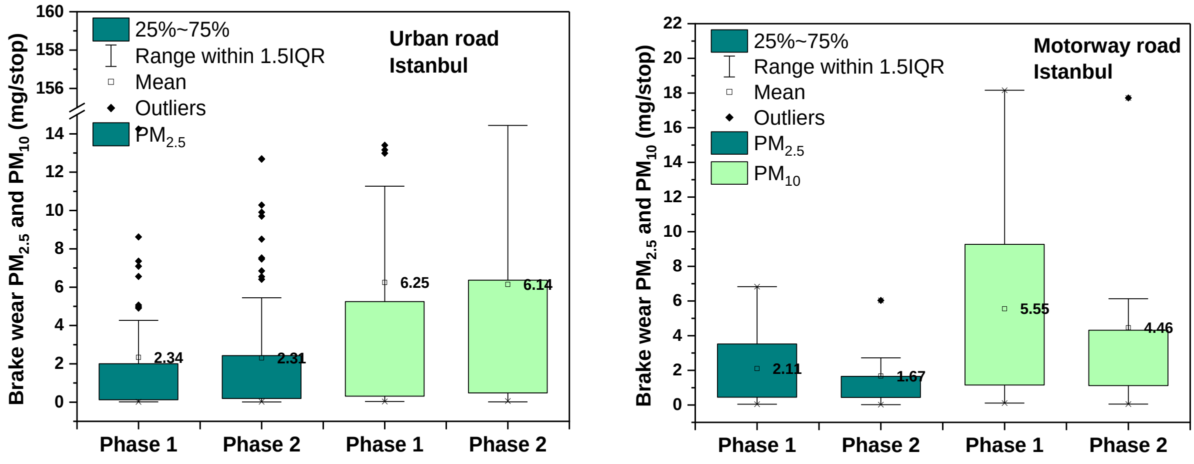
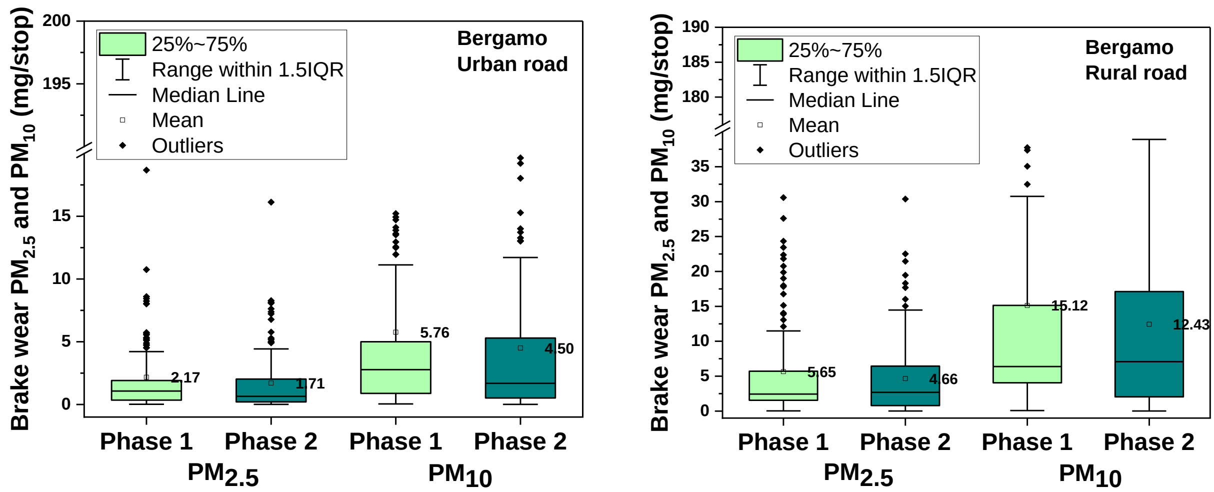


Figure 4.7: Before and after brake wear $PM_{2.5}$ and PM_{10} emissions by road types in Istanbul

In Bergamo, the brake wear $PM_{2.5}$ and PM_{10} emissions on motorways in Figure 4.8 were significantly higher than those on urban and rural roads, with approximately 5 times higher emissions on rural roads and 13 times higher emissions on motorway roads. Moreover, brake wear emissions were decreased after the implementation of the training. More precisely, the mean values regarding $PM_{2.5}$ and PM_{10} emissions from brake wear were reduced on urban roads from 2.17 mg/stop to 1.17 mg/stop and from 5.76 mg/stop to 4.50 mg/stop, respectively. On the rural roads, a decrease in $PM_{2.5}$ and PM_{10} emissions was observed from 5.65 mg/stop to 4.66 mg/stop and from 15.12 mg/stop to 12.43 mg/stop, respectively. On motorways, the $PM_{2.5}$ and PM_{10} contribution from brake wear declined from 28.34 mg/stop to 22.19 mg/stop and from 77.49 mg/stop to 60.57 mg/stop, respectively. It means that implementing low-emission driver training programmes is an effective strategy to mitigate brake wear emissions and improve air quality.



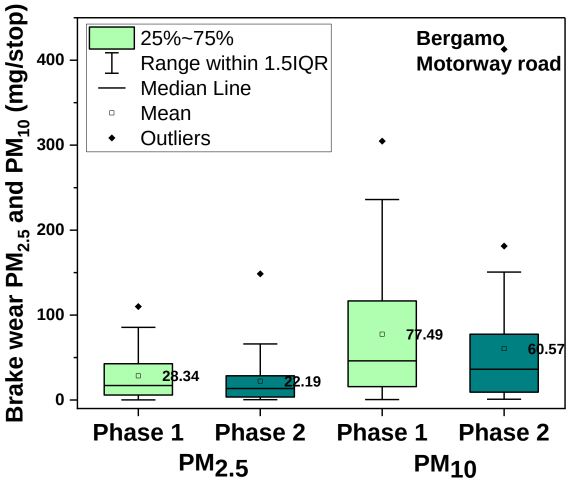
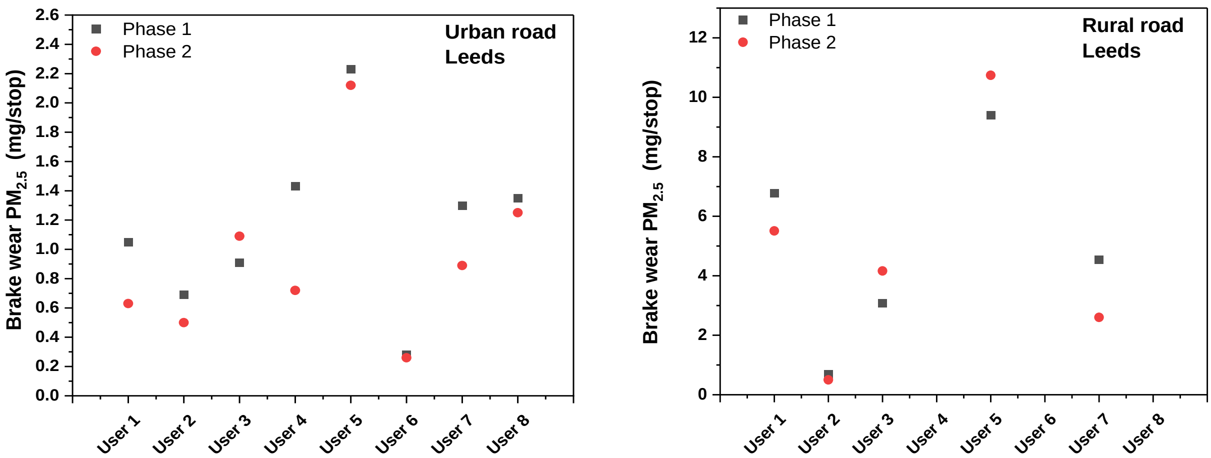


Figure 4.8: Before and after brake wear PM$_{2.5}$ and PM$_{10}$ emissions by road types in Bergamo

4.3 Effect of individual drivers

Individual drivers with varying driving styles have the potential to impact brake wear emissions (Liu et al., 2021; Xu et al., 2020). Aggressive driving behaviours can increase brake wear emissions, while smoother driving behaviour can help minimise brake wear emissions. In this section, a comparative analysis of all users on various types of roads was performed.

Figure 4.9 presents brake wear PM$_{2.5}$ emissions for different individual drivers before and after low-emission driver training in Leeds. It can be seen that the majority of drivers experienced a reduction in brake wear PM$_{2.5}$ on urban roads following the training. However, no improvement in the brake wear PM$_{2.5}$ emissions was observed for user 3 on urban and rural roads. In addition, it is interesting to find an improvement in brake wear PM$_{2.5}$ emissions on urban roads for User 5; however, no such improvement was observed on rural roads. On motorways, all users experienced a reduction in brake wear PM$_{2.5}$ emissions following the training videos and use of the app.



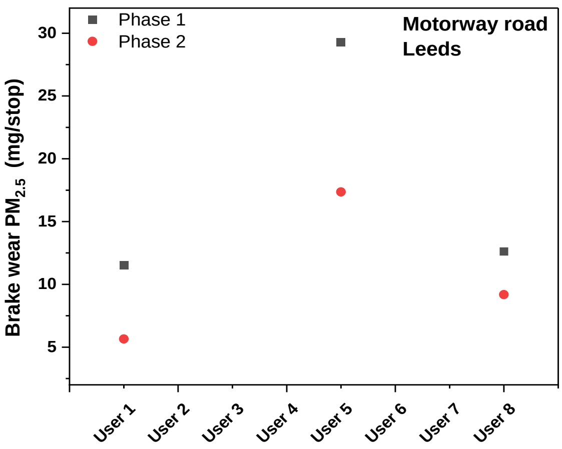
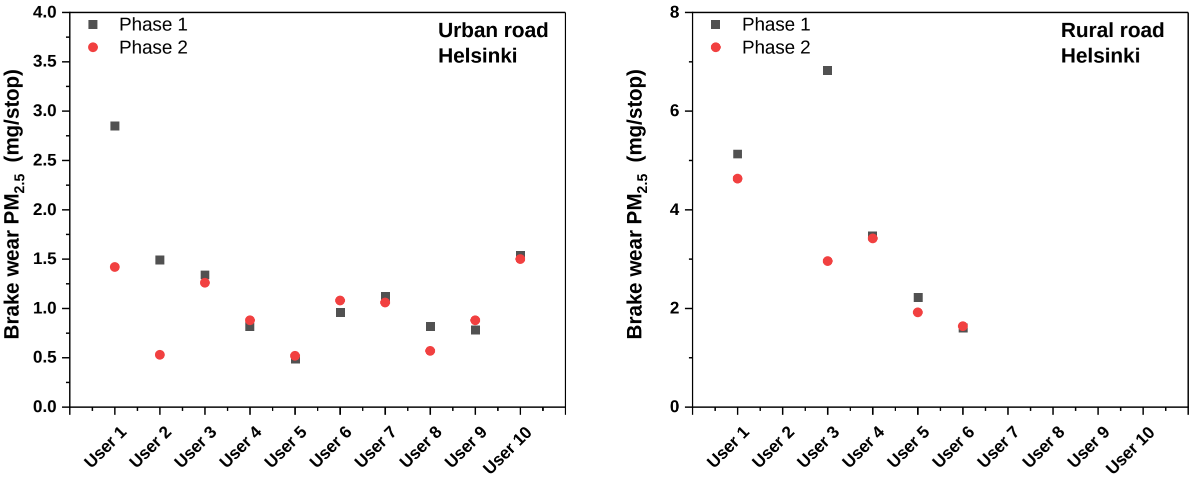


Figure 4.9: Before and after brake wear $PM_{2.5}$ for individual drivers in Leeds

Figure 4.10 shows the brake wear $PM_{2.5}$ emissions for individual drivers before and after the low-emission training in Helsinki. It can be observed that brake wear $PM_{2.5}$ emissions were reduced significantly for User 1 and User 2 on urban roads compared to other users after the training. On rural roads, a reduction in brake wear emissions was observed for User 1, User 2, and User 5 during the transition from Phase 1 to Phase 2, whereas it was noted that brake wear emissions increased for User 3 and User 5. On motorways, brake wear emissions were reduced for three users following the training. The observations above indicate that some users demonstrated a higher level of adoption after receiving the training, which are more receptive and capable of modifying their driving behaviour to reduce brake wear emissions. In addition, different users have various learning curves and abilities to apply the obtained knowledge. Thus, to enhance the effectiveness of low-emission driving initiatives, training programmes should ideally be tailored to as many different user types as possible.



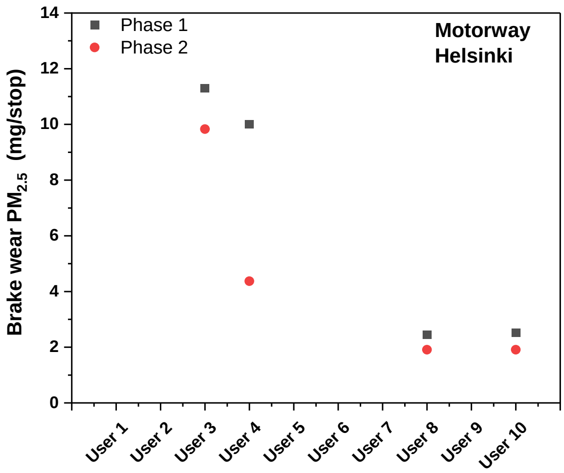


Figure 4.10: Before and after brake wear $PM_{2.5}$ for individual drivers in Helsinki

In Barcelona, the $PM_{2.5}$ emissions from brake wear were observed in Figure 4.11 to decrease from Phase 1 to Phase 2 for all users except for User 2. On rural roads during the transition from Phase 1 to Phase 2, there was a reduction in brake wear $PM_{2.5}$ emissions for all the users.

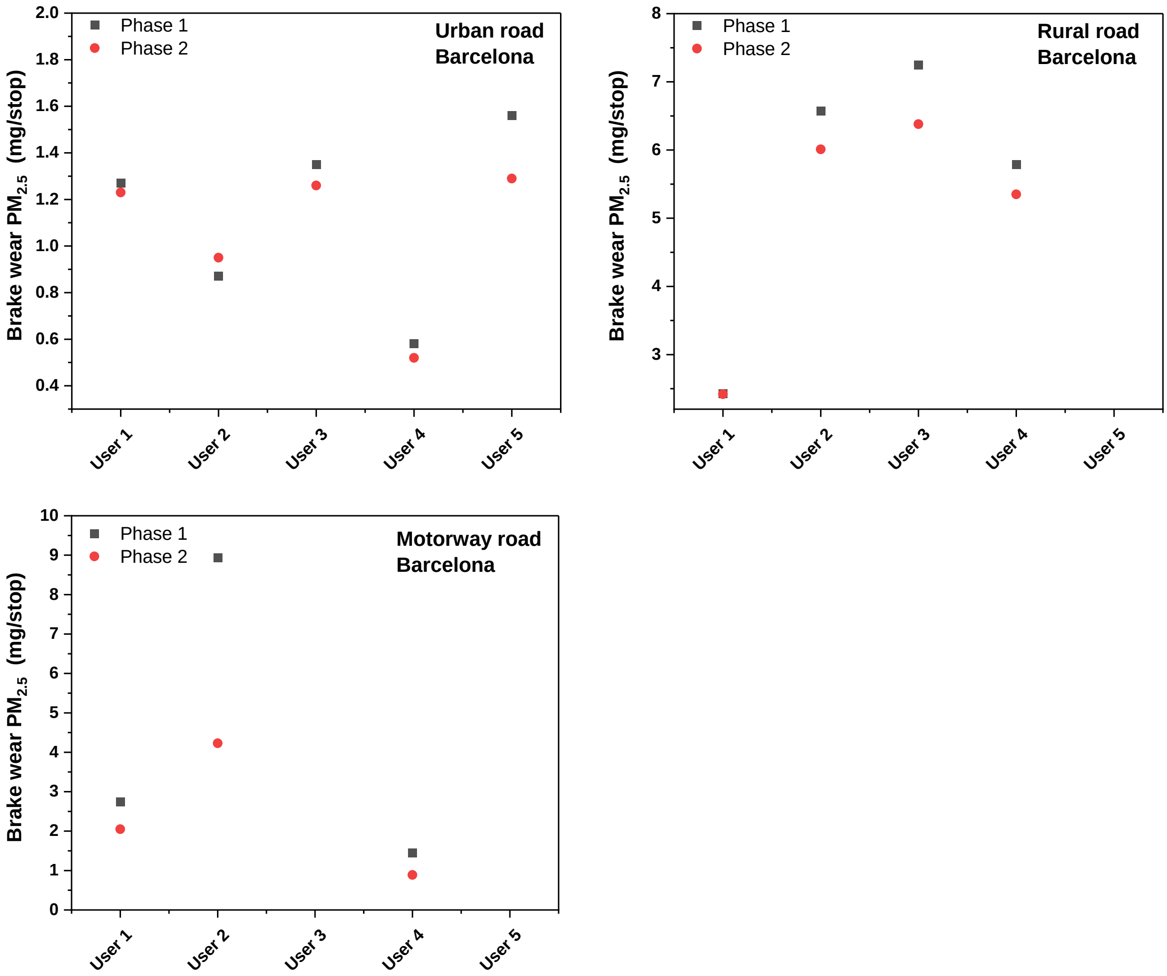


Figure 4.11: Before and after brake wear $PM_{2.5}$ for individual drivers in Barcelona

However, it was observed that brake wear emissions remained almost constant for User 1. Moreover, on motorways, all users experienced a decrease in brake wear $PM_{2.5}$ emissions after participating in the training.

From Figure 4.12, the $PM_{2.5}$ emissions from brake wear remained almost constant for User 1 on urban roads in Luxembourg from Phase 1 to Phase 2, while it was observed that corresponding $PM_{2.5}$ emissions lowered significantly for other users in the same context. On rural roads, the users observed a reduction in $PM_{2.5}$ emissions from brake wear, with the exception of User 4, after the training. On motorways, two users modified their driving behaviour and reduced brake wear $PM_{2.5}$ emissions following the low-emission driver training and app usage.

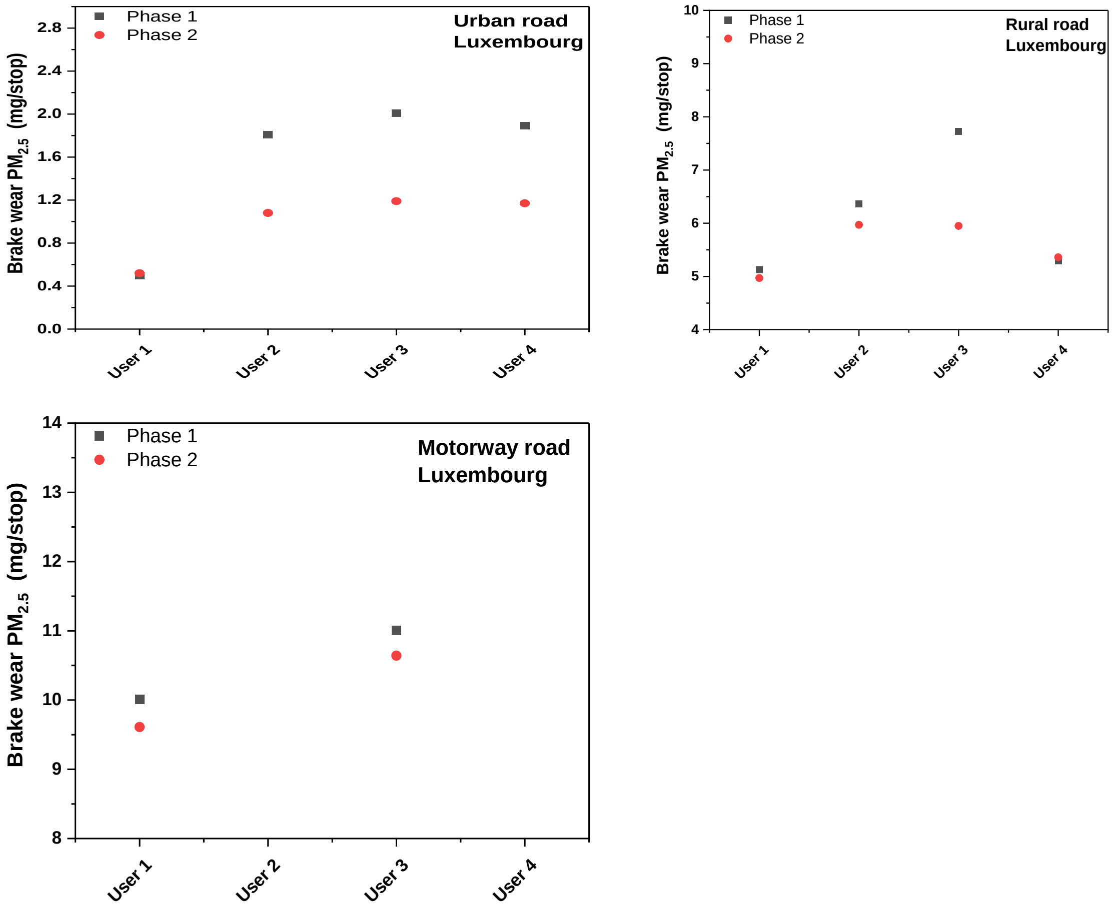


Figure 4.12: Before and after brake wear $PM_{2.5}$ for individual drivers in Luxembourg

Figure 4.13 illustrates brake wear $PM_{2.5}$ emissions for individual users before and after low-emission driver training programmes in Thessaloniki. Compared to other cities, the brake wear $PM_{2.5}$ emissions were observed for most users to increase from Phase 1 to Phase 2 in Thessaloniki. For instance, the brake wear $PM_{2.5}$ emissions increased slightly for two users on urban roads. On rural roads, there was a significant reduction in brake wear $PM_{2.5}$ emissions for one user during the transition from Phase 1 to Phase 2, whereas the corresponding brake wear $PM_{2.5}$ emissions increased for one user. Also, the corresponding value for User 2 remained almost constant. On motorways, the brake wear $PM_{2.5}$ emissions were observed to reduce for two users, but a significant increase in brake wear emissions was observed for User 3.

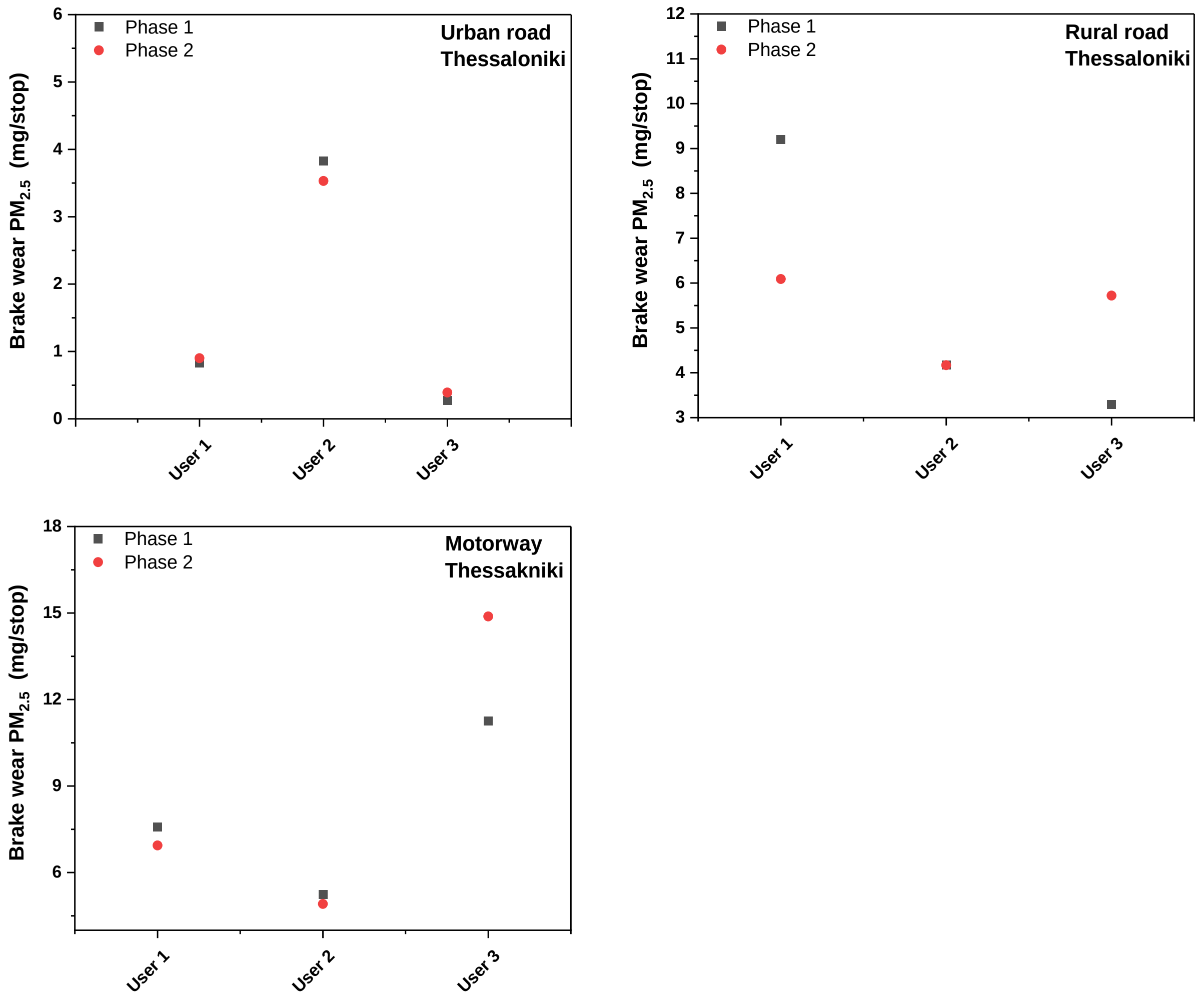


Figure 4.13: Before and after brake wear $PM_{2.5}$ for individual in Thessaloniki

In Istanbul, only records regarding brake wear emissions for users were available on urban roads and motorways. From Figure 4.14, the brake wear $PM_{2.5}$ emissions showed little variation for three users on urban roads from Phase 1 to Phase 2. The brake wear $PM_{2.5}$ emissions for the other two users exhibited contrasting trends. The total mean values of brake wear $PM_{2.5}$ emissions showed a slight reduction for all users on urban roads after the low-emission driver training programmes, as evidenced by Figure 4.7. On motorways, data from only one user was available between Phase 1 and Phase 2. The $PM_{2.5}$ emissions from brake wear decreased from 2.11 mg/stop to 1.67 mg/stop after participating in the low-emission driver training.

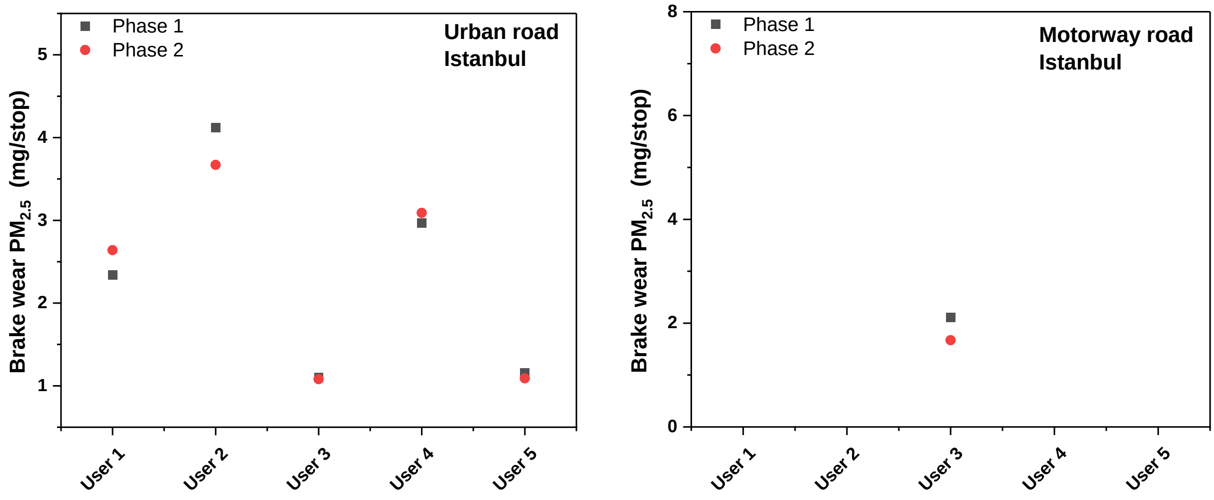


Figure 4.14: Before and after brake wear $PM_{2.5}$ for individual drivers in Istanbul

4.4 Effect of gender

The effect of driver gender on brake wear emissions has been a subject of interest in recent research (Xu et al., 2020). Understanding how driver gender contributes to changes in brake wear emissions can provide valuable insight into the key factors that influence vehicle emissions. Brake wear emissions, such as $PM_{2.5}$ and PM_{10}, have been recognised as significant contributor to air pollution. Examining the potential influence of driver gender on brake wear emissions is able to identify any gender-related disparities and explore the underlying reasons behind them, which is beneficial to the development of targeted strategies and interventions to reduce brake wear emissions and mitigate their environmental impact. In this section, we evaluated the effect of driver gender on brake wear emissions in Leeds and Helsinki.

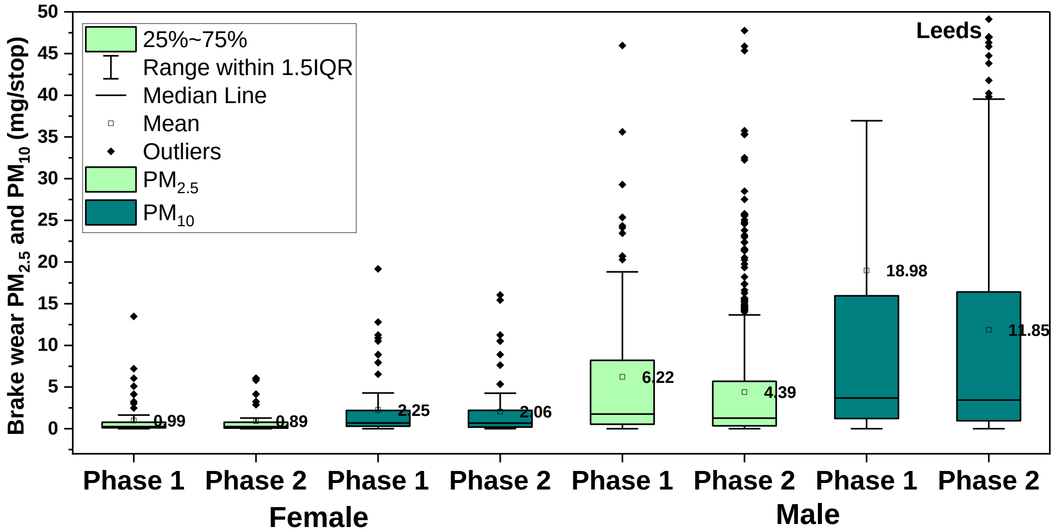


Figure 4.15: Effect of driver gender on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Leeds

As shown in Figure 4.15, regardless of $PM_{2.5}$ and PM_{10} emissions from brake wear, the mean values for female drivers were noticeably lower than those for male drivers. More precisely, the brake wear $PM_{2.5}$ emissions for female drivers were 6.3 and 4.9 times lower than those for male drivers during Phase 1 and Phase 2, respectively. In terms of PM_{10} emissions from brake wear, the mean values for female drivers were 8.4 and 5.8 times lower than those for male drivers, respectively. However, it should be mentioned that a greater reduction in $PM_{2.5}$ and PM_{10} emissions from brake wear was observed compared to female drivers after the low-emission driver training. Specifically, the mean values of brake wear $PM_{2.5}$ emissions for female and male drivers decreased by 10.1% and 29.4%, respectively. In terms of PM_{10} emissions, the corresponding mean values for female and male drivers reduced by 8.4% and 37.6%, respectively.

Figure 4.16 presents brake wear $PM_{2.5}$ and PM_{10} emissions of female and male drivers before and after the training in Helsinki. Similar to Leeds, the mean values of $PM_{2.5}$ and PM_{10} emissions from brake wear for female drivers were lower than those for male drivers. In addition, there were significant reductions in brake wear $PM_{2.5}$ and PM_{10} emissions among both female and male drivers following the training. However, the extent of the reductions was different between the two groups. For female drivers, the mean values of brake wear $PM_{2.5}$ emissions decreased by 8.9 % and 10.7 %, respectively. On the other hand, male drivers experienced a more substantial reduction in brake wear $PM_{2.5}$ emissions, with a decrease of 23.5%. Regarding PM_{10} emissions, male drivers saw a notable decrease, with a reduction of 24.4%.

Overall, the low-emission driver training programmes had positive effects on reducing brake wear $PM_{2.5}$ and PM_{10} emissions for both female and male drivers, particularly among male drivers. However, further research may be needed to explore the underlying factors contributing to the observed gender differences and to develop targeted interventions to achieve comparable reductions for female drivers.

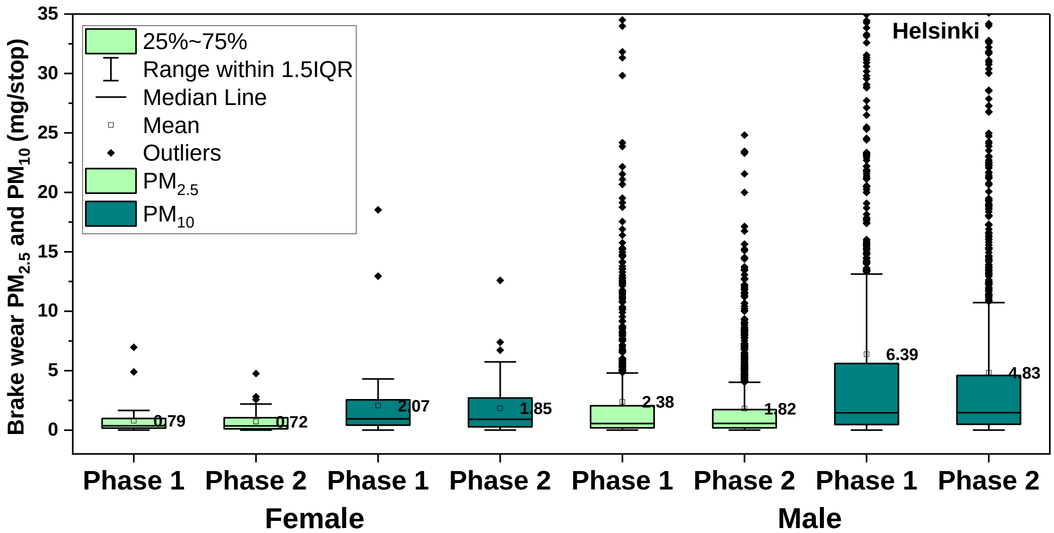


Figure 4.16: Effect of driver gender on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Helsinki

4.5 Effect of experience

Driving experience can have a significant impact on various aspects of vehicle performance and emissions. As drivers gain experience on the road, they develop different driving habits and behaviour that can affect brake wear emissions. Understanding the effect of driving experience on brake wear emissions is crucial for devising effective strategies to reduce PM emissions and improve air quality. In this section, how driving experience influences brake wear emissions will be discussed.

To compare the effect of driving experience on brake wear emissions, the drivers were divided into two groups, including experienced drivers and novice drivers. The experienced drivers were professional drivers with at least 5 years of driving experience. In comparison, the novice drivers had less than 5 years of driving experience. Figure 4.17 shows brake wear $PM_{2.5}$ and PM_{10} emissions for drivers with various driving experiences before and after the low-emission driver training in Leeds. It can be seen that the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions of experienced drivers were significantly lower than those of novice drivers. Specifically, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions were 0.78 mg/stop and 1.23 mg/stop for experienced drivers before the training and app use, whereas the corresponding mean values for novice drivers were 6.87 mg/stop and 16.65 mg/stop, respectively. This observation is likely ascribed to the fact novice drivers are less skilled and more intense in braking deceleration (Huang et al., 2021). However, compared to experienced drivers, novice drivers can improve their driving skills after the training. For instance, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions were reduced only by 7.7% and 10.6% for experienced drivers during the transition from Phase 1 to Phase 2. However, novice drivers experienced a reduction of 36.1% and 29.2% in the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions, respectively. it means that low-emission driver training programmes should be more effective in improving the performance of novice drivers in Leeds.

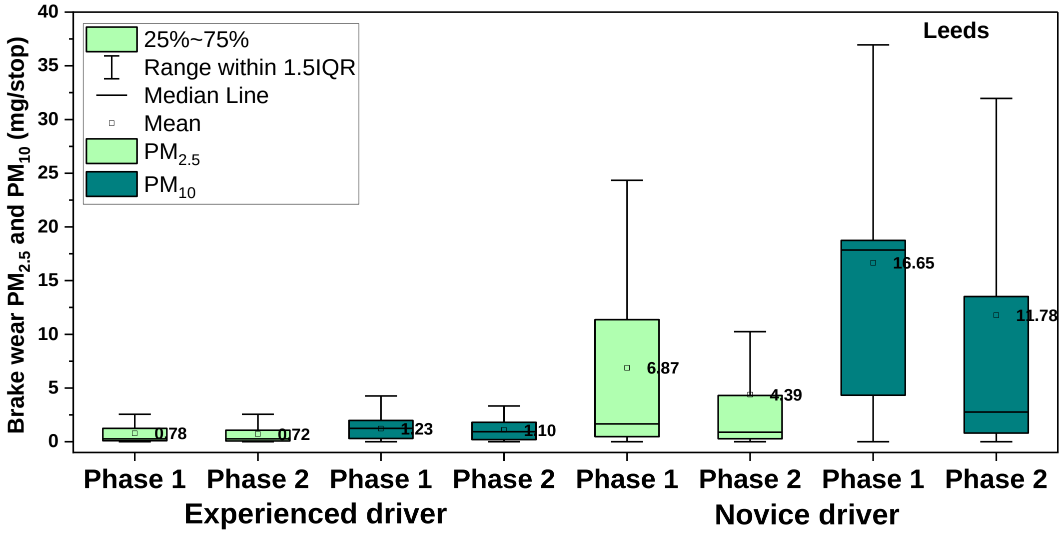


Figure 4.17: Effect of driving experience on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Leeds

Figure 4.18 shows the effect of driving experience on brake wear $PM_{2.5}$ and PM_{10} emissions before and after the training in Helsinki. Similarly, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions were lower for experienced drivers compared to novice drivers. More precisely, after the training and using the app, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions for experienced drivers were 0.90 mg/stop and 2.33 mg/stop, respectively, while the corresponding mean values for novice drivers were 1.82 mg/stop and 4.83 mg/stop, respectively. In Helsinki, when compared to experienced drivers, novice drivers showed greater improvement in their driving skills after the training. The mean values of brake wear $PM_{2.5}$ and PM_{10} emissions decreased by 30.2% and 31.5% respectively for experienced drivers from Phase 1 to Phase 2. In contrast, novice drivers experienced a significant reduction of 23.8% and 24.4% in the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions respectively. This indicates that experienced and novice drivers dramatically improved braking skills toward low emissions after the training in Helsinki.

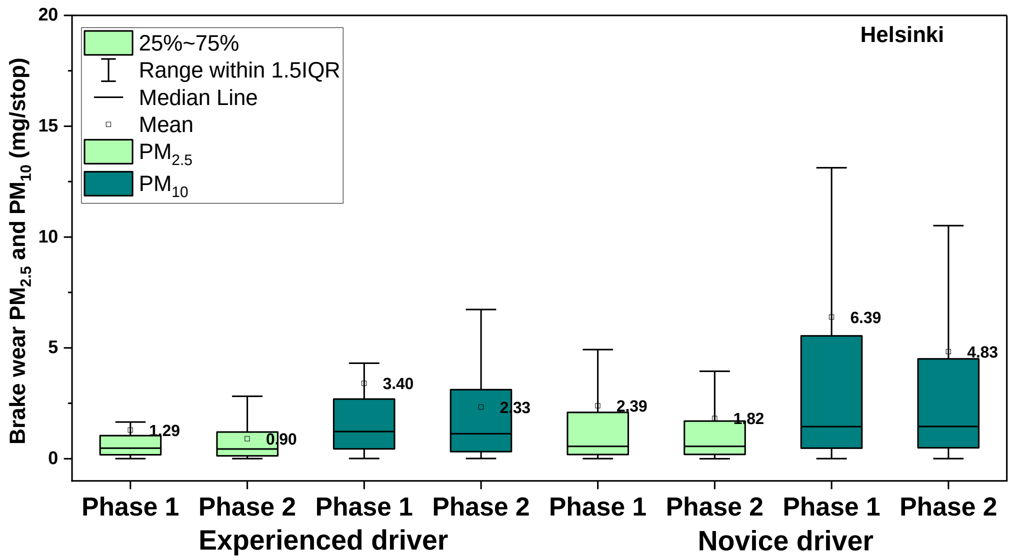


Figure 4.18: Effect of driving experience on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Helsinki

As seen in Figure 4.19 in Barcelona, the brake wear emissions of experienced drivers were also lower than those of novice drivers. Compared to novice drivers, the brake wear $PM_{2.5}$ emissions of experienced drivers were 33.3% and 5.7% lower, respectively, in Phase 1 and Phase 2. In terms of PM_{10} emissions from brake wear, the corresponding mean values of experienced drivers were 26.7% and 37.4 lower compared to those of novice drivers, respectively. From Phase 1 to Phase 2, it was assessed that the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions decreased by 10.4% and 37.4% for experienced drivers, respectively. Regarding novice drivers, the mean values of brake wear $PM_{2.5}$ and PM_{10} emissions reduced by 36.6% and 26.7%, respectively.

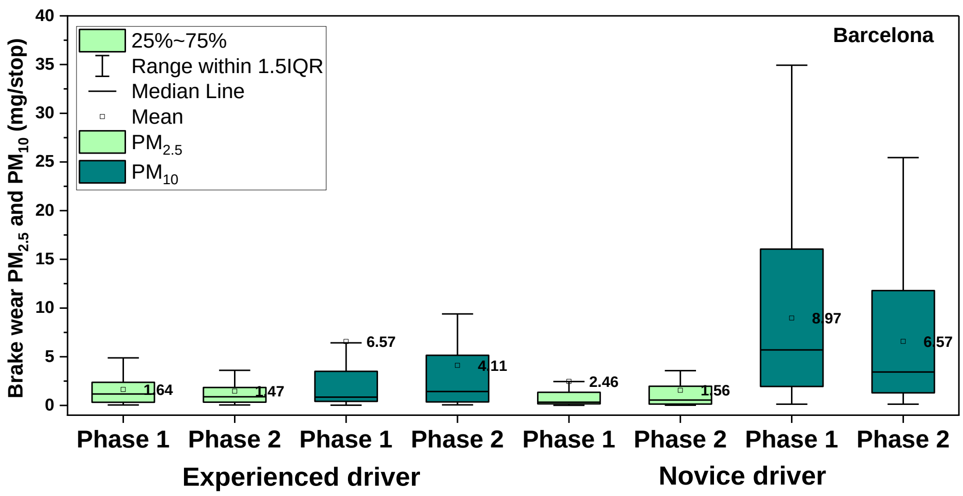


Figure 4.19: Effect of driving experience on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Barcelona

Compared to other cities above, regardless of experienced and novice drivers, the $PM_{2.5}$ and PM_{10} emissions from brake wear showed a slight increase in Thessaloniki during the transition from Phase 1 to Phase 2, as shown in Figure 4.20. However, experienced drivers still exhibited lower brake wear $PM_{2.5}$ emissions compared to novice drivers, with reductions of 27.0% and 28.5% observed during Phase 1 and Phase 2, respectively. Moreover, in relation to PM_{10} emissions from brake wear, the mean values of experienced drivers were found to be 27.5% and 29.1% lower compared to those of novice drivers, respectively.

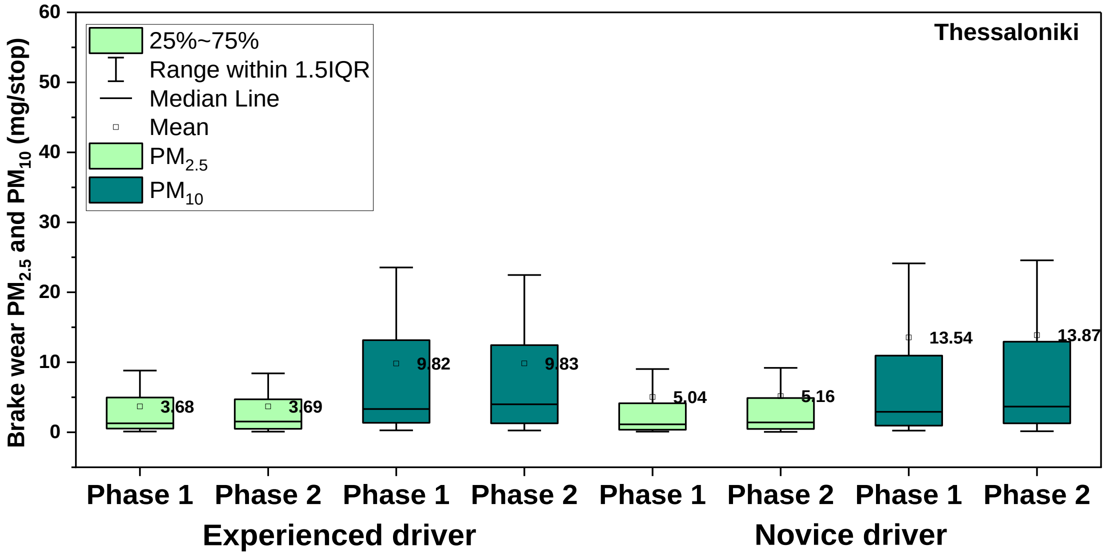


Figure 4.20: Effect of driving experience on before and after brake wear $PM_{2.5}$ and PM_{10} emissions in Thessaloniki

4.6 Effect of MODALES app on real-time brake wear PM concentration and in-cabin sound level

This dedicated study aimed to measure brake particle concentrations and size distributions from two test vehicles under real-world driving and braking conditions with and without using the MODALES app. Moreover, the in-cabin sound was measured during the two scenarios.

The measurements took place as follows:

- Background measurements while driving with a low speed (approx. 30 km/h to avoid any acronymic disturbances).
- Measurements with free-style driving for 5 kms. The measurements were done with the app deactivated and activated.
- Background measurement with the same configuration after the brake PM measurements, in order to have the background particle concentration before and after the tests.

One diesel and one full electric vehicle were used in this study, driven by one participant from the Greek site. A detailed description of the tests is given in the MODALES D6.2.

4.6.1 BMW passenger car

Figure 4.21 shows the results of the total particle concentration (0.3-10.0 µm) for the 4 different measurement phases. Comparing the median of the phases with and without the App with the average of the median of the two background phases we see that the concentration is 12% higher in the cases of without the App and 8% with the App activated, resulting thus to a 4% reduction in brake particles concentration with the use of the App. Another interesting finding is the narrower interquartile range that is evidence of a less variance in the PM concentration from the brakes.

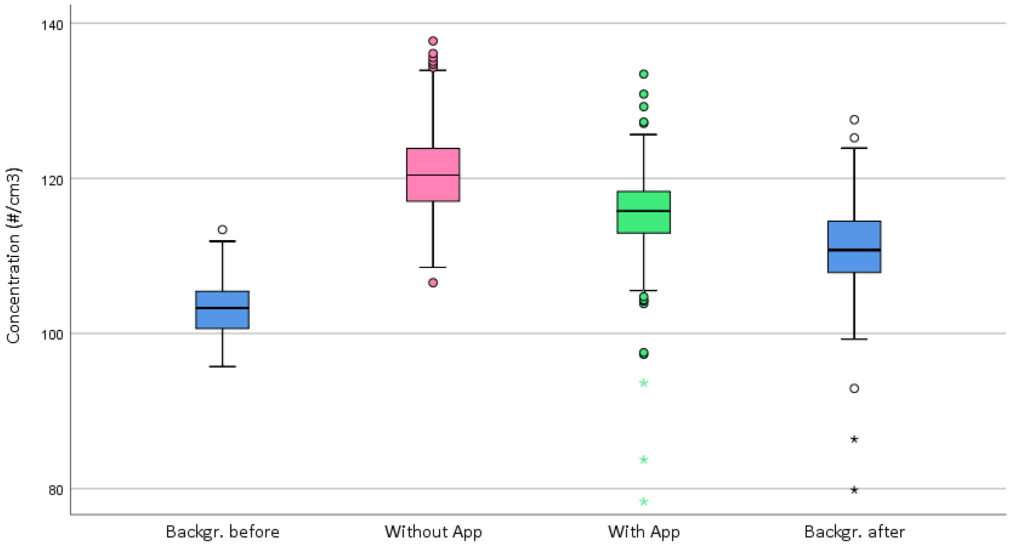


Figure 4.21: Variation of PM concentration (BMW)[2]

In Figure 4.22, we compared the speed and deceleration values with and without the App. It is obvious that the median deceleration for the case of using the App is lower and also the interquartile range is narrower comparing to the case of not using the App. Concerning the speed, the median of 30 km/h, a test requirement as set, has been followed, however the smoother driving style is evident in the "with App" case by the narrower interquartile range than the range of the "without App", which is about 1.5 times winder (ranging from about 17 to 50 km/h).

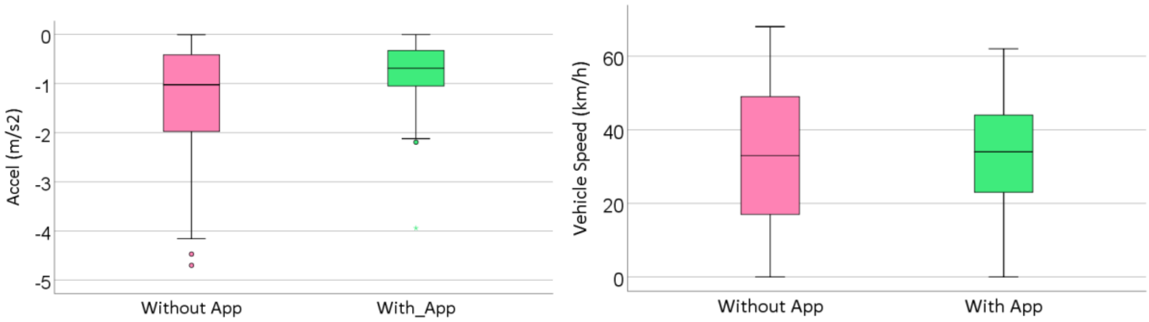


Figure 4.22: Vehicle deceleration and speed during the two test scenarios (BMW)

The sound levels in vehicle cabins can vary depending on various factors such as the type of vehicle, speed, road conditions, and insulation of the cabin. In passenger cars, the recommended maximum sound levels in the cabin typically range from 65 to 70 decibels (dB) at cruising speeds. Looking at the

[2] The blue boxplots represent the background ambient air values and the pink & green the brake emissions

maximum sound in the cabin, which was measured in both scenarios, it is noticeable the positive effect of using the App (Figure 4.23). The difference of the medians might be slight (55.7 dBA versus 56.5 dBA), however we have to take into account that this was an electric vehicle with already reduced in-cabin sound due to the silent vehicle performance.

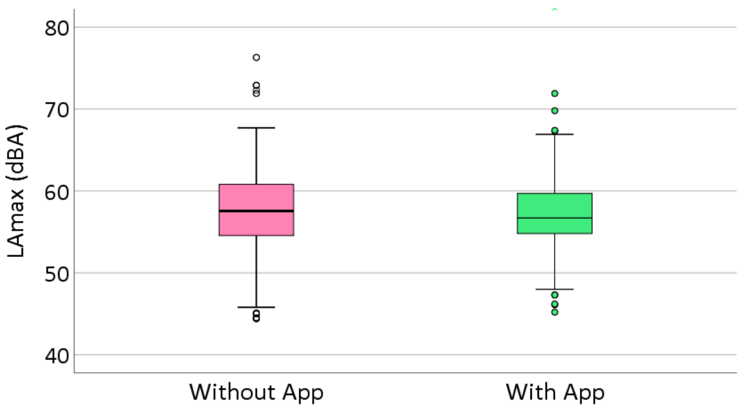


Figure 4.23: In-cabin maximum sound level (dBA) with and without using the MODALES App (BMW)

4.6.2 FIAT passenger car

Figure 4.24 depicts the outcomes concerning the total particle concentration (0.3-10.0 µm) during the four distinct measurement phases. Comparing again the medians of the phases with and without the App with the average of the medians from the two background phases, it becomes apparent that the concentration is 34% higher in the scenario where the App is not utilized, while it is 24% higher when the App is activated. Consequently, the utilization of the App leads to a 10% reduction in brake particle concentration. Another noteworthy discovery is again the much narrower interquartile range in the "With App" scenario, indicating a decrease in variance in the particulate matter (PM) concentration emitted from the brakes.

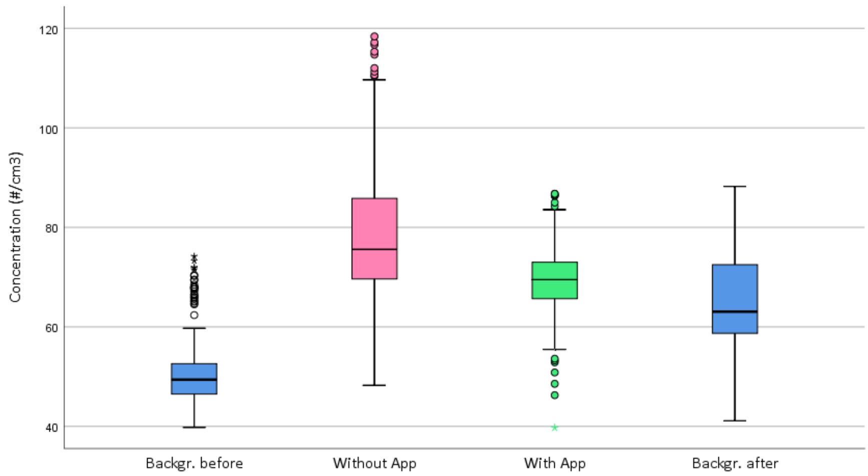


Figure 4.24: Variation of PM concentration (FIAT)[3]

[3] The blue boxplots represent the background ambient air values and the pink & green the brake emissions

In Figure 4.25, we examined and compared the speed and deceleration values in the presence and absence of the App. it is apparent that the median deceleration is lower when the App is used, and the interquartile range is also narrower compared to the scenario without the App. Regarding the speed, the median values of 35.9 km/h and 34.7 km/h aligns with the prescribed test requirement. However, a smoother driving style is evident when the App is utilized, as indicated by the narrower speed range in comparison to the range observed without the App. In the case without the App, the speed range is narrower in FIAT tests than in the BMW which can be declared by the easiness of acceleration with an electric vehicle.

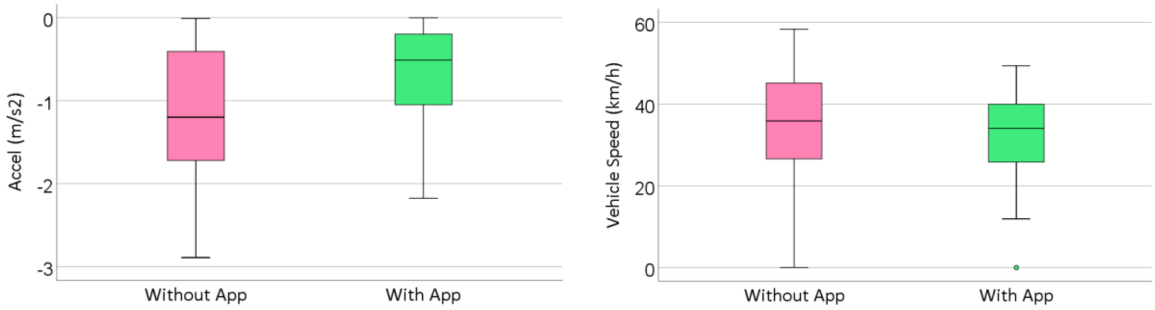


Figure 4.25: Vehicle deceleration and speed during the two test scenarios (FIAT)

In terms of the maximum sound level inside the cabin, the overall impact of using the App is again noticeable as observed in Figure 4.26, though subtle when comparing the medians (63.9 dBA versus 63.5 dBA). It is worth noting that the sound level is 7-8 dBA higher than in the BMW cabin and this can be declared by the presence of an ICE (diesel engine). However, even a small reduction in sound level in the cabin of the FIAT has a greater effect in the annoyance of the vehicle occupants than in the BMW, because of the much higher average values.

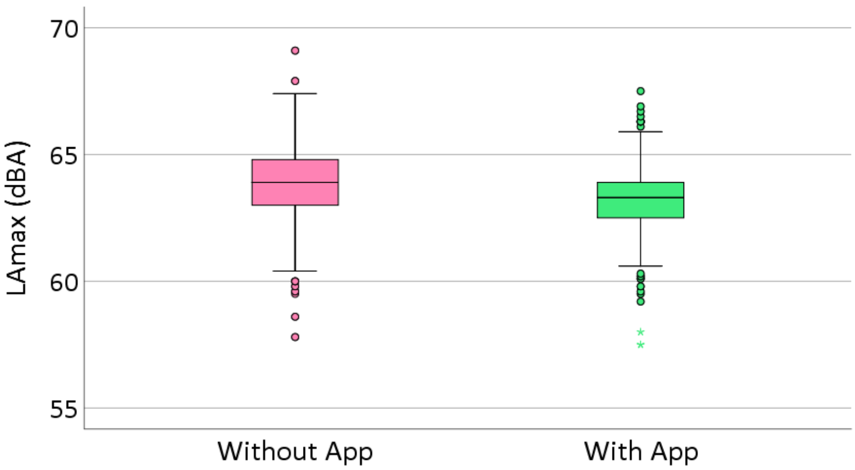


Figure 4.26: In-cabin maximum sound level (dBA) with and without using the MODALES App (FIAT)

4.7 Summary for brake wear emissions

In this chapter, the differential influences of driving behaviour, such as road types, individual drivers, driver gender, and driver experience, were evaluated on brake wear $PM_{2.5}$ and PM_{10} emissions in seven European cities; the impact of MODALES tools to real-time PM concentration from brake wear and in-cabin sound level was investigated under real-world driving conditions. The main conclusions are as follows:

- Generally, there were significant reductions in brake wear emissions in various cities, while Istanbul had slight reductions. Barcelona demonstrated the most substantial improvements. Overall, the implementation of low-emission driver training programmes contributes to a more sustainable and healthier environment.
- Motorway roads exhibited the highest mean values of brake wear $PM_{2.5}$ and PM_{10} emissions per stop, followed by rural and urban roads. This is likely due to the higher average speeds on motorways, leading to more intense braking and increased brake wear emissions per stop.
- Individual drivers exhibited variations in their impact on brake wear emissions. Overall, the training programmes proved effective for most users in reducing brake wear emissions on all road types.
- The training programmes effectively reduced brake wear $PM_{2.5}$ and PM_{10} emissions for both female and male drivers. However, male drivers experienced greater reductions compared to female drivers. Further research is required to understand the underlying factors and develop targeted interventions to achieve comparable emission reductions for female drivers.
- Experienced drivers had lower initial brake wear emissions compared to novice drivers. After the training, both groups showed improvements, but novice drivers experienced a greater reduction in brake wear emissions.
- The results revealed a difference ranging from 4-10 % in the total concentration of 0.3-10.0 µm size particles emitted from the brakes when using the App. The reduction in brake particle emissions is strongly related to the smoother driving style that the driver has adopted following the MODALES recommendations (42 % - 140 % reduced median deceleration with the App activated).

5 Differential influences of driving behaviour on tyre wear emissions

Tyre wear is unavoidable during usage and is influenced mainly by vehicle type, tyre characteristics, and driving conditions (Oroumiyeh and Zhu, 2021; Panko et al., 2018). Tyre wear would generate different sizes of particles, which would damage not only the atmospheric environment and human health but also water systems. On the one hand, the debris with sizes below 5 mm from tyre wear, as the larger categories of microplastics, have a large specific surface area and thus have the capacity to readily adsorb pollutants (Bakir et al., 2014; Gualtieri et al., 2005; Lee et al., 2020). On the other hand, tyre wear is one of the important contributors to the non-exhaust airborne PM from vehicles (Harrison et al., 2020). As a result, understanding the differential influences of driving behaviours on tyre wear emissions is essential for developing effective strategies to mitigate their environmental consequences. In this chapter, the differential influences of driving behaviour on various road types, individual drivers, driver gender, and driver experience, on tyre wear emissions will be evaluated and discussed.

5.1 Overall results for tyre wear emissions

The total tyre wear mass was assessed under real-world driving conditions. Figure 5.1 shows tyre wear emissions before and after low-emission driver training programmes in seven European cities. It can be observed that there was a reduction in tyre wear emission levels on average for these cities. Specifically, it was evaluated that the mean value of tyre wear mass was reduced by 2.2% in Leeds following the training. In Helsinki and Barcelona, there were decreases of 2.5% and 3.6% in tyre wear emissions from Phase 1 to Phase 2, respectively. During the transition from Phase 1 to Phase 2, Luxembourg and Thessaloniki experienced reductions of 1.6% and 1.8%, respectively. In Istanbul and Bergamo, the mean values of tyre wear emissions lowered from 87.68 mg/km to 80.65 mg/km as well as from 89.91 mg/km to 75.01 mg/km, respectively, with reductions of 8.0% and 16.6%. Among the studied cities, Bergamo demonstrated the most substantial enhancements in tyre wear emissions, with a reduction of 16.6%. However, there was least improvement in tyre wear emissions in Luxembourg, i.e. 1.6%. The results above indicate that low-emission driver training programmes had a positive impact on reducing tyre wear emissions in several European cities.

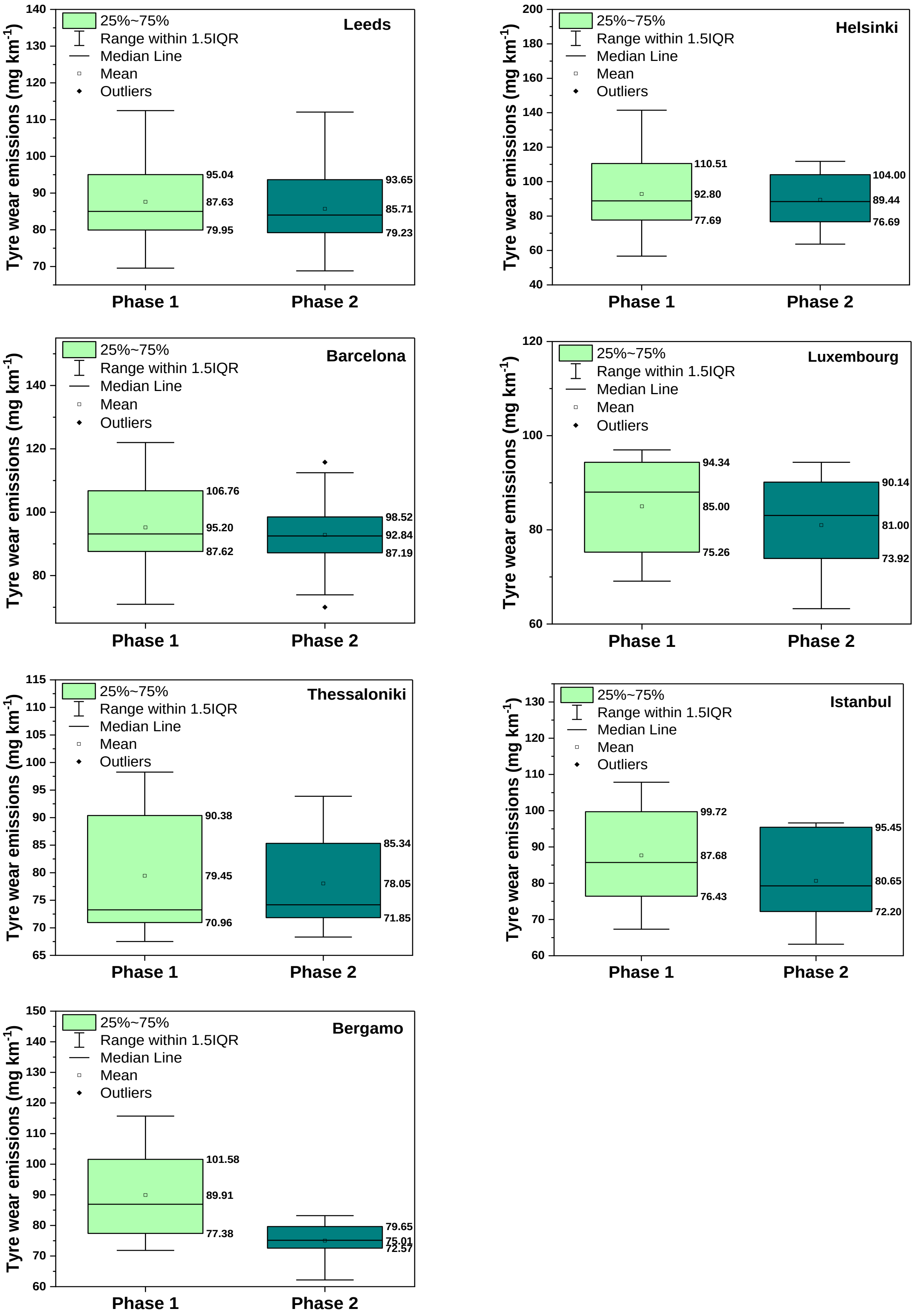


Figure 5.1: Before and after tyre wear emissions by trial sites

5.2 Effect of road types

Road types play a crucial role in tyre wear emissions. Tyre wear, caused by the interaction between tyres and road surfaces, is a significant source of PM emissions. Different road types, such as urban roads, rural roads, and motorways, exhibit distinct characteristics that can impact tyre wear and subsequent emissions. In this section, the tyre wear emissions on different types of roads were evaluated.

Figure 5.2 depicts tyre wear emissions before and after low-emission driver training on different types of roads in Leeds. From Figure 5.2, the mean values of tyre wear emissions on motorways in Leeds were the largest, followed by rural and urban roads in both Phase 1 and Phase 2. On urban roads, the mean values of tyre wear emissions reduced from 85.63 mg/km to 83.80 mg/km after the implementation of the training. There was a reduction from 88.68 mg/km to 87.35 mg/km on rural roads and from 89.77 mg/km to 88.92 mg/km on motorways after participating in the training and using the app.

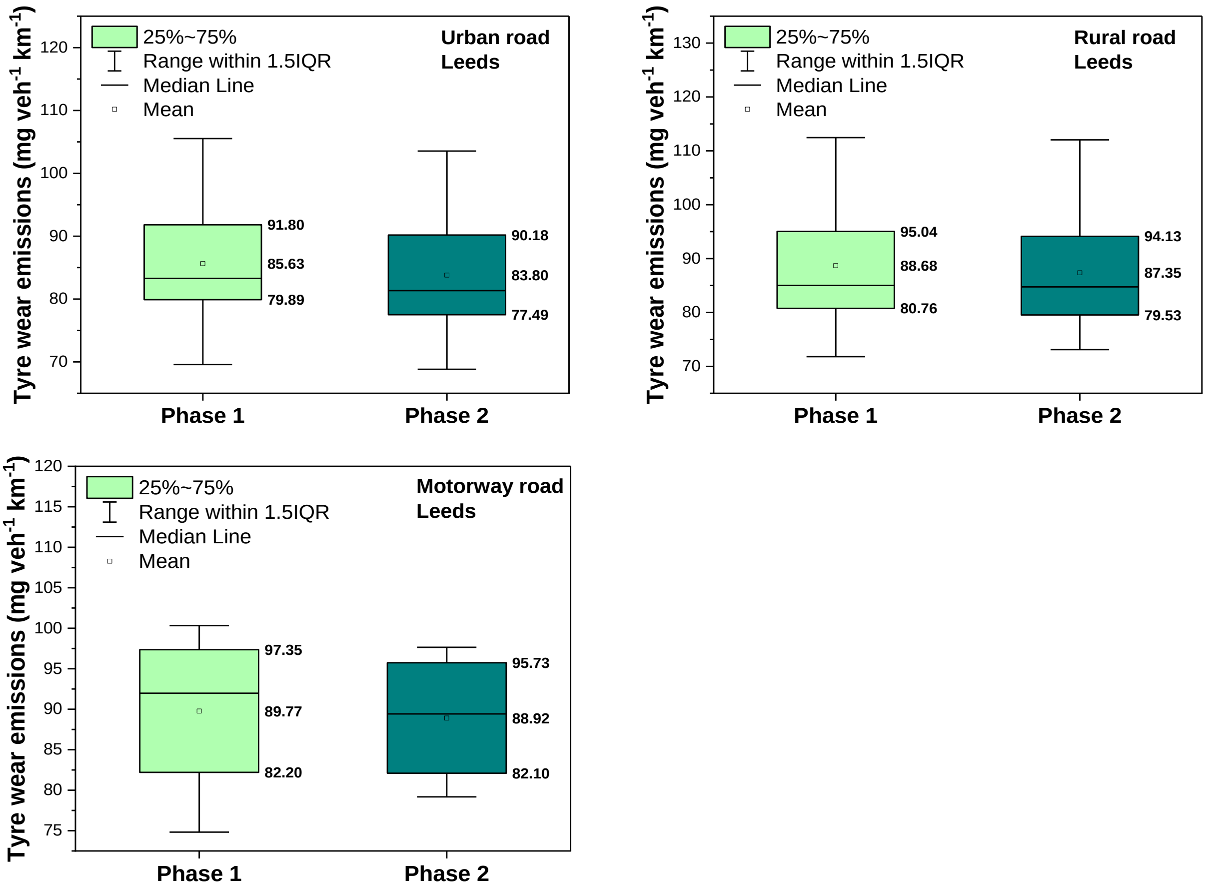


Figure 5.2: Before and after tyre wear emissions by road types in Leeds

Similarly, the mean values of tyre wear emissions were the largest on motorways in Helsinki during both Phase 1 and Phase 2, followed by Rural roads and urban roads, as shown in Figure 5.3. After taking the training, slight reductions in tyre wear emissions were observed on all road types except for urban roads. Specifically, the mean values from tyre wear reduced from 92.4 mg/km to 87.9 mg/km on rural roads. There was a reduction in mean values of tyre wear emissions from 101.3 mg/km to 93.6 mg/km on motorways during the transition from Phase 1 to Phase 2. However, mean values of tyre wear emissions increased slightly from 85.4 mg/km to 86.7 mg/km on urban roads from Phase 1 to Phase 2.

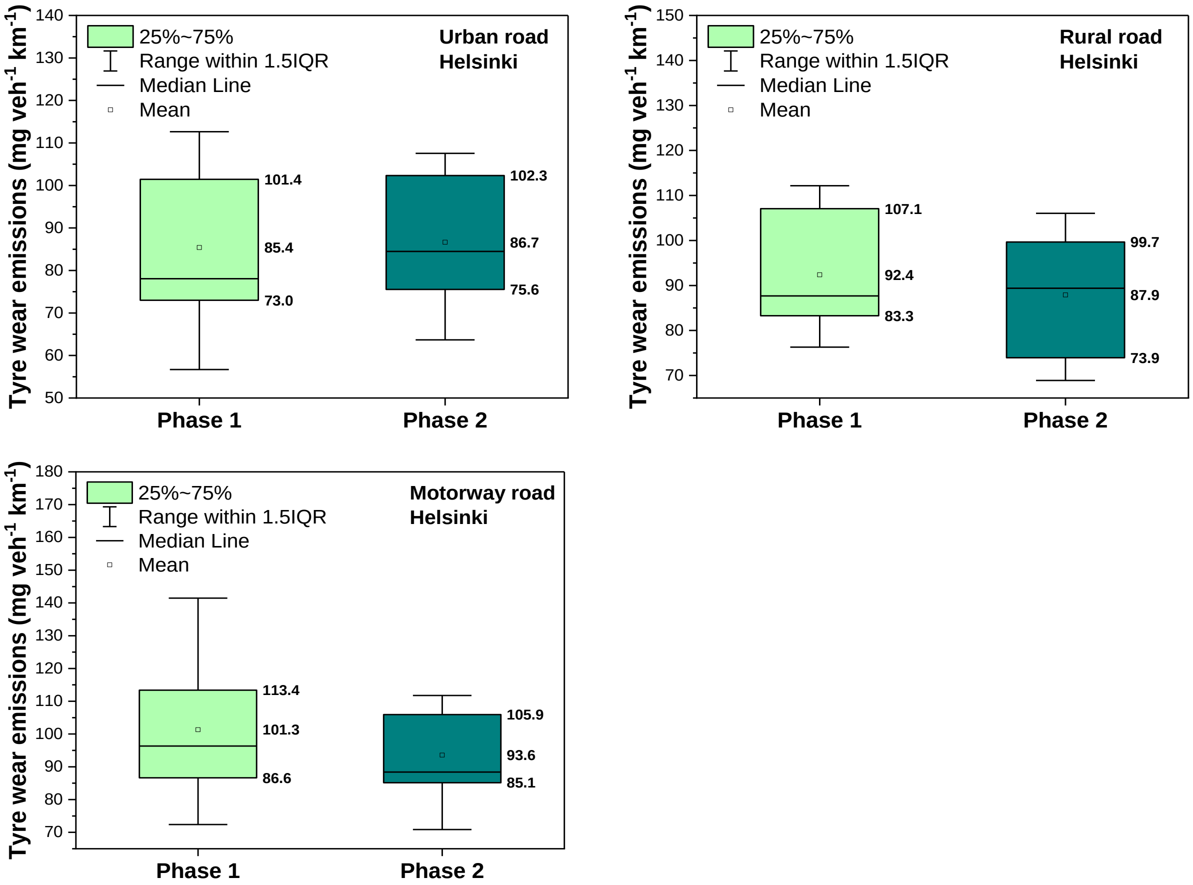
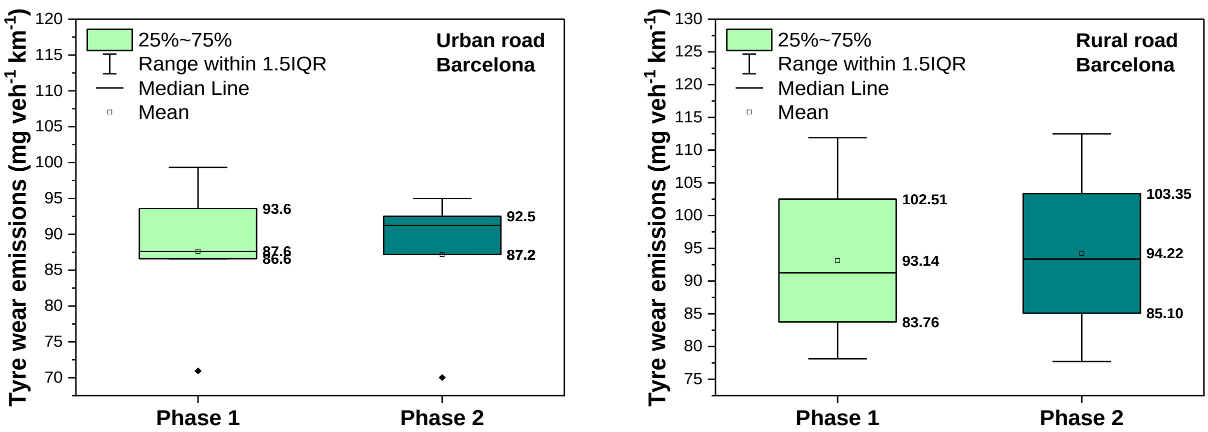


Figure 5.3: Before and after tyre wear emissions by road types in Helsinki

Figure 5.4 illustrates tyre wear emissions before and after low-emission driver training on different types of roads in Barcelona. It can be observed that the highest levels of emitted tyre wear emissions occurred on motorways. Rural and urban roads followed, showing slightly lower emissions during Phase 1 and Phase 2. Following the training, tyre wear emissions reduced significantly on motorway roads, with a decrease of 7.7%. On urban roads, there was a marginal decrease in tyre wear emissions from 87.6 mg/km to 87.2 mg/km, whereas the tyre wear emissions increased slightly from 93.1 mg/km to 94.2 mg/km.



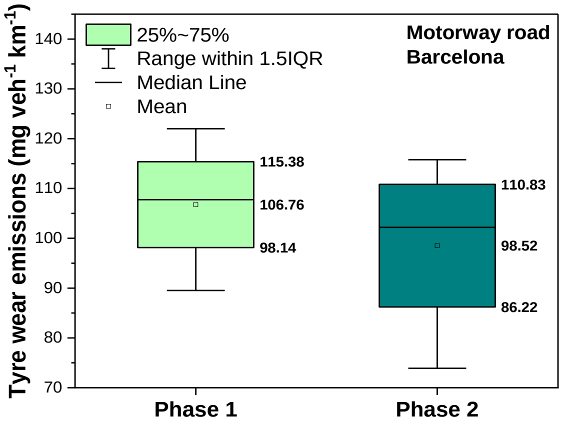


Figure 5.4: Before and after tyre wear emissions by road types in Barcelona

As shown in Figure 5.5 in Luxembourg, the tyre wear emissions on motorways were the largest, followed by rural and urban roads in both Phase 1 and Phase 2. After implementing the low-emission driver training, there was a reduction of 6.8% in tyre wear emissions on motorways. However, the impact was less significant on rural roads, where there was a slight decrease from 85.0 mg/km to 84.4 mg/km in tyre wear emissions. On the contrary, tyre wear emissions experienced a slight increase from 78.2 mg/km to 79.0 mg/km on urban roads.

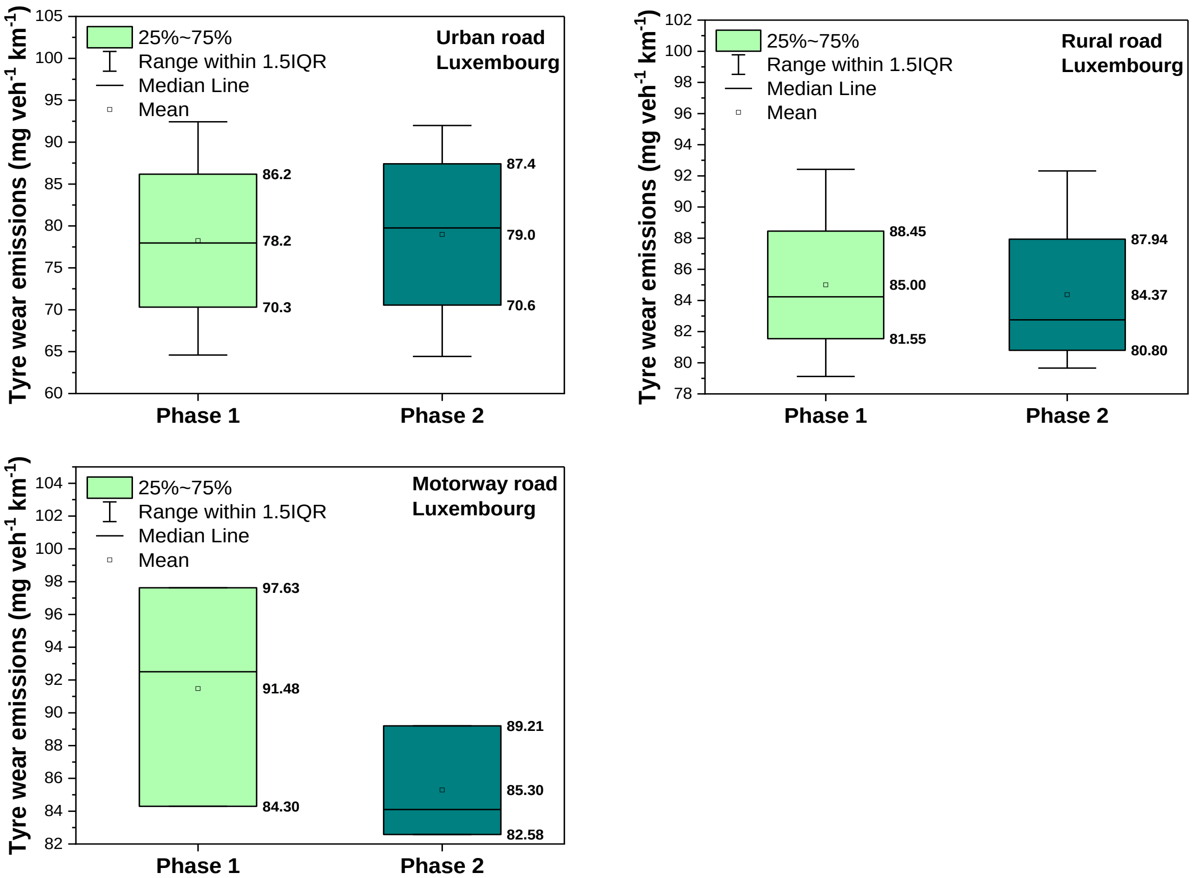


Figure 5.5: Before and after tyre wear emissions by road types in Luxembourg

Figure 5.6 presents tyre wear emissions before and after the low-emission driver training programmes on different types of roads in Thessaloniki. Unlike to results above, the mean values of tyre wear emissions on urban roads were marginally higher than those on rural roads in both Phase 1 and Phase 2. However, it was observed that the corresponding mean values on motorways were significantly higher than those on urban and rural roads. Following the training, there was a reduction in mean values of tyre wear emissions from 71.9 mg/km to 71.1 mg/km on rural roads. Similarly, the mean values of tyre wear emissions decreased from 94.3 mg/km to 90.6 mg/km. However, there was a slight increase in mean values of tyre wear emissions from 72.1 mg/km to 72.4 mg/km.

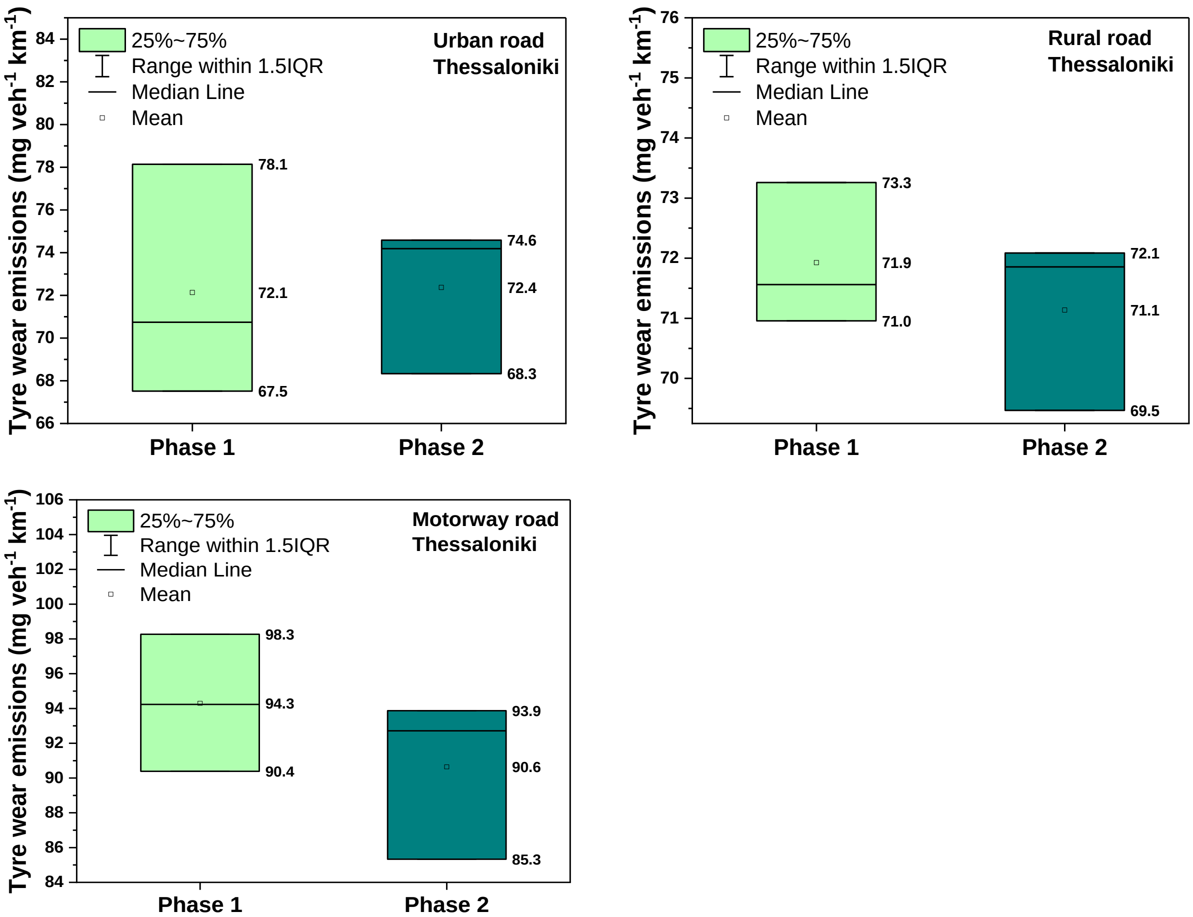


Figure 5.6: Before and after tyre wear emissions by road types in Thessaloniki

In Istanbul, data regarding tyre wear emissions on only urban roads and motorways were available, as shown in Figure 5.7. It can be observed that mean values of tyre wear emissions on motorway roads were significantly higher than those on urban roads, with higher of 22.7% and 20.2% respectively in both Phase 1 and Phase 2. The low-emission driver training resulted in a decrease in tyre wear emissions. More precisely, the mean values of tyre wear emissions decreased from 76.6 mg/km to 71.2 mg/km on urban roads, with a reduction of 7.0%. On motorways, there was a reduction in tyre wear emissions from 99.2 mg/km to 90.4 mg/km, with a reduction of 8.9%

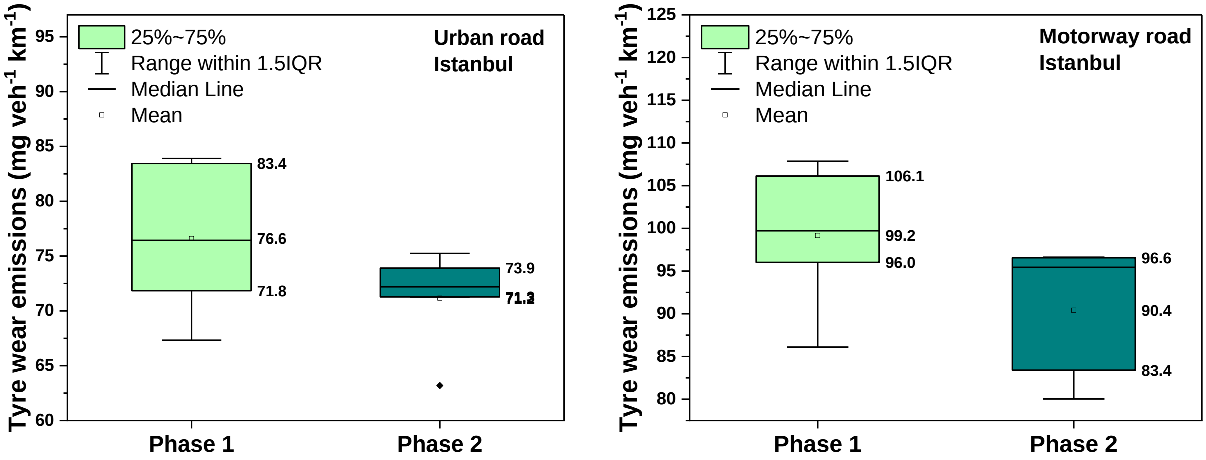


Figure 5.7: Before and after tyre wear emissions by road types in Istanbul

In Bergamo, substantial reductions were observed from Figure 5.8 in the tyre wear emissions across all road types from Phase 1 to Phase 2. Specifically, on urban roads, the mean values of tyre wear emissions decreased from 79.4 mg/km to 69.49 mg/km following the training. Similarly, there was a reduction in tyre wear emissions from 87.9 mg/km to 73.5 mg/km on rural roads. On motorways, mean values of tyre wear emissions reduced significantly from 97.9 mg/km to 80.8 mg/km. In Bergamo, the low emission driver training programme had a greater impact on reducing tyre wear emissions across all types of roads compared to the other cities studied.

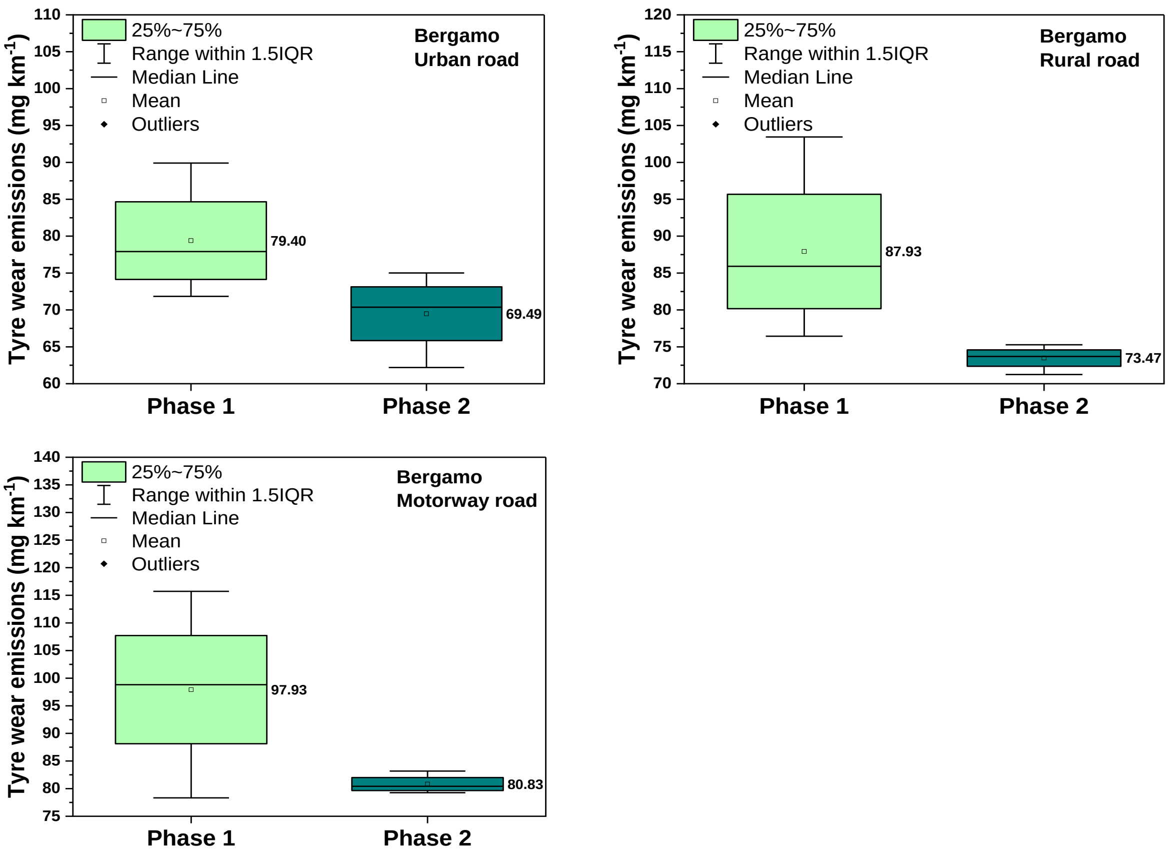


Figure 5.8: Before and after tyre wear emissions by road types in Bergamo

5.3 Effect of individual drivers

Individual drivers with varying driving styles would result in the difference in tyre wear emissions since driving styles are the main factors affecting non-exhaust emissions (Lee et al., 2020; Liu et al., 2022a). By examining the behaviour and driving habits of individual drivers, valuable insights can be gained into the primary factors that contribute to tyre wear emissions, facilitating the identification of potential strategies for emission reduction. In this section, the influence of individual drivers on tyre wear emissions in seven European cities will be discussed.

Figure 5.9 illustrates tyre wear emissions of individual drivers before and after the training in Leeds. It can be observed that the majority of drivers experienced a reduction in mean values of tyre wear emissions across all types of roads, following the training. No improvement in the tyre wear emissions was observed for User 1 and User 8 on urban roads and for User 3 and User 5 on rural roads. On motorways, all users experienced a reduction in tyre wear emissions following the training.

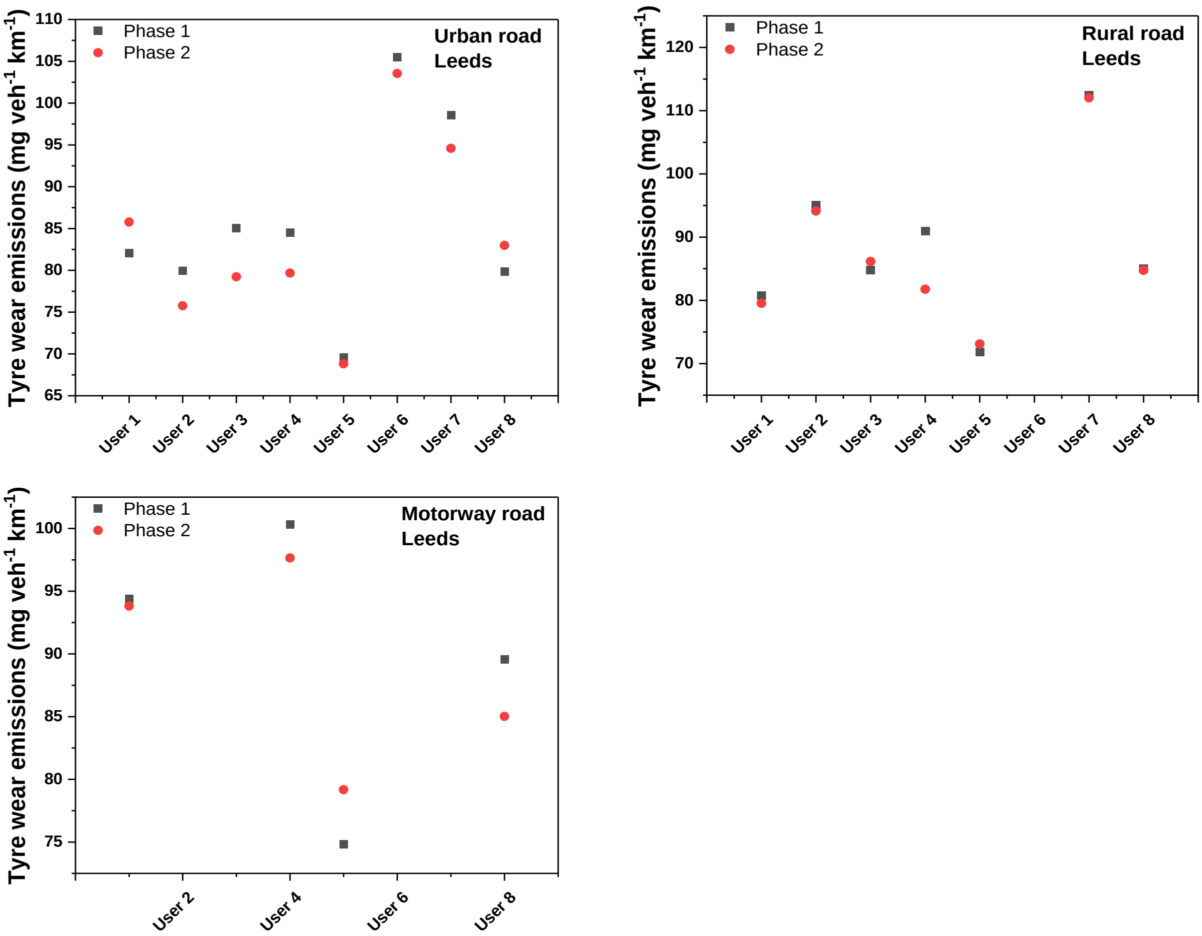


Figure 5.9: Before and after tyre wear emissions of individual drivers in Leeds

In Helsinki, the mean values of tyre wear emissions were observed from Figure 5.10 to reduce for all users on motorways. However, the mean values of tyre wear emissions for User 8 and User 10 exhibited a slight increase on rural roads from Phase 1 to Phase 2. Furthermore, there were substantial reductions in mean values of tyre wear emissions for User 2, User 3, and User 6 on urban roads, while the corresponding mean values for User 7 and User 8 increased significantly on urban roads after receiving the training. The tyre wear emissions of other users remained almost constant on urban roads from Phase 1 to Phase 2.

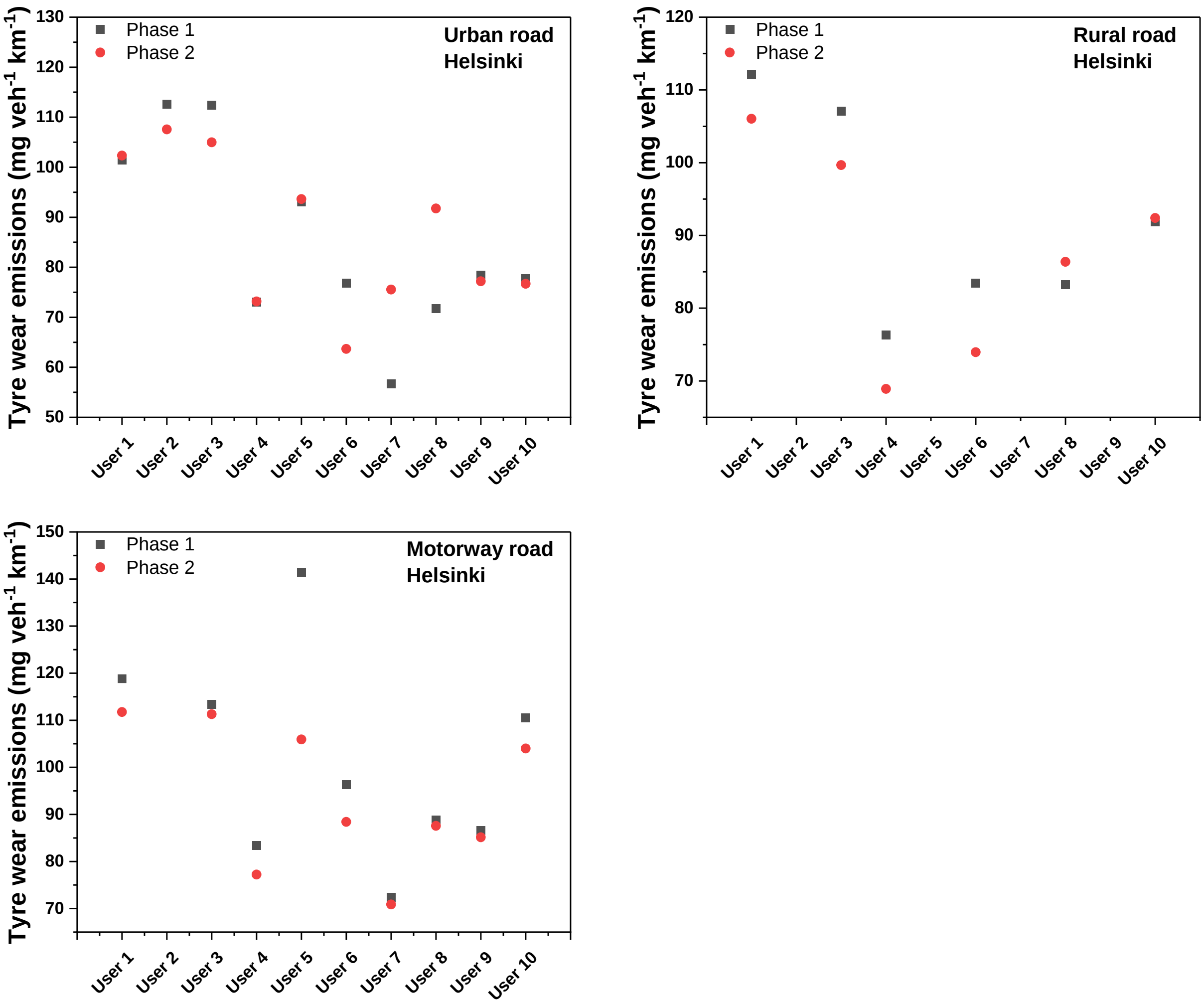


Figure 5.10: Before and after tyre wear emissions of individual drivers in Helsinki

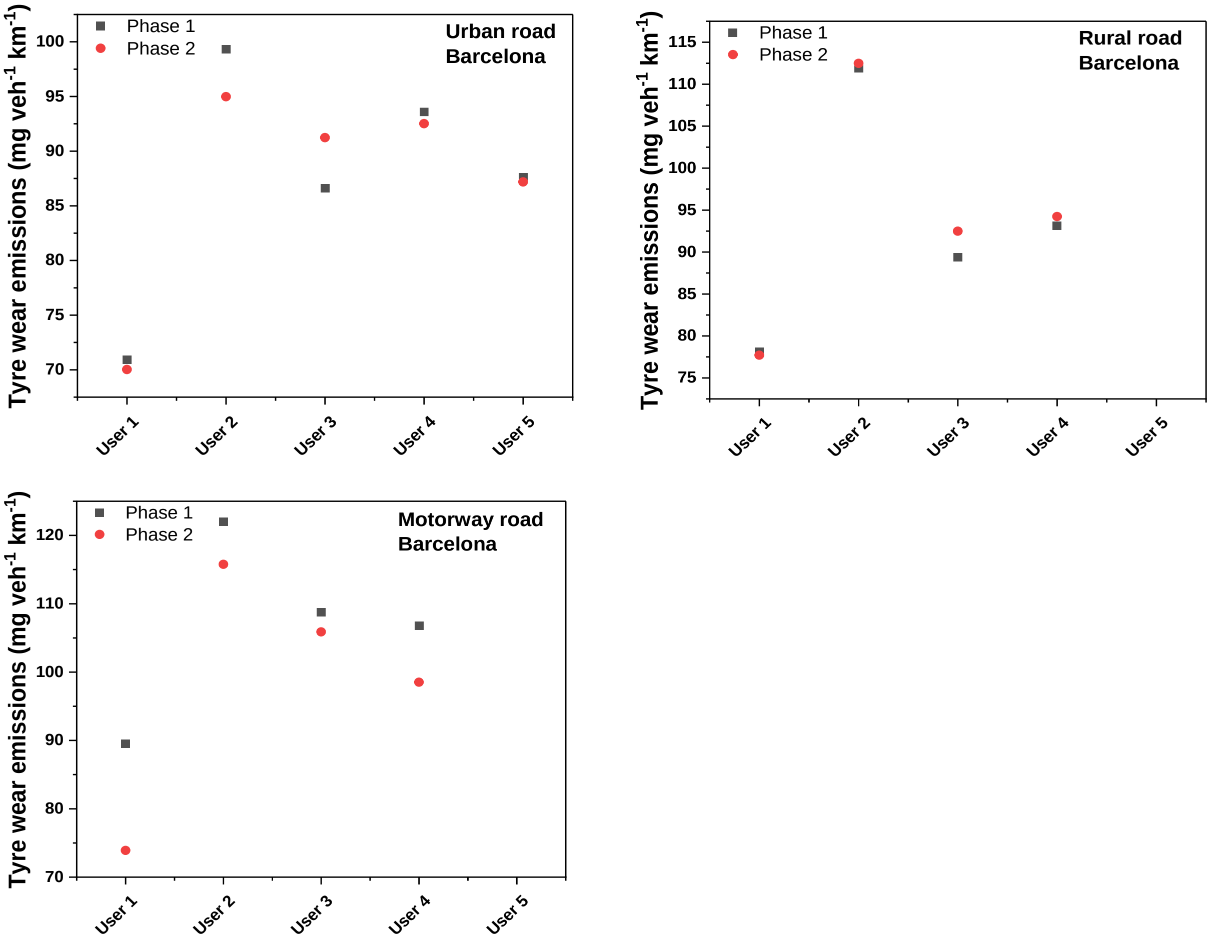


Figure 5.11: Before and after tyre wear emissions of individual drivers in Barcelona

From Figure 5.11, the mean values of tyre wear emissions for all users in Barcelona except for User 3 reduced from Phase 1 to Phase 2 on urban roads. On rural roads, it was observed an increase in mean values of tyre wear emissions for User 3, whereas the corresponding mean values for other users remained relatively consistent. On motorways, low-emission driver training had positive effects on all users, where the mean values of tyre wear emissions decreased from Phase 1 to Phase 2. In addition, it was found that the tyre wear emissions of User 3 increased on both urban and rural roads, whereas the corresponding values of User 3 were reduced on motorways.

Figure 5.12 illustrates tyre wear emissions of individual drivers before and after low-emission driver training in Luxembourg. It can be observed that tyre wear emissions for User 1 and User 3 remained relatively stable, while User 2 and User 4 showed contrasting trends in tyre wear emissions on urban roads from Phase 1 to Phase 2. On rural roads, tyre wear emissions were improved for all users with the exception of User 4, after receiving the training. On motorways, an improvement in tyre wear emissions was observed for all users.

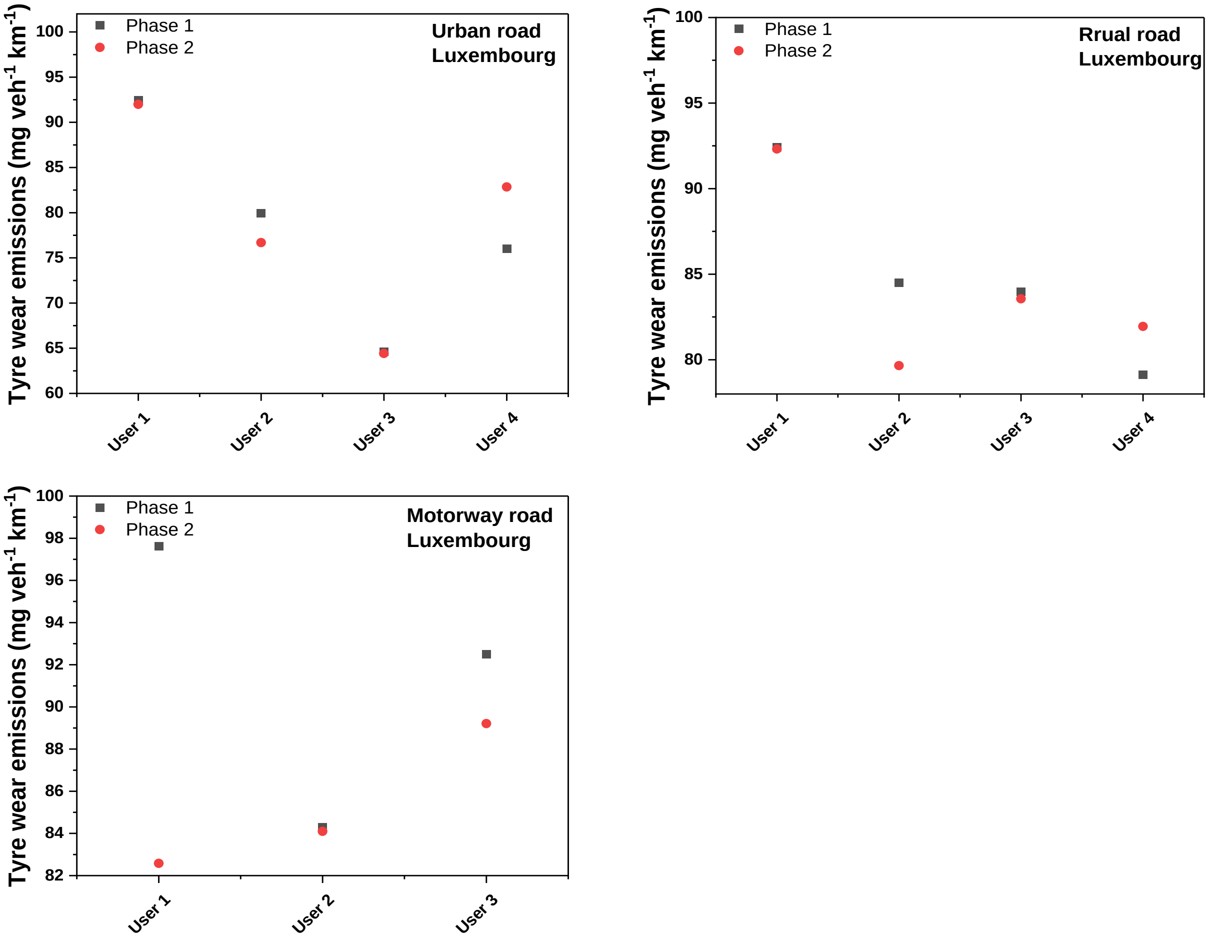
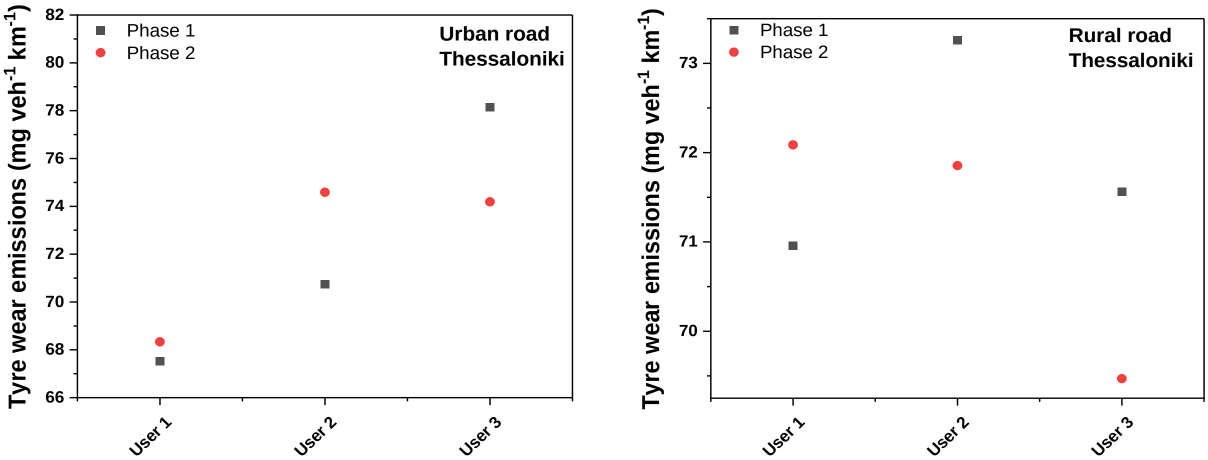


Figure 5.12: Before and after tyre wear emissions of individual drivers in Luxembourg

In Thessaloniki, it can be seen from Figure 5.13 that the tyre wear emissions of three users showed different variations before and after low-emission driver training. Specifically, User 1 and User 2 experienced an increase in tyre wear emissions on urban roads following the training, while the tyre wear emissions of User 3 decreased from Phase 1 to Phase 2. On rural roads, the tyre wear emissions of User 2 and User 3 were observed to reduce, whereas User 1 exhibited an increase in tyre wear emissions from Phase 1 to Phase 2. There was a decrease in tyre wear emissions for all users on motorways.



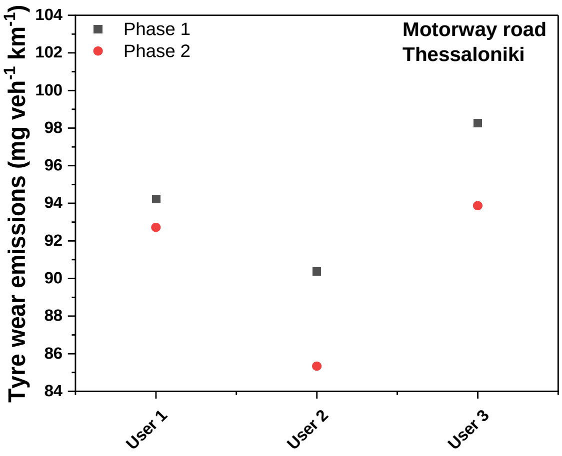


Figure 5.13: Before and after tyre wear emissions of individual drivers in Thessaloniki

From Figure 5.14, the tyre wear emissions exhibited a reduction of all users in Istanbul except for User 5 from Phase 1 to Phase 2 on urban roads. On motorways, the mean values of tyre wear emissions for four users reduced significantly after participating in the training programmes, while the tyre wear emissions of User 3 increased slightly from Phase 1 to Phase 2.

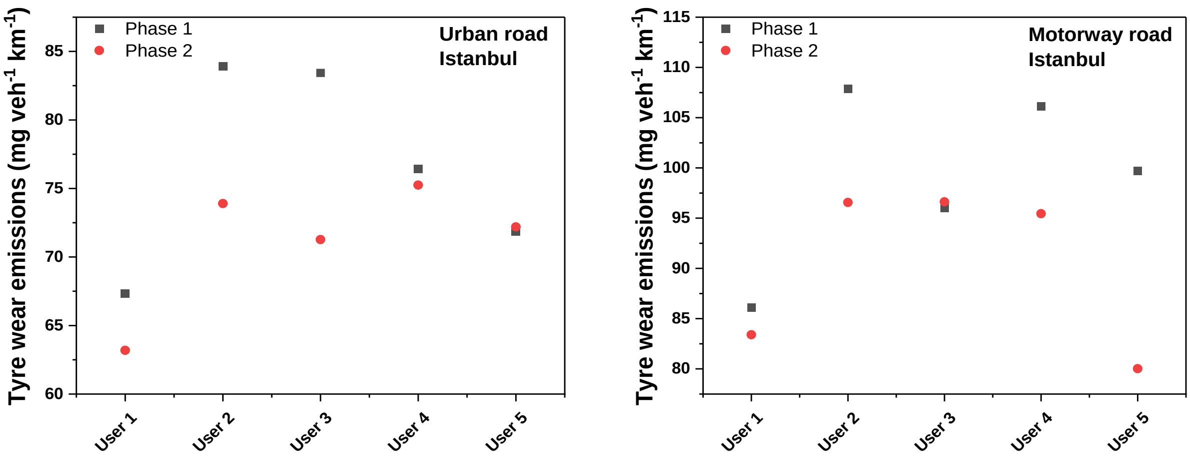


Figure 5.14: Before and after tyre wear emissions of individual drivers in Istanbul

5.4 Effect of gender

Driver gender can play a role in driving behaviour and habits, which in turn inevitably affects tyre wear emissions (Khader and Martin, 2019). Investigating the relationship between driver gender and tyre wear emissions is helpful in providing insights into potential differences and implications for sustainable transportation practices. This section explored the impact of driver gender on tyre wear emissions, shedding light on the importance of gender-specific considerations for promoting eco-friendly driving practices and reducing environmental footprints in the transportation sector.

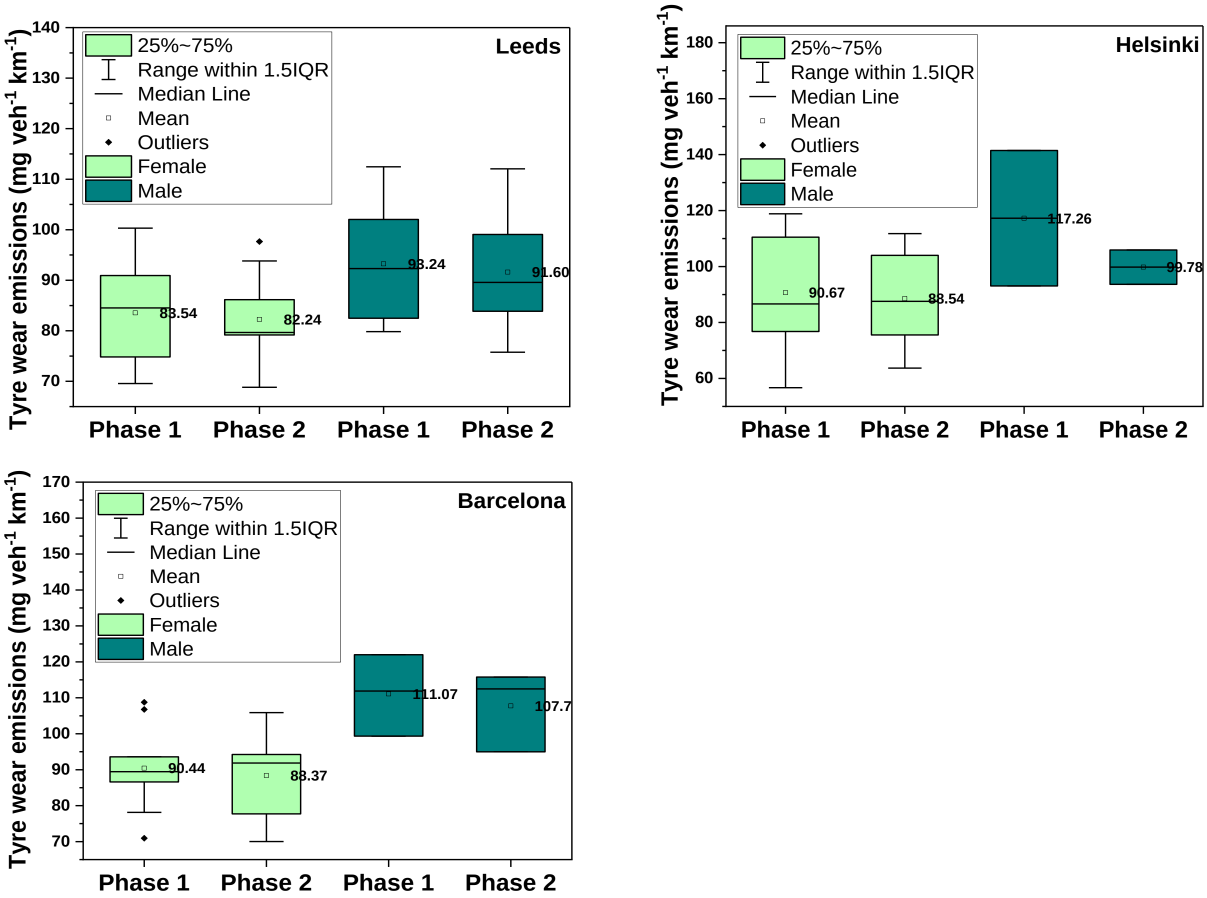


Figure 5.15: Effect of driver gender on before and after tyre wear emissions

Figure 5.15 shows tyre wear emissions of different gender drivers before and after low-emission driver training programmes. It can be seen that the mean values of female drivers were lower than those of male drivers in all cities involved. Specifically, the mean values of tyre wear emissions for female drivers were 10.4% and 10.2% lower than those for male drivers in Leeds during Phase 1 and Phase 2, respectively. In Helsinki, the corresponding mean values for female drivers were 22.7% and 11.3% lower than those for male drivers, respectively. In Barcelona, it was observed that female drivers had mean values of tyre wear emissions that were 18.6% and 17.9% lower compared to their male counterparts. During the transition from Phase 1 to Phase 2, the mean values of tyre wear emissions for female and male drivers in Leeds reduced by 1.6% and 1.8%, respectively. In Helsinki, the mean values of tyre wear emissions for female drivers decreased by 2.3% from Phase 1 to Phase 2, while for male drivers, the reduction was 14.9%. The mean values of tyre wear emissions exhibited a 2.3% reduction for female drivers and a 3.0% reduction for male drivers from Phase 1 to Phase 2 in Barcelona. The results above indicate the low-emission driver training programmes had positive effects on reducing tyre wear emissions for both female and male drivers, particularly for male drivers.

5.5 Effect of experience

Analysing the impact of driver experience on tyre wear emissions is essential for understanding the factors that contribute to environmental impacts in the field of transportation. Driver experience, which encompasses both driving skill and knowledge gained over time, can influence driving behaviours and habits that directly affect tyre wear emissions. This section investigates the effect of driver experience on tyre wear emissions.

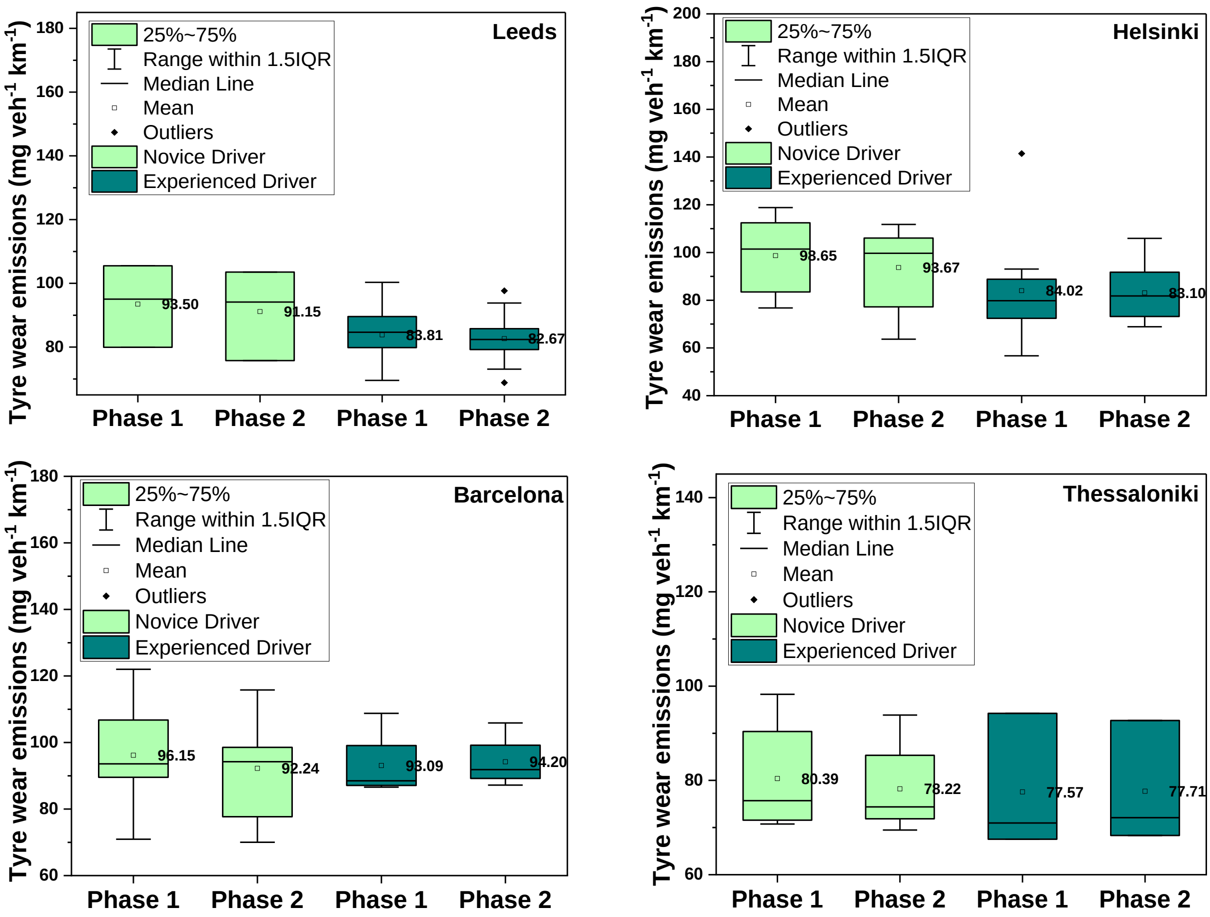


Figure 5.16: Effect of driver gender on before and after tyre wear emissions

To compare the effect of driving experience on the mean values of tyre wear emissions of experienced drivers were significantly lower than those of novice drivers., the drivers were divided into two groups, including experienced drivers and novice drivers. The experienced drivers were professional drivers with at least 5 years of driving experience. In comparison, the novice drivers had less than 5 years of driving experience. Figure 5.16 presents tyre wear emissions for novice and experienced drivers before and after the training programmes. Overall, the mean values of tyre wear emissions for experienced drivers were lower than those of novice drivers, except for drivers in Barcelona. In addition, it was found that mean values of tyre wear emissions for experienced and novice drivers reduced after the training. More precisely, there were reductions of 2.5% and 1.7% in tyre wear emissions for novice and experienced drivers from Phase 1 to Phase 2 in Leeds. In Helsinki, mean values of tyre wear emissions for novice and experienced drivers reduced by 5.0% and 1.1% from Phase 1 to Phase 2, respectively. In Barcelona, it was observed a reduction of 4.1% for novice drivers from Phase 1 to Phase 2, while the corresponding values increased by 1.2% for experienced drivers. Similarly, in Thessaloniki, the mean values of tyre wear emissions for novice drivers decreased by 2.7%, whereas there was a slight increase of 0.2% in tyre wear emissions for experienced drivers.

5.6 Summary for tyre wear emissions

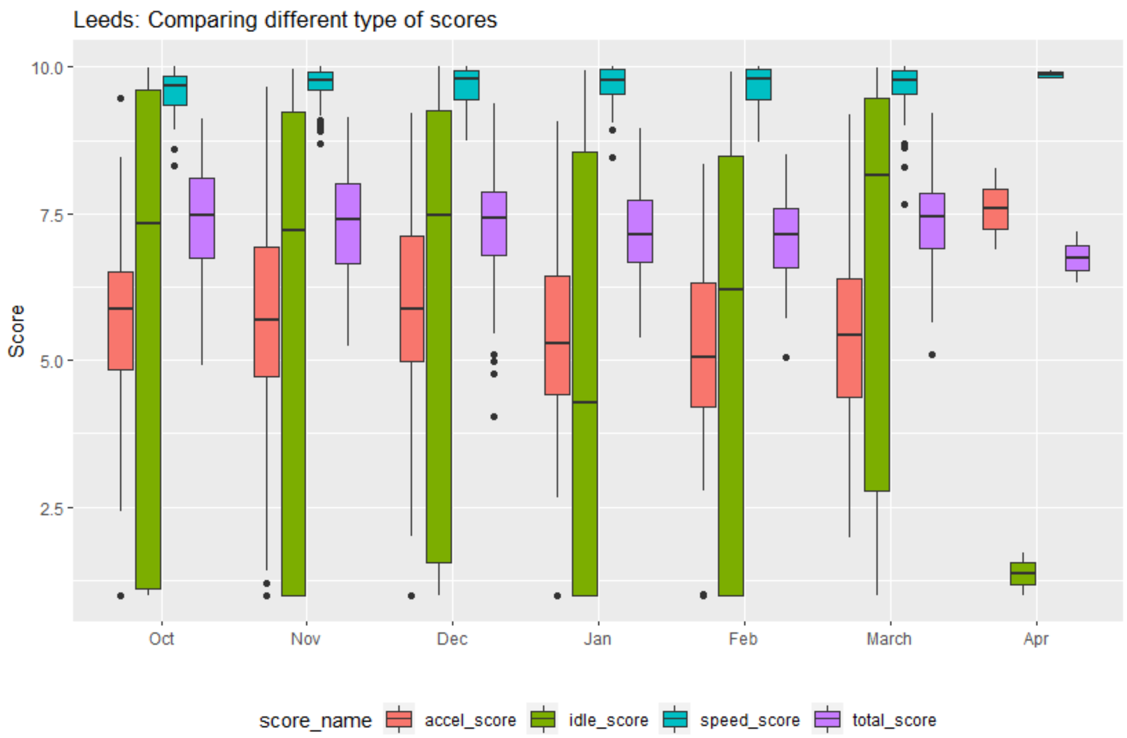
In this chapter, the differential influences of driving behaviour, such as road types, individual drivers, driver gender, and driver experience, were evaluated on tyre wear emissions in seven European cities. The main conclusions can be summarised as follows:

- Generally, low-emission driver training programmes can contribute to reductions in tyre wear emissions. Bergamo demonstrated the most substantial improvements in tyre wear emissions, while there was the least improvement in Thessaloniki.
- The mean values of tyre wear emissions were highest on motorways, followed by rural and urban roads.
- There were variations among individual drivers in terms of their influence on tyre wear emissions. However, the training and app demonstrated overall effectiveness in reducing tyre wear emissions for the majority of users across all road types.
- The low-emission driver training successfully decreased tyre wear emissions for both female and male drivers. However, male drivers experienced more significant reductions compared to their female counterparts.
- Following the training and app usage, novice drivers experienced a more substantial reduction in tyre wear emissions compared to experienced drivers.

6 Differential influences of journey-based driving behaviour on emissions

6.1 Different types of journey scores

Prior to detailed analysis of the journey scores, fuel consumption, and emission data, it is important to understand that different type of scores were calculated for each journey type, which included total score, acceleration score, speed score, and idle score. These scores are presented in Figure 6.1 (upper-panel) for each month for Leeds site, where the driving trial started in October 2022 and ended in April 2023. The scores ranged from 0 to 10, where higher score showed better driving behaviour in terms of acceleration and deceleration (braking) frequency and duration. Different types of journey scores demonstrated strong positive association with each other (Figure 6.1). Therefore, in this report only total score is analysed because of two reasons: (a) analysis of various types of scores for different sites will make the report unnecessarily long and cumbersome; (b) total score has strong correlation with other score types. As an example, scatter plot between total score and acceleration score is shown in Figure 6.1 (lower-panel), which demonstrated a correlation coefficient of 0.86 and r – squared of 0.73.



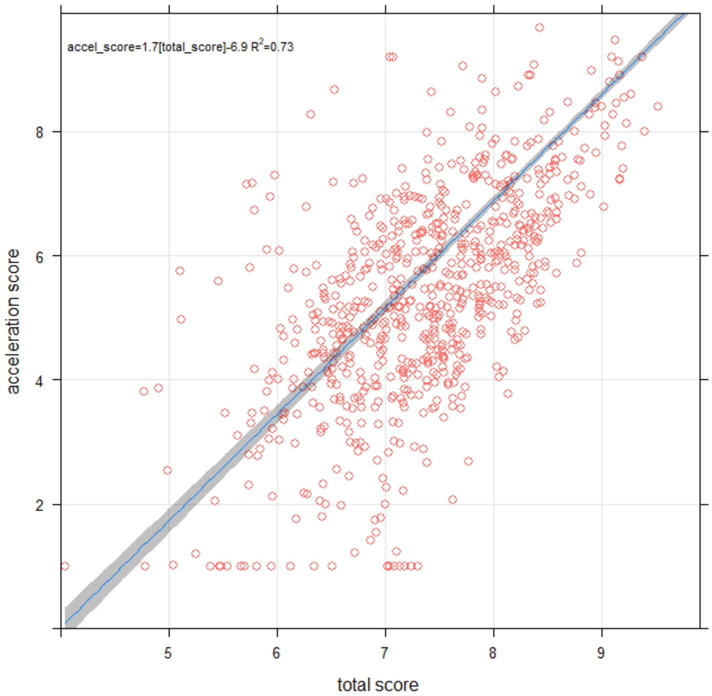


Figure 6.1: Association between different types of score (box plot: upper-panel), and scatter plot (lower-panel) for Leeds

Total score was used to estimate the amount of fuel consumption and pollutant emissions. The following regression equations (which were developed by Okan University) were used to estimate total emissions, PM emissions, and fuel consumption.

$$Y = -0.0021X+0.0444 \qquad (6.1)$$

Y is the aggregated or total emissions and X is the total score.

$$Y = -0.3734X+7.7068 \qquad (6.2)$$

Y is the fuel consumption and X is the total score.

$$Y = -0.182X+2.8668 \qquad (6.3)$$

Y is the PM emissions and X is the total score.

Figure 6.2 shows how total score is correlated with fuel consumption, total emissions, and PM emissions. Total score is inversely correlated with total emission, PM emission and fuel consumption. On the other hand, fuel consumption, total emissions and PM emission are directly correlated with other. Figure 6.2 shows very strong correlation between these variable.

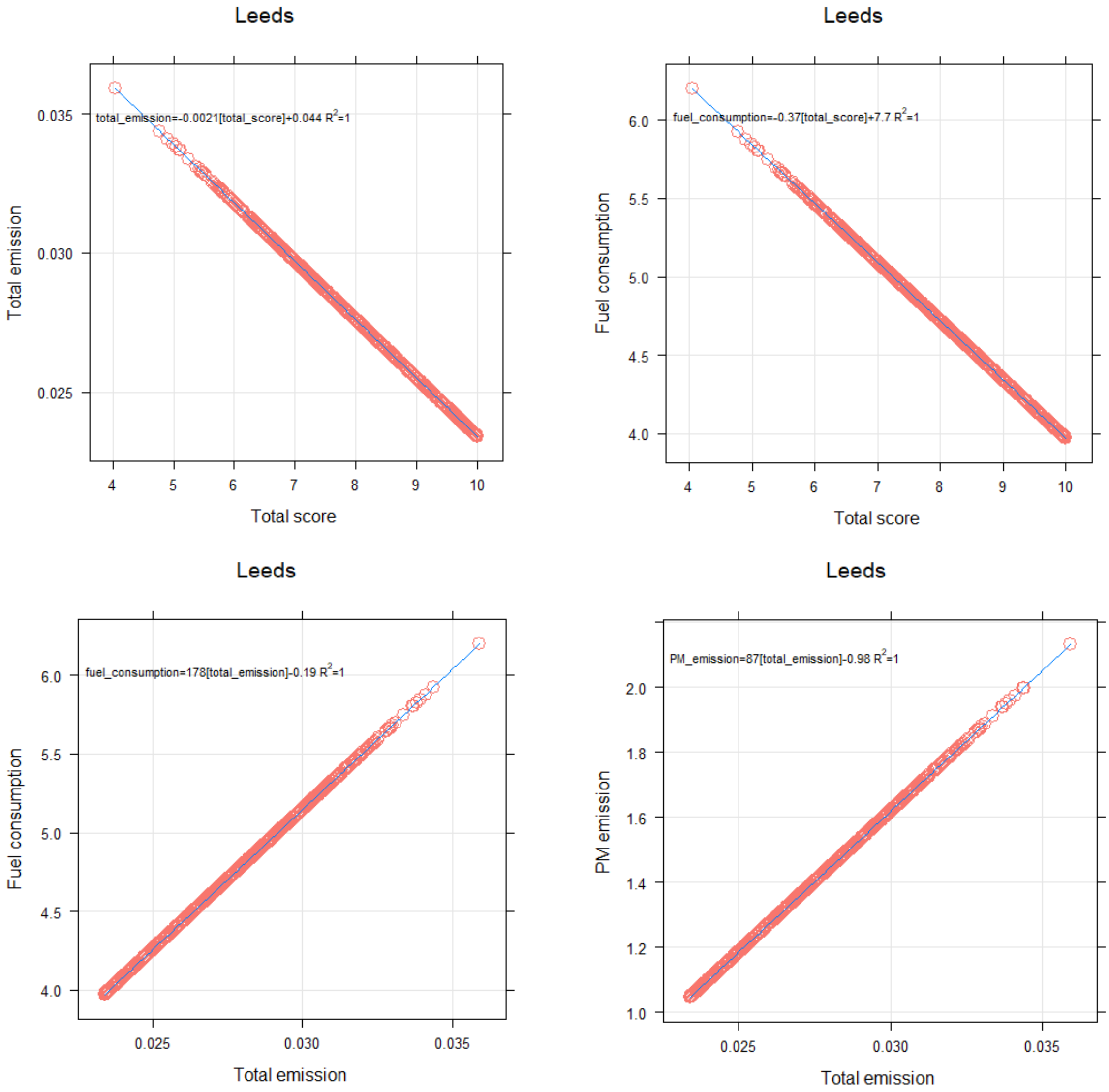


Figure 6.2: Correlation between total score, total emission, PM emission and fuel consumption at Leeds

6.2 Analysis of Phase 1 vs. Phase 2

Firstly, the average total score is analysed for Phase 1 vs. Phase 2 using both graphical presentations and statistical tests at different sites. Average total scores for different sites in Phase 1 and Phase 2, their difference, and % difference are shown in Table 6.1. All sites demonstrated higher scores in Phase 2, which showed that total scores have improved in Phase 2 as a result of the training intervention. The greatest percentage change was shown by the Bergamo site (16%), followed by Barcelona (12%). Paired t-test and its nonparametric alternative Wilcoxon test showed significant difference between Phase 1 vs. Phase 2 at all sites. Box plots in Figure 6.3, in addition to mean values, show more information i.e. median, interquartile range, minimum and maximum scores for each site.

Table 6.1: Total scores and their difference for Phase 1 vs. Phase 2 for different sites

Site	Phase 1	Phase 2	Difference	% Difference	t-test /Wilcoxon test
Leeds	7.94	7.99	0.05	0.63	0.02/0.01
Barcelona	7.97	8.88	0.91	11.42	$2.79 \times 10^{-10}/4.782 \times 10^{-10}$
Helsinki	8.71	8.92	0.21	2.41	0.0001 / 0.0031
Istanbul	8.09	8.69	0.60	7.42	0.002/0.001
Bergamo	7.93	9.21	1.28	16.14	2.2×10^{-16} / 9.9×10^{-15}
Thessaloniki	8.94	9.17	0.23	2.57	0.013 / 0.035
Luxembourg	8.23	8.75	0.52	6.32	0.005/0.011

Figure 6.3: Box plots of total scores of Phase 1 vs. Phase 2 for different sites

Figure 6.4 demonstrated reduction in the levels of PM emission, total emission and fuel consumption in Phase 2 for users at the Leeds site. The same trends were also observed for other sites. This demonstrates that the training and active recommendations by the MODALES App have helped the drivers to improve their driving behaviour and as a results pollutant emissions have decreased in Phase 2.

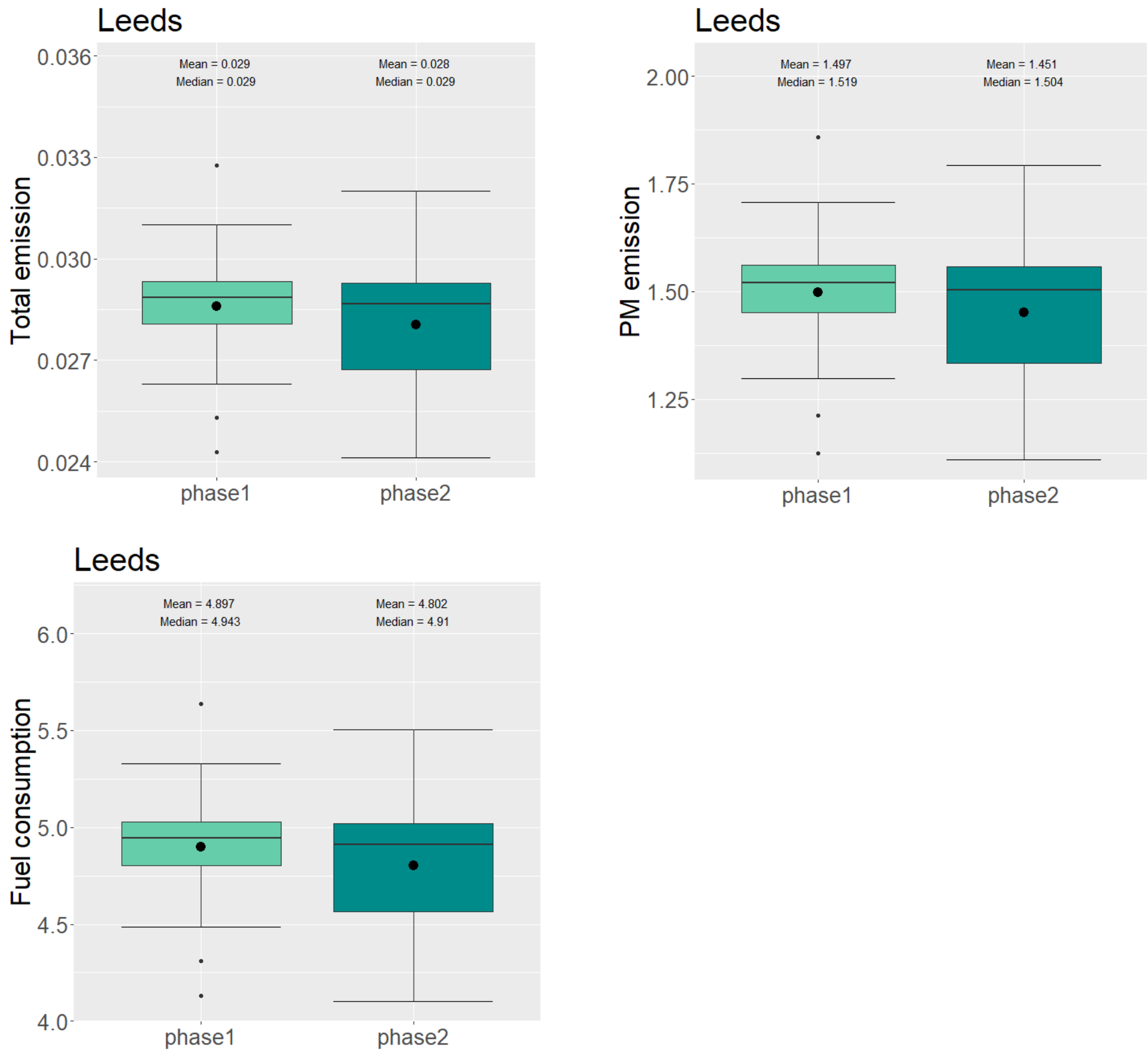


Figure 6.4: Box plots of fuel consumption, total emissions and PM emissions of Phase 1 vs. Phase 2 for Leeds

6.3 Effect of road types

Total scores were compared in Phase 1 vs. Phase 2 on different road types for different trial sites. The results are summarised in Table 6.2. Total scores have increased in Phase 2 for urban (U) and urban-rural (UR) trips, whereas the score has slightly decreased on urban-motorway (UM) and urban-motorway-rural (UMR) trips in Leeds. It is important to mention that U, M and R stands for urban, motorways and rural roads, respectively. When two or three road types are combined such as UMR, this means the trip was carried out using urban, motorways and rural roads. When a road type is not shown, this means either Phase 1 or Phase 2 data did not exist for that particular road type. A single journey score was calculated for each trip, therefore it was not possible to apportion a part of the trip to a particular road type. It is interesting to see that different types of roads have demonstrated slightly different pattern for different sites. For example, for urban trips total score has increased in Phase 2 for all sites, except Helsinki, likewise total score for urban-motorways trips has decreased in Phase 2 for Leeds and Helsinki but increased for Istanbul and Luxembourg.

Table 6.2: Total scores for Phase 1 vs. Phase 2 by different road types for different sites

In the table U = urban, M = motorways, R = rural.

Site	Road type	Mean		Median	
		Phase 1	Phase 2	Phase 1	Phase 2
Leeds	U	8.06	8.33	8.06	8.33
	UM	7.13	6.56	7.13	6.56
	UMR	7.89	7.64	7.89	7.64
	UR	8.05	8.29	8.05	8.29
Barcelona	M	8.75	9.96	9.38	9.96
	U	7.81	8.4	8.33	8.59
	UM	8.66	8.59	9.01	8.74
	UMR	8.24	8.76	8.34	8.69
	UR	8.53	9.17	8.95	9.59
Helsinki	R	9	9.91	9.38	9.88
	U	9.16	8.54	9.43	8.65
	UM	8.55	8.26	8.68	8.3
	UMR	9.05	9.22	9.33	9.55
	UR	8.86	9.08	8.93	9.56
Istanbul	M	7.51	6.92	7.41	6.85
	MR	7.52	9.85	6.85	9.85
	R	7.85	8.46	7.81	8.46
	U	8.05	8.61	8.08	8.66
	UM	8.09	9.12	8.44	9.39
	UMR	7.88	8.38	7.97	8.41
Bergamo	R	8.65	9.95	8.65	9.95
	U	8.63	9.27	8.5	9.53
	UMR	6.95	8.57	6.9	8.64
	UR	7.53	9.21	7.48	9.7
Luxembourg	M	8.76	8.86	8.92	8.86
	U	8.83	8.90	8.65	8.65
	UM	7.53	8.58	7.43	8.58
	UMR	7.81	8.66	7.84	8.58
	UR	7.83	8.22	7.87	7.73
Thessaloniki	MR	9.38	9.8	9.74	9.8
	R	9.49	9.3	9.49	9.59
	U	8.76	8.84	8.69	8.78
	UMR	8.88	9.12	9.19	9.45
	UR	8.89	9.29	9.16	9.47

ANOVA and Kruskal-Wallis rank sum test showed significant difference between different roads types at all sites.

Figure 6.5 shows box plots of total score for Leeds and Helsinki. In Helsinki all road types are shown even those which do not have data for Phase 2. Best vs. worst road type in terms of total score change in Phase 1 vs. Phase 2 are analysed and the results are depicted in Figure 6.6. Bergamo UR trips demonstrated the highest increased in total score in Phase 2, which was 24 %. Figure 6.7 depicts fuel consumption and PM emissions for Helsinki which shows the opposite trend to total score. Emissions and fuel consumption demonstrated opposite trend to total score for all sites. Analysis of variance (p-value < 0.05) demonstrated significant difference between different road types for total scores as well as for fuels consumption and emission.

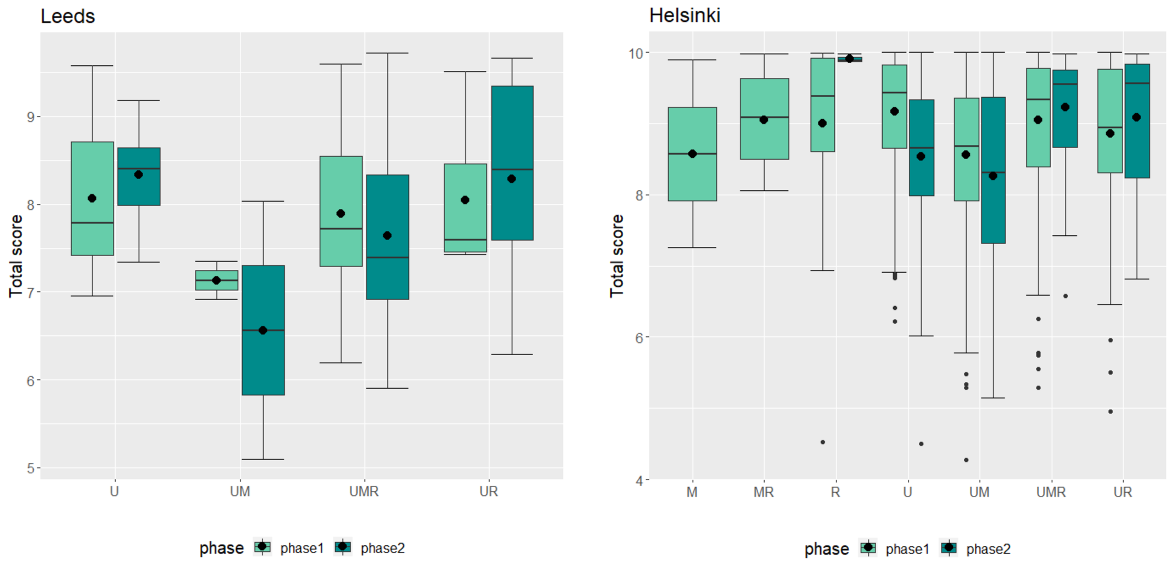
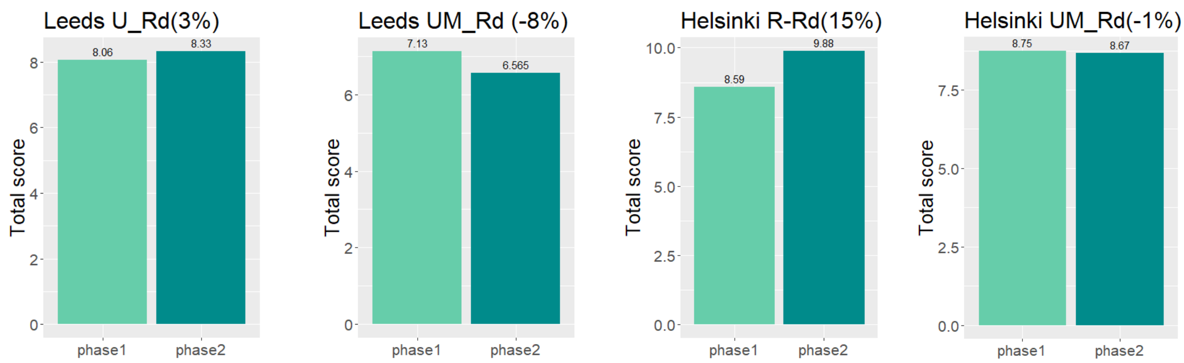


Figure 6.5: Total score of Phase 1 vs. Phase 2 by different road types for Leeds (upper panel) and Helsinki (lower panel)



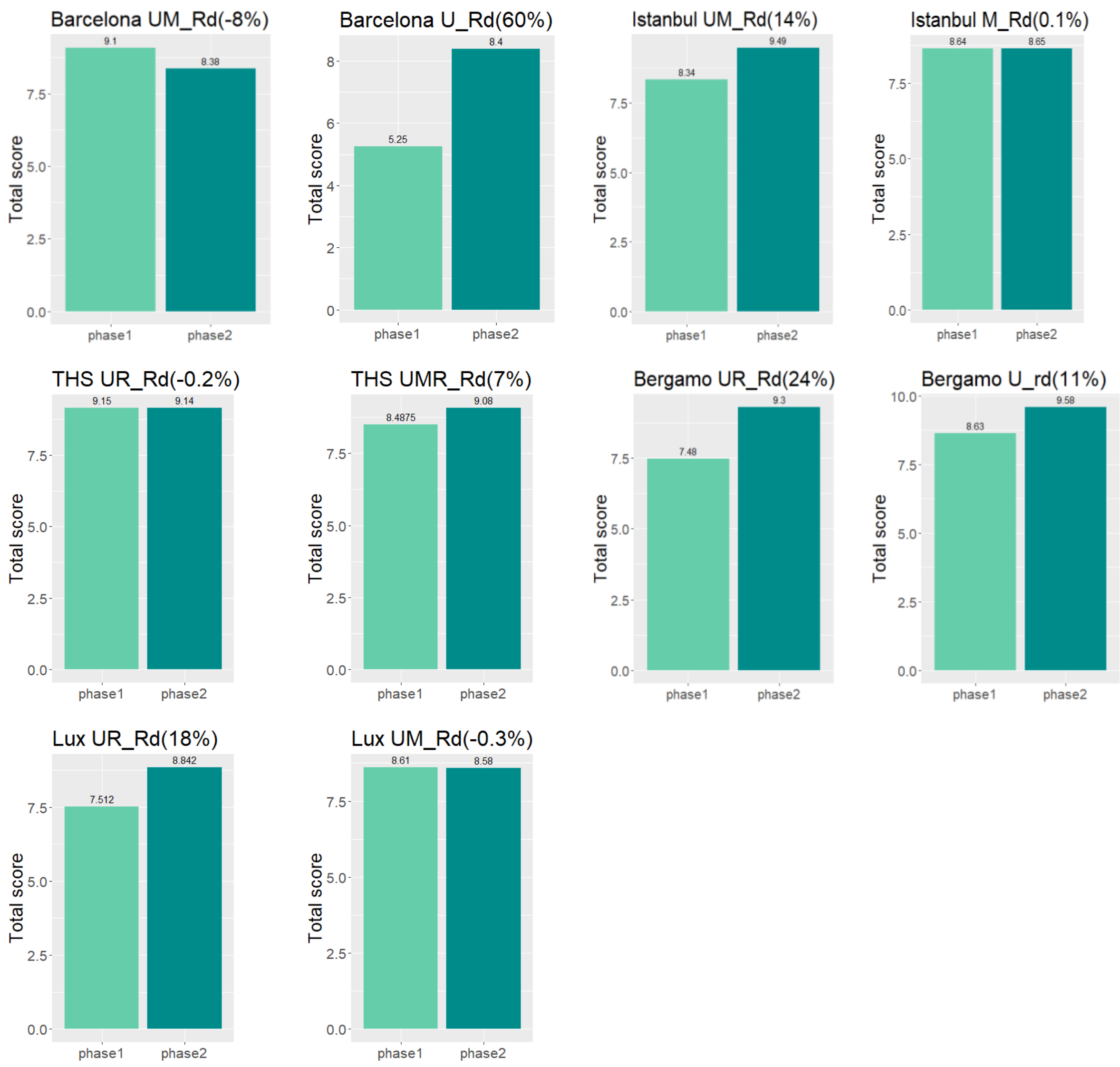


Figure 6.6: Best vs. worst road type in terms of total score change in Phase 1 vs. Phase 2

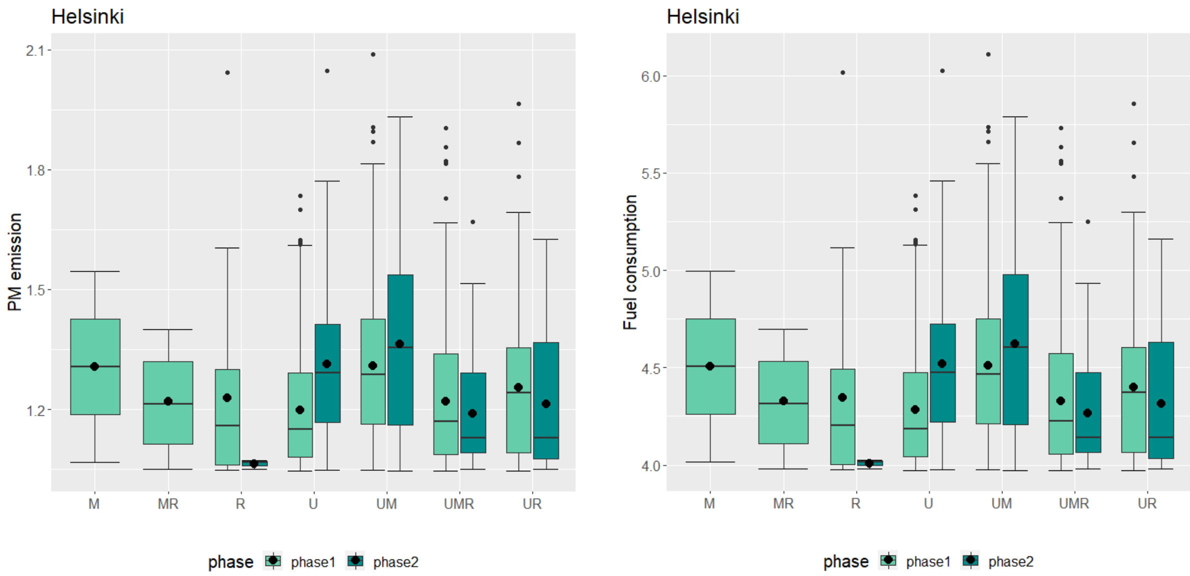


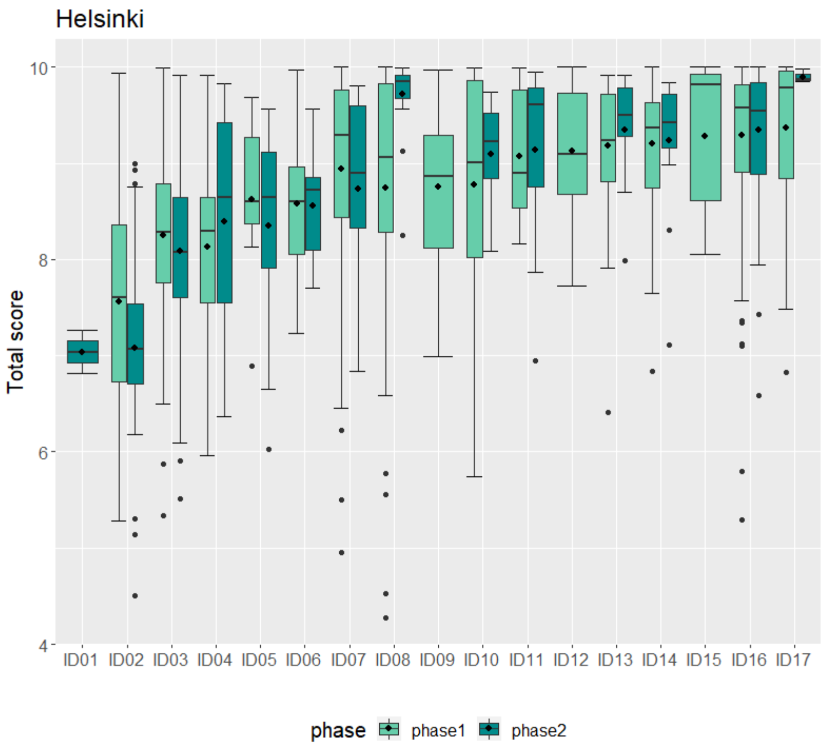
Figure 6.7: PM emissions (upper-panel) and fuel consumption (lower-panel) of Phase 1 vs. Phase 2 for different road types for Helsinki site

6.4 Effect of users

Different users have different driving styles and driving behaviour, therefore, they are affected differently by interventions. Furthermore, the effect of intervention is affected by driving environment, road type and personal characteristics such as age and gender. In this section, the effect of the training intervention and active recommendation is analysed for each user at different monitoring sites. Table 6.3 presents the results for each user, their difference and percent difference for Leeds. It can be noticed in the table that only 15 drivers have collected data in both Phase 1 and Phase 2. The drivers that had not collected data in Phase 2 are not shown in the table. Out of these 8 drivers have improved their scores in Phase 2, whereas 7 drivers have not improved their scores in Phase 2. Overall, the average score has improved in Phase 2 for Leeds. However, due to the limited duration, especially in Phase 2, the results are not improved for all drivers for any site. Total score for Helsinki along with fuel consumption is depicted in Figure 6.8, where 9 drivers improved their score and decreased their emission and fuel consumption. More details are provided in Table 6.4, which presents the results for Helsinki and in addition to the effect of user, compares total scores for different road types for each user. Analysis of variance test showed significant difference (p-value < 0.05) between different users at each site.

Table 6.3: Total score of Phase 1 vs. Phase 2 by user ID for Leeds

ID	Phase1	Phase 2	diff	percent
ID01	6.20	5.90	-0.30	-4.84
ID03	7.18	8.41	1.23	17.13
ID04	7.14	6.77	-0.37	-5.18
ID06	7.24	7.34	0.10	1.38
ID07	7.46	7.92	0.46	6.17
ID08	7.58	7.48	-0.10	-1.32
ID10	7.85	7.70	-0.15	-1.91
ID12	7.60	7.92	0.32	4.21
ID13	7.79	7.77	-0.02	-0.26
ID15	8.17	8.39	0.22	2.69
ID16	8.48	8.06	-0.42	-4.95
ID18	8.67	8.45	-0.22	-2.54
ID21	8.89	9.18	0.29	3.26
ID22	8.93	9.18	0.25	2.80
ID24	9.55	9.64	0.09	0.94
Mean	7.92	8.01	0.09	1.17



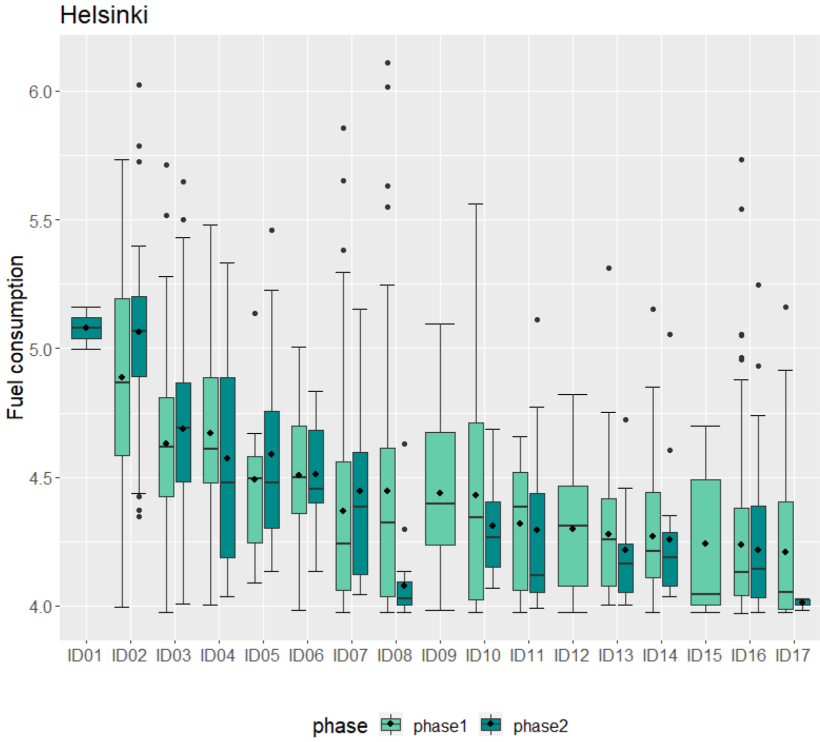


Figure 6.8: Total score (upper-panel) and fuel consumption (lower-panel) for Phase 1 vs. Phase 2 for different users at Helsinki

Figure 6.9 presents best and worse scores for drivers at each site. Luxembourg demonstrated the highest improvement in score (64%) followed by Barcelona (60 %). When like-for-like in terms of road type comparison was made for Bergamo, only one driver had data for both phases and had improved score by 19 % (not presented in Figure 6.9). To compare personal drivers (the drivers who drive only for commuting, socialising and shopping etc.) and professional drivers (e.g., taxi drivers, bus drivers, driving school trainers etc.), data was analysed for Leeds and Barcelona sites. In Leeds trial there were 6 professional drivers and 21 personal drivers, where in Barcelona there were 3 professional and 23 personal drivers. For other sites either the data was not available or they had only personal drivers. The results are presented in Figure 6.10 for both Leeds and Barcelona, which shows that professional drivers have not improved their total score, whereas personal drivers have improved their score in Phase 2. This is interesting to see that professional drivers are more reluctant to change their driving behaviour compared to personal drivers. Fuel consumption and emissions decreased in Phase 2 for personal drivers but not for professional drivers at both Barcelona and Leeds.

Table 6.4: Total score of Phase 1 vs. Phase 2 by user ID and road type at Helsinki

ID	Road type	Phase 1		Phase 2	
		Mean	Median	Mean	Median
ID02	U	8.32	8.32	7.23	7.29
ID02	UM	7.38	7.39	7.05	6.96
ID03	U	8.71	9.08	8.89	8.89
ID03	UM	8.17	8.23	7.93	7.99
ID03	UMR	8.16	8.24	8.39	8.37
ID03	UR	8.4	8.29	8.52	8.51
ID04	U	8.55	8.55	8.02	7.97
ID04	UMR	7.66	7.66	7.80	7.80
ID04	UR	7.87	8.16	9.44	9.44
ID05	U	8.62	8.6	8.35	8.65
ID06	UM	8.16	7.7	8.63	8.63
ID06	UMR	8.69	8.76	8.81	8.81
ID06	UR	8.08	8.04	8.10	8.10
ID07	UM	8.41	8.61	6.84	6.84
ID07	UMR	9.04	9.34	8.90	8.90
ID07	UR	8.86	9.22	9.26	9.73
ID08	R	8.59	9.07	9.88	9.88
ID08	U	9.03	9.22	9.61	9.61
ID08	UM	8.32	8.87	9.92	9.92
ID08	UMR	8.43	8.65	9.75	9.81
ID08	UR	9.02	9.47	9.64	9.85
ID10	U	9.00	9.00	9.08	9.08
ID10	UMR	7.87	8.48	9.14	9.39
ID10	UR	8.82	8.64	9.07	9.10
ID11	U	8.54	8.54	9.02	9.13
ID11	UM	9.88	9.88	8.56	9.07
ID11	UR	8.53	8.53	9.24	9.52
ID13	U	9.16	9.44	9.46	9.66
ID13	UM	9.2	9.23	9.23	9.39
ID14	U	9.31	9.44	9.81	9.81
ID14	UM	9.13	9.32	9.19	9.36
ID16	U	9.47	9.78	8.91	8.65
ID16	UM	9.19	9.34	9.46	9.47
ID16	UMR	9.28	9.58	9.33	9.61
ID16	UR	9.35	9.58	9.82	9.82
ID17	UM	9.65	9.76	9.85	9.85
ID17	UMR	9.35	9.87	9.98	9.98
Mean		8.71	8.86	8.92	9.00

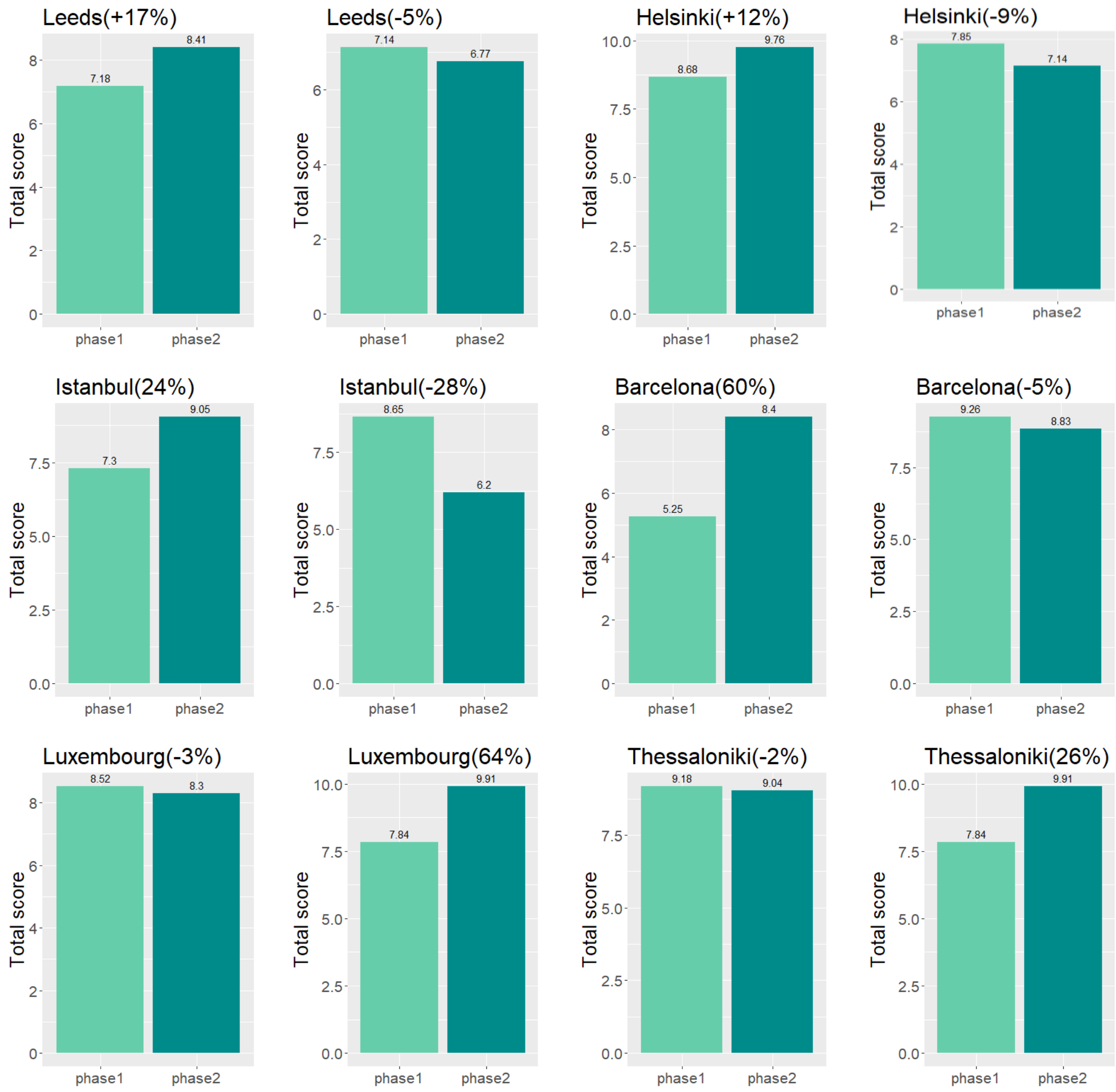


Figure 6.9: Best vs. worst driver in terms of total score change in Phase 1 vs. Phase 2 at different sites

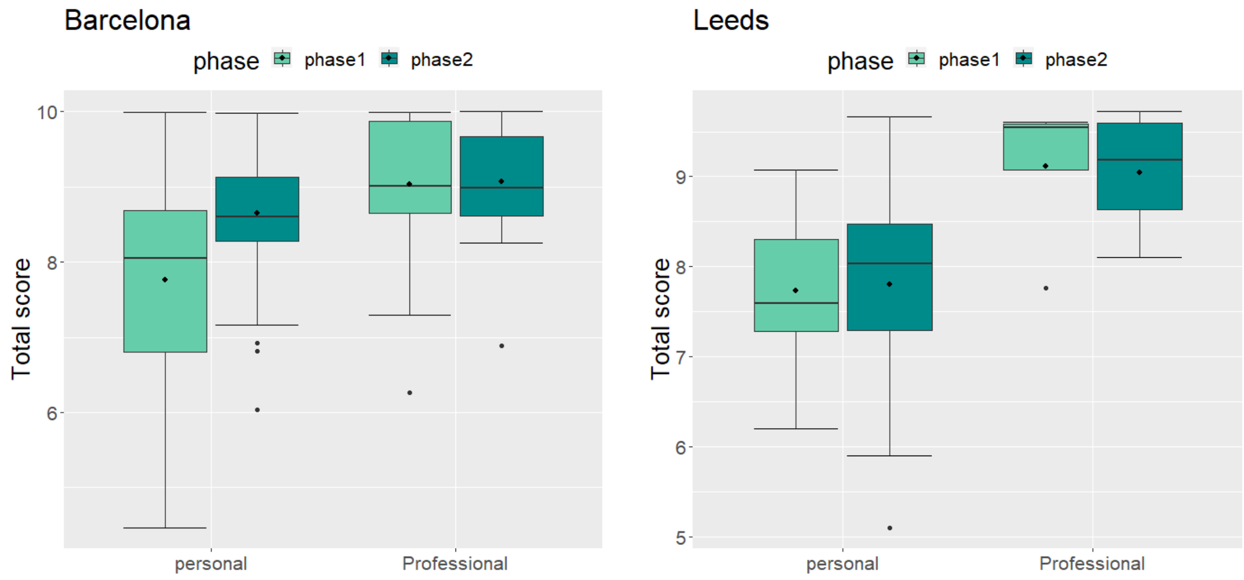
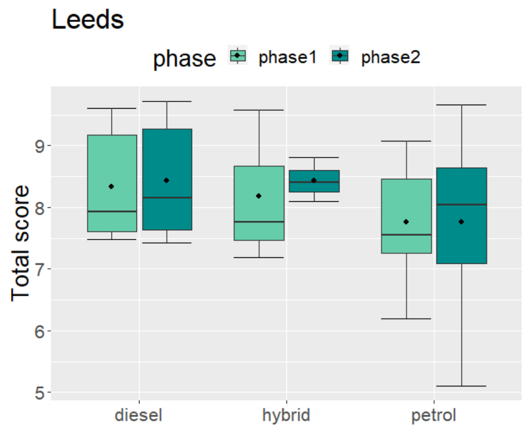
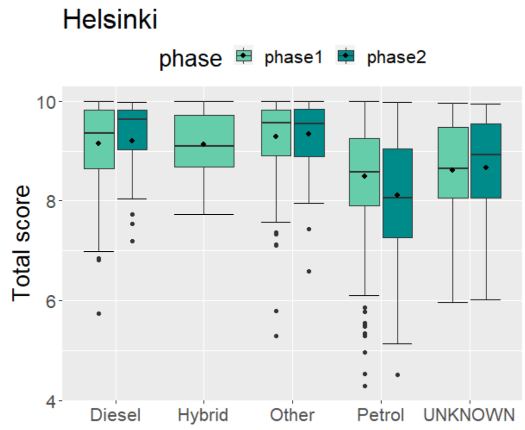


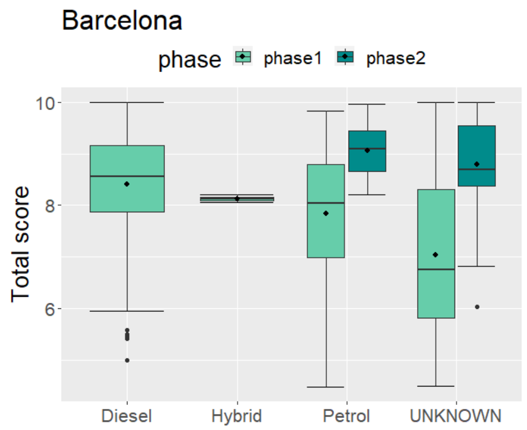
Figure 6.10: Personal vs. professional and male vs. female drivers in terms of total scores for Phase 1 vs. Phase 2 for Leeds and Barcelona

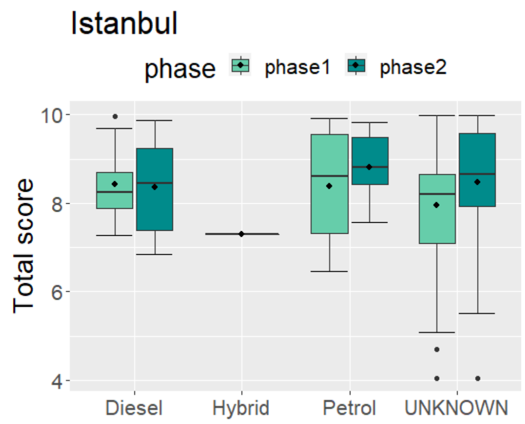
6.5 Effect of vehicle types

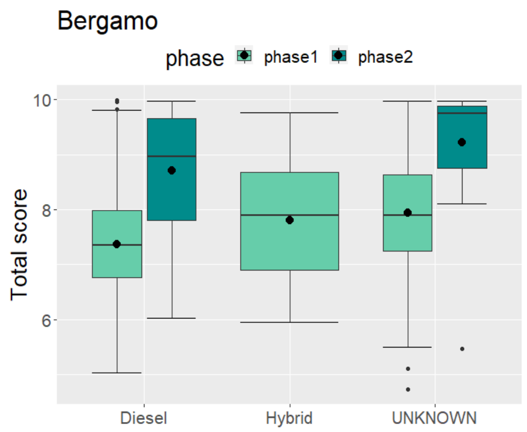
It is interesting to see that drivers of different type of vehicles have responded differently to the intervention training. The change in total score, fuel consumption and emissions in Phase 2 varied from site to site. How total scores have changed with vehicle types at each site is shown in Figure 6.11, where different types of vehicles shown are petrol, diesel, hybrid, electric, other and unknown. Other are those vehicles that are not the four main types: petrol, diesel, hybrid, and electric, therefore these could be alternative fuels vehicles such as biodiesel, compressed natural gas (CNG), liquid petroleum gas (LPG), hydrogen, ethanol etc. Unknown are vehicle that have not specified by the user. Where data are shown only for Phase 1, this mean data for Phase 2 was not available. The results varied from site to site, for example, total scores of petrol vehicles have increased in Phase 2 for Leeds, Barcelona, Istanbul and Luxembourg, and decreased for Helsinki. Data for hybrid vehicles for both phases was only available for Leeds and Thessaloniki, where score in Phase 2 has increased for Leeds, and decreased for Thessaloniki. Data for electric vehicles for both phases was only for Luxembourg and Thessaloniki, where both sites showed improvement in total score in Phase 2. Analysis of variance test demonstrated significant difference (p-value < 0.05) in total scores between vehicle types at different sites. Percent change in total score in Phase 2 for different fuel types for different sites are presented in Table 6.5. Top 5 highest increase in scores were 29 % for electric vehicle at Luxembourg, 25% for unknown vehicles at Barcelona, 18% for diesel vehicles at Bergamo, 16 % for petrol vehicle at Barcelona, and 16% for unknown vehicles at Bergamo (Table 6.5).

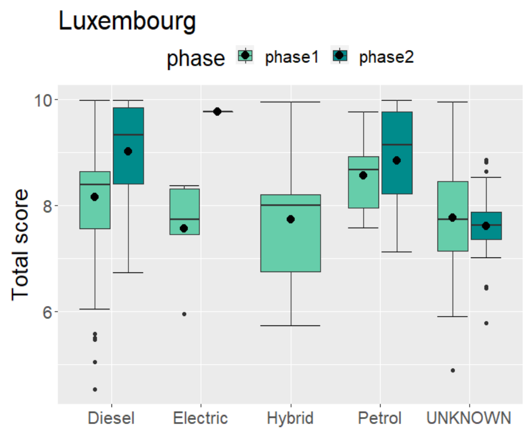

Leeds
phase
phase1
phase2
Total score
diesel
hybrid
petrol


Helsinki
phase
phase1
phase2
Total score
Diesel
Hybrid
Other
Petrol
UNKNOWN


Barcelona
phase
phase1
phase2
Total score
Diesel
Hybrid
Petrol
UNKNOWN


Istanbul
phase
phase1
phase2
Total score
Diesel
Hybrid
Petrol
UNKNOWN


Bergamo
phase
phase1
phase2
Total score
Diesel
Hybrid
UNKNOWN


Luxembourg
phase
phase1
phase2
Total score
Diesel
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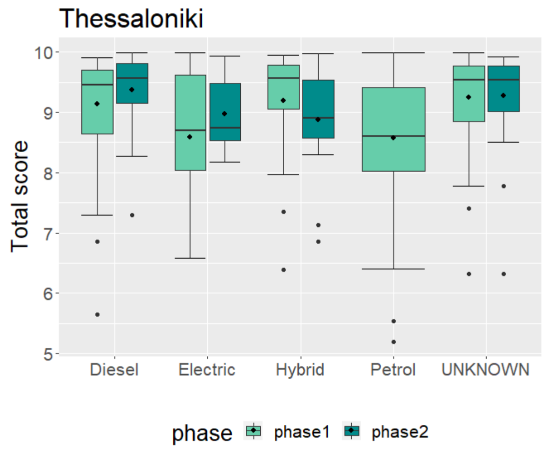


Figure 6.11: Total score of Phase 1 vs. Phase 2 by vehicle types at different sites

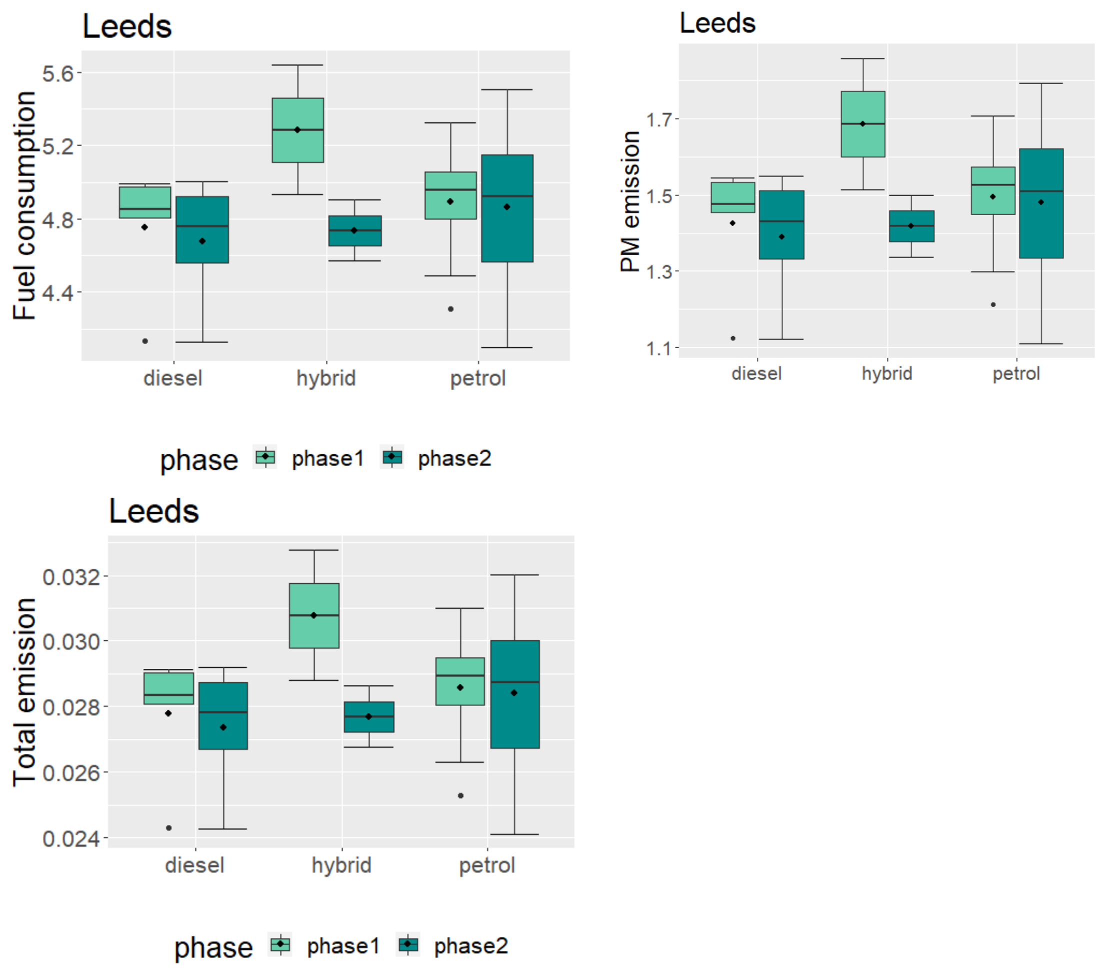


Figure 6.12: Fuel consumption, PM emissions and total emissions of Phase 1 vs. Phase 2 by vehicle types at Leeds site

Table 6.5: Total score of Phase 1 vs. Phase 2 for different fuel types

Site	Fuel type	Phase1	Phase2	Difference	% difference
Leeds	Diesel	8.48	8.24	-0.25	-2.89
	Electric	9.90	NA	NA	NA
	Hybrid	8.86	8.69	-0.17	-1.90
	Petrol	8.06	8.44	0.37	4.44
Luxembourg	Diesel	8.16	9.02	0.86	10.54
	Electric	7.56	9.77	2.21	29.16
	Petrol	8.57	8.85	0.28	3.26
	Unknown	7.77	7.62	-0.15	-1.95
Thessaloniki	Diesel	9.14	9.37	0.24	2.58
	Electric	8.59	8.98	0.39	4.49
	Hybrid	9.19	8.88	-0.31	-3.40
	Petrol	8.57	NA	NA	NA
Barcelona	Diesel	8.41	NA	NA	NA
	Hybrid	8.13	NA	NA	NA
	Petrol	7.83	9.06	1.23	15.68
	Unknown	7.03	8.79	1.77	25.15
Helsinki	Diesel	9.15	9.21	0.06	0.60
	Hybrid	9.13	NA	NA	NA
	Other	9.29	9.34	0.06	0.61
	Petrol	8.49	8.12	-0.38	-4.43
	UNKNOWN	8.61	8.66	0.05	0.57
Istanbul	Diesel	8.42	8.35	-0.07	-0.80
	Hybrid	7.30	NA	NA	NA
	Petrol	8.39	8.81	0.42	5.02
	UNKNOWN	7.94	8.47	0.52	6.60
Bergamo	Diesel	7.37	8.71	1.35	18.27
	Hybrid	7.80	NA	NA	NA
	UNKNOWN	7.93	9.21	1.28	16.16

6.6 Effect of age groups and gender

In this section, we analysed how total score, fuel consumption, total emission and PM emission have varied in Phase 1 and 2 by age group of the drivers. The age groups for which data existed were 20 – 29, 30 – 49, 50 – 64, and 65+ for Leeds, whereas for Barcelona, Bergamo and Helsinki data was available only for the first three groups. Leeds and Helsinki demonstrated exactly similar results for the first three age groups. Minimum total score was observed for the age group 65+, followed by 20 – 29 age group. When Phase 1 was compared to Phase 2, total score decreased in Phase 2 for the age groups 30 – 49 and 65+, whereas total score increased in Phase 2 for 20 – 29 and 50 – 64 for Leeds. Age group 30 – 49 also demonstrated reduction in total score in Phase 2, whereas the score increased for the other two groups for Helsinki (Figure 6.13). However, no data was available for age group 20 – 29, whereas total score increased in age group 30 – 49 and 50 – 64 for Barcelona (Figure 6.14). No data was available for any site for the age group 65+, except Leeds.

In contrast, fuel consumption, PM emission and total emissions demonstrated the opposite trend to total score, which meant their levels decreased in Phase 2 for the age group 20 – 29 and 50 – 64 and increased for the other two age groups. Difference in emission and fuel consumption was significant between different age group (p-value < 0.05). It is interesting to see that for Leeds youngest and oldest age group demonstrated the opposite results. In other words, the younger drivers were probably more willing to improve their driving behaviour. In contrast, the more experienced drivers are probably more reluctant to change as a result of the training intervention.

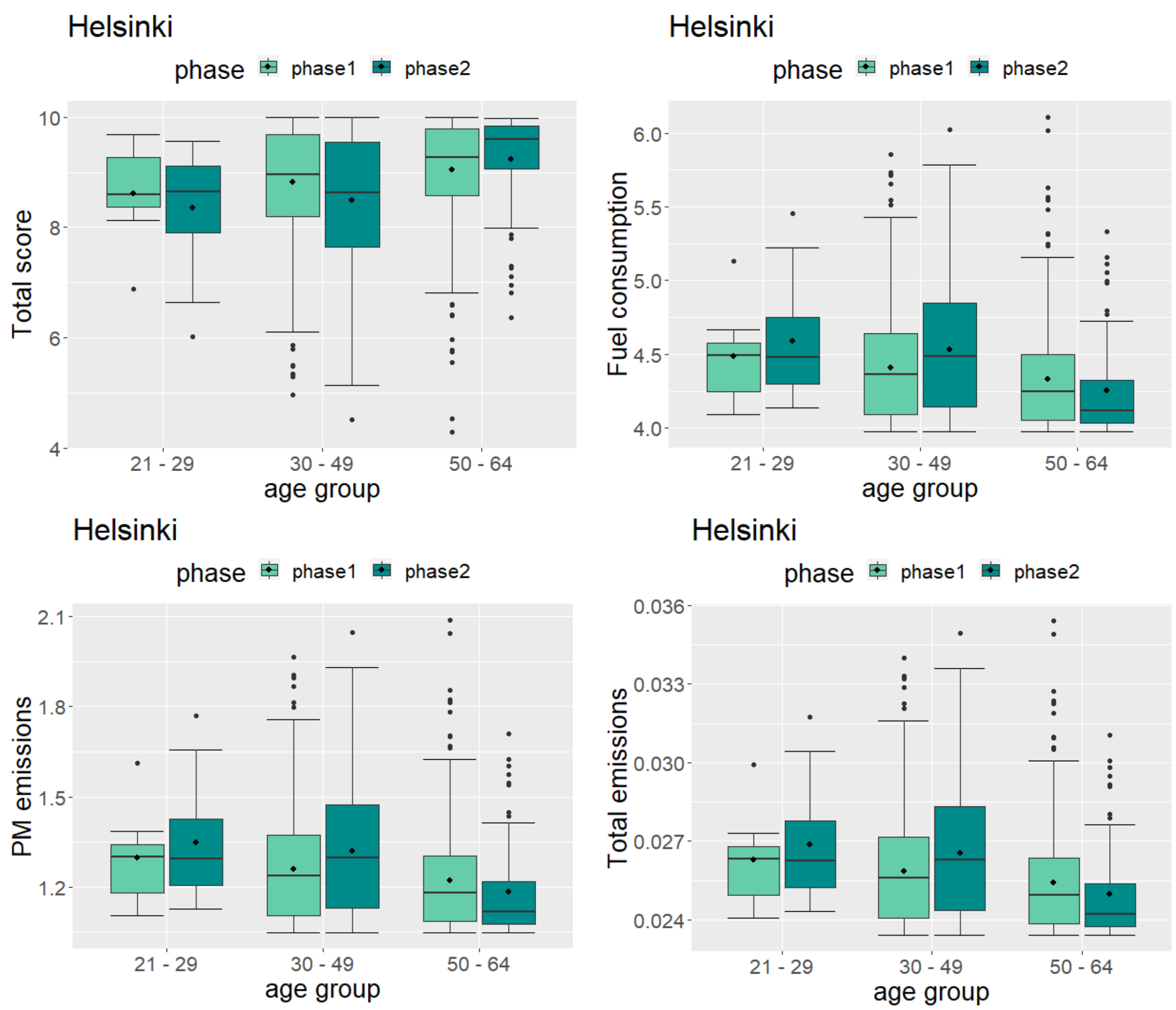


Figure 6.13: Total score, fuel consumption, PM emissions and total emissions of Phase 1 vs. Phase 2 by age group at Helsinki site

When total score was analysed for male vs. female in Phase 1 and Phase 2, the results were different for different sites (Figure 6.15). Leeds, Barcelona, Helsinki and Bergamo demonstrated improvement in total score for females (F) in Phase 2, however, males (M) demonstrated increase for other sites, except Helsinki, where total score decreased for male drivers in Phase 2. Finally, total score is classified by gender and age groups (Table 6.6). Only two age groups existed for females (30-49 and 50-64) at the Leeds site, where total score increased 4.55 % for the first groups. For male drivers the score increased by 2.64 % for 20-29 age groups and decreased by 4.78 % for the 70-79 age groups at Leeds. For Helsinki total score increased for male age groups 50-64 by 2.58 % and decreased for age groups 21-29 and 30-49 by 3.77 % and 3.16 %, respectively. The only female age group in the Helsinki trial was 50-64 which demonstrated about 1 % increase in total score. In Barcelona the female driver age group 50-64 showed 23.23 % increase and male drivers' age group 30-49 showed 6.20 % increase. In Bergamo the female age group 30-49 showed 13.10 % increase, and the male age group 30-49 showed 18.11 % increase. It is clear from the analysis that data did not exist for all age groups for both male and female drivers. Therefore, results are not conclusive as to how age groups and gender affected total score as the results varied from site to site. In particular data for lower and upper age groups was missing for most of the sites.

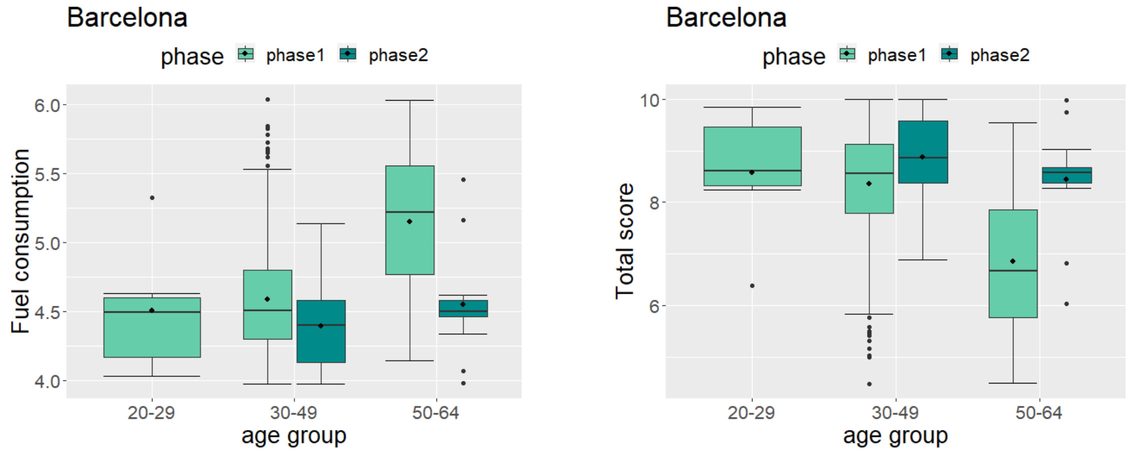


Figure 6.14: Total score, fuel consumption of Phase 1 vs. Phase 2 by age group at Barcelona site

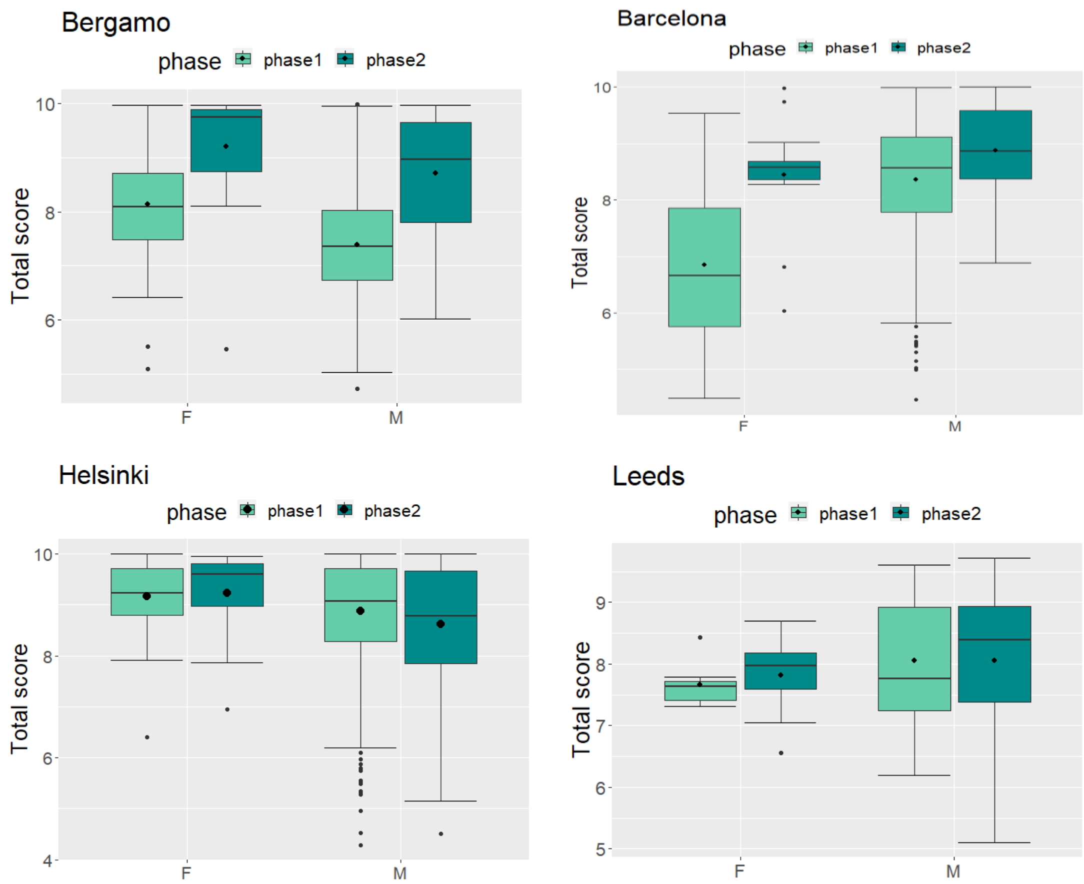


Figure 6.15: Total score of Phase 1 vs. Phase 2 by gender at Barcelona, Bergamo, Leeds, and Helsinki site

Table 6.6: Total score of Phase 1 vs. Phase 2 for different age groups and gender

Site	Gender	Age group	Phase1	Phase2	Difference	% Difference
Leeds	F	30-49	7.55	7.89	0.34	4.55
		50-64	7.85	7.70	-0.14	-1.79
	M	20-29	8.17	8.39	0.22	2.64
		30-49	8.42	8.40	-0.01	-0.13
		50-64	7.98	7.99	0.02	0.21
		65+	6.20	5.90	-0.30	-4.78
Helsinki	F	50 - 64	9.17	9.23	0.05	0.59
	M	21 - 29	8.62	8.35	-0.27	-3.16
		30 - 49	8.83	8.50	-0.33	-3.77
		50 - 64	9.02	9.25	0.23	2.58
Barcelona	F	50-64	6.85	8.45	1.59	23.26
	M	30-49	8.35	8.87	0.52	6.20
Bergamo	F	30-49	8.15	9.21	1.07	13.10
	M	30-49	7.38	8.71	1.34	18.11

6.7 Summary for influences of journey-based driving behaviour

The driving trial aimed to collect driver's profile data in the real driving conditions. The main way to monitor driver's behaviour was using the OBD Dongle, mobile app (MODALES App) and the web platform developed in WP5, which allowed the collection, analysis and recommendation of actions to be performed by a particular driver profile. The trials were carried out in seven sites: Leeds (UK), Helsinki (Finland), Barcelona (Spain), Istanbul (Turkey), Thessaloniki (Greece), Bergamo (Italy), and Luxembourg. The number of drivers varied from site to site, and consisted drivers of different age and gender. In Phase 1 the drivers used the OBD dongles and the MODALES App with no active recommendation for over 3 to 5 months. Phase 2 lasted 2 to 3 months, which started with watching a training video and MODALES App with active recommendations. Driver's behaviour is defined in terms of various journey scores, fuel consumption and pollutant emissions in this chapter. These parameters have been analysed for different types of roads, users, and vehicle types. The levels of these parameters have been compared in Phase 1 vs. Phase 2 using visual presentation and different statistical tests, such as paired t-test, Wilcoxon test, analysis of variance (ANOVA) and Kruskal-Wallis test by rank. Using various models total score was converted to emissions and fuel consumption. It is important to mention that various types of journey scores were positively correlated with each other, whereas the journey scores were inversely correlated with fuel consumption and pollutant emission. Therefore, total score was analysed as a representative of all other scores, however, fuel consumption and emissions were also analysed for most of the sites.

Firstly, total score of Phase 1 was compared to Phase 2, which showed that total scores have improved in Phase 2 as a result of the training intervention. Highest % change was shown by Bergamo site (16%), followed by Barcelona (12%). Paired t-test and Wilcoxon test showed significant difference between Phase 1 vs. Phase 2 at all sites. In contrast, the levels of PM emission, total emission and fuel consumption decreased in Phase 2. This demonstrates that the training and active recommendations by the MODALES App have helped the drivers to improve their driving behaviour and as a results pollutant emissions have decreased in Phase 2. Furthermore, total scores, fuel consumption and emissions were analysed for different road types, vehicles types, user types, age group and gender.

Total scores have increased in Phase 2 for urban and urban-rural trips, whereas the score has decreased on urban-motorway and urban-motorway-rural trips in Leeds. It is interesting to see that different road types have demonstrated slightly different pattern for different sites. For example, for urban trips total score increased in Phase 2 for all sites, except Helsinki. Likewise, total score for urban-motorways trips decreased in Phase 2 for Leeds and Helsinki but increased for Istanbul and Luxembourg. Bergamo urban-rural trips demonstrated the highest increased in total score in Phase 2, which was 24 %. Emissions and fuel consumption demonstrated opposite trend to total score for all sites. Analysis of variance (p-value < 0.05) demonstrated significant difference between different road types for total scores as well as for fuels consumption and emission.

At Leeds 15 drivers had collected data for both Phase 1 and Phase 2. Out of these 8 drivers improved their scores in Phase 2, whereas 7 drivers did not improve their scores in Phase 2. Overall, the average score improved in Phase 2 for Leeds. Total score for Helsinki was improved for 9 and decreased for 4 drivers, whereas their emissions and fuel consumption showed the opposite trend. Analysis of variance test showed significant difference (p-value < 0.05) between different users at each site. Luxembourg demonstrated the highest improvement in score for a single driver (64%) followed by Barcelona (60 %). To compare personal drivers and professional drivers, data was analysed for Leeds and Barcelona sites, which showed that professional drivers have not improved their total score, whereas personal drivers have improved their score in Phase 2. This is interesting to see that professional drivers are more reluctant to change their driving behaviour compared to personal drivers or maybe they were already following the useful guidelines. Fuel consumption and emissions decreased in Phase 2 for personal drivers but not for professional drivers at both Barcelona and Leeds.

Total score, fuel consumption and emission data was also analysed to assess the effect of age groups and gender. Leeds and Helsinki demonstrated exactly similar results for the first three age groups, which were 20 – 29, 30 – 49, and 50 – 64, however, there was no data for the 70 – 79 age group at Helsinki. Minimum total score was observed for the age group 70 - 79, followed by 20 – 29 age group T Leeds. When Phase 1 was compared to Phase 2, total score decreased in Phase 2 for the age groups 30 – 49 and 70 – 79, whereas total score increased in Phase 2 for 20 – 29 and 50 – 64 for Leeds. Age group 30 – 49 also demonstrated reduction in total score in Phase 2, whereas the score increased for the other two groups for Helsinki. However, no data was available for age group 20 – 29 and total score increased in age group 30 – 49 and 50 – 64 in Phase 2 for Barcelona. No data was available for any site for the age group 70 – 79, except Leeds, where score decreased in Phase 2 for this age group. In contrast, fuel consumption, PM emission and total emissions demonstrated the opposite trend to total score, which meant their levels decreased for the age group 20 – 29 and 50 – 64 and increased for the other two age groups. Difference in emission and fuel consumption was significant between different age group (p-value < 0.05). It is interesting to see that for Leeds youngest and oldest age group demonstrated the opposite results. In other words, the younger drivers were probably more willing to improve their driving behaviour, whereas the more experienced drivers are probably more reluctant to change as a result of the training. When total score was analysed for male vs. female in Phase 1 and Phase 2, the results were different at each site. Leeds demonstrated reduction in total score in Phase 2 for females and increase for males. Helsinki demonstrated the opposite results i.e. reduction in males and increase in female scores. Barcelona showed improvement in total score for both male and female drivers, whereas Bergamo did not show any changed in male and female drivers in both phases of the trial.

It is interesting to see that drivers of different type of vehicles have responded differently to the training. The change in total score, fuel consumption and emissions in Phase 2 due to vehicle type varied from site to site. For example, total scores of petrol vehicles have increased in Phase 2 for Leeds, Barcelona, Istanbul and Luxembourg, and decreased for Helsinki. Data for hybrid vehicles for both phases was only available for Leeds and Thessaloniki, where score in Phase 2 has increased for Leeds, and decreased for Thessaloniki. Data for electric vehicles for both phases was only available for Luxembourg and Thessaloniki, where both sites showed improvement in total score in Phase 2. Analysis of variance test demonstrated significant difference (p-value < 0.05) in total scores between vehicle types at different sites. The top 5 highest percent increase in scores were 29 % for electric vehicle at Luxembourg, 25% for unknown vehicles at Barcelona, 18% for diesel vehicles at Bergamo, 16 % for petrol vehicle at Barcelona, and 16% for unknown vehicles at Bergamo. More details on the effect of hybrid and electric vehicles on total score, fuel consumption and emission are provided in Chapter 8.

7 The Nanjing case study

Although great efforts were made to align the Nanjing use case with the major European trials, several difficulties were encountered in data collection, transmission and storage. The main problem was that the MODALES app, which requires data transfer from China to Luxembourg, was not possible to use in Nanjing. This cross-border data transfer raised a twofold concern. One is that the app developer partner LIST was concerned about the risk of responsibility for data coming from some non-European countries (e.g. China). On the other hand, Chinese partners, including logistics companies participating in the trial, were concerned that if their user data was sent outside of China, it could potentially result in violations of Chinese data security regulations. Although several solutions were discussed, such as storing the trial data locally in China, there was no time or resources to modify the app to get this done.

Another typical issue with the MODALES App was that many Google services (e.g. Google Play Store) are blocked in China. The Android version of the app required such a service to allow the participants to install it. This implied that up to 70% of the participants would not be able to download and use the app.

Therefore, it was concluded that it was not possible to use the MODALES app in the Nanjing trial. An alternative data collection method and the corresponding preparation procedure for collecting the data (shown in Figure 7.1), the analysis of the collected data and its results are described in detail in the next sections.

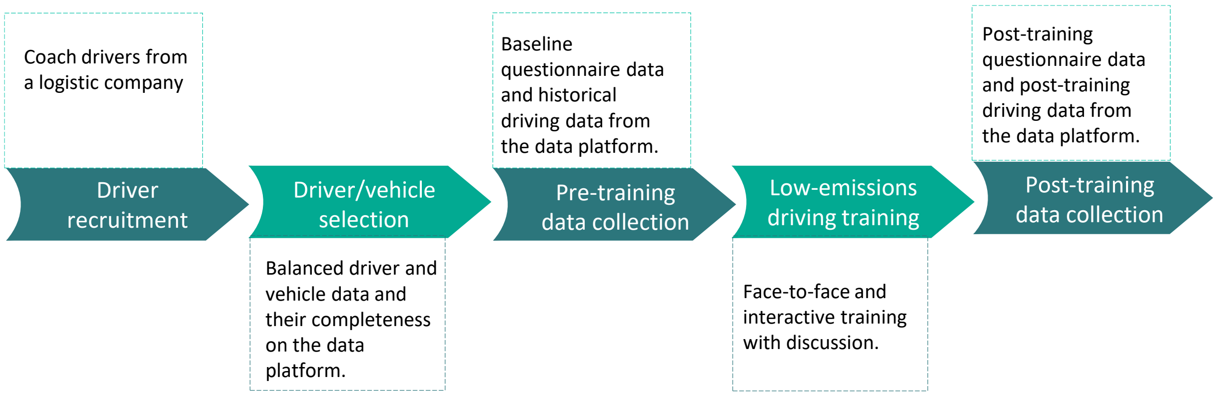


Figure 7.1: Preparation for data collection at the Nanjing trial site

7.1 Data collection

7.1.1 Real world driving data collection

An alternative solution to the use of the MODALES app was to consider a heavy-duty diesel vehicle OBD remote online monitoring system (referred to hereinafter as data platform) available in the Nanjing trial. Therefore, instead of recruiting private car drivers, the focus was on coach drivers who were already registered in the data platform, which was designed to help local environmental protection departments handle the installation and maintenance of heavy-duty diesel vehicle OBD equipment, alarming immediately for abnormal exhaust emissions, as well as the collection, transmission, storage and analysis of OBD data applications (Figure 7.2).

Figure 7.2: OBD remote online monitoring system for heavy-duty diesel vehicles in Nanjing

By searching the license plate number, it is possible to get information of a driver, vehicle and driving information of the vehicle (Figure 7.3). In this way, for drivers selected on the platform, the pre-training (or baseline) data for the first phase of data collection and the post-training data for the second phase of data collection were taken from their real driving data for the two months before and two months after training on the platform, respectively.

Figure 7.3: OBD remote online monitoring system interface for heavy-duty diesel vehicles in Nanjing

An overview of the information provided by the data platform is as follows (some of the data is missing). From this platform, information retrieved includes vehicle driving information, OBD data, engine information and statistical information. Of which, the driving information is trip-based, with variable times, including start time and end time, duration (h), mileage (km), fuel consumption (L), average fuel consumption (L/h), tank level difference (%), maximum speed (km/h), average speed (km/h) and accumulated mileage (km). In addition, driver trajectories can also be accessed as shown in Figure 7.4.

Figure 7.4: Schematic diagram of driving trajectory in Nanjing

The OBD data is also trip-based, which corresponds to the vehicle driving information, mainly include data collection time, OBD diagnostic protocol, MIL status, diagnostic support status, diagnostic readiness status, vehicle identification number (VIN), software calibration identification code, calibration verification number (CVN), IUPR value, total number of fault codes, and fault code information list. The system allows access to the engine information, which is the data used to calculate the emission factor, in 10s intervals, with some data missing or unavailable. It includes data recording time, vehicle speed (km/h), atmospheric pressure (kPa), net engine output torque (%), friction torque (%), engine speed (rpm), engine fuel flow (L/h), SCR upstream NOx sensor output (ppm), SCR downstream NOx sensor output (ppm), reactant residual (%), inlet air volume (kg/h), SCR inlet temperature (℃), SCR outlet temperature (℃), DPF differential pressure (kPa), engine coolant temperature (℃), fuel tank level (%), positioning status, longitude, latitude, and accumulated mileage (km).

The system provides statistical data including current day and historical mileage (km), urea consumption (L), fuel consumption (L), and NOx emission (mg). The historical data, which starts with the time when the vehicle enters the system and stops with the current time, cannot be changed.

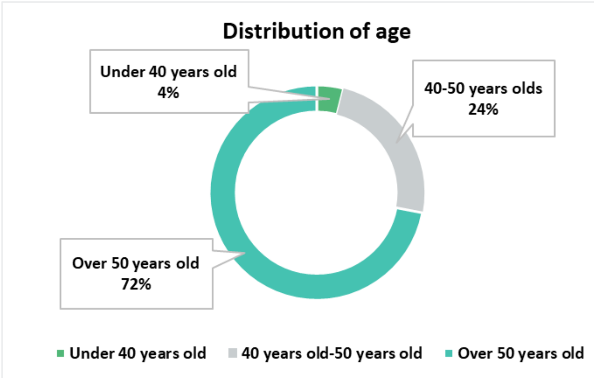
7.1.2 Questionnaire data collection

To understanding behavioural changes in driving, vehicle maintenance, and acceptance of low-emissions driving as a result of low-emission training, a pre-training (baseline) and post-training questionnaires were administered, mostly in a face-to-face manner, before and after the training to prevent them from being unclear about the questionnaire, unless some were unable to attend the event and responded the online version instead. There are 25 questions in the baseline training questionnaire, covering vehicle maintenance, regulated driving, eco-mode use, driving habits, driving style, etc. The post-training questionnaire was similar to the baseline questionnaire, with the addition of questions regarding changes in average fuel consumption before and after the training, idle handling, and recommendations for implementing low-emissions driving. The effectiveness of low-emissions training related to the content covered by the questionnaire can be assessed by comparing driver responses to pre- and post-training questionnaires.

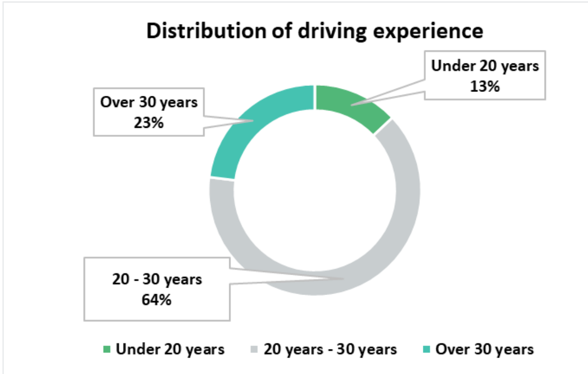
7.2 Low emission driving behaviour training

7.2.1 Driver recruitment

Before the driver and vehicle selection process, 122 coach drivers of a coach company based in Nanjing were initially recruited, of which 117 were male and 5 were female. The age of the drivers ranged from 34 to 61 years old, of which 88 were over 50 years old, accounting for about 72%, as shown in Figure 7.5a. There were 48 drivers with high school education or above, accounting for 39% of the total. All drivers hold A1 licenses, of these, 23 % have over 30 years of driving experience, while only 13 % have less than 20 years, as shown in Figure 7.5b. A total of 23 models of coaches were used by these recruited drivers, and the details of the coaches selected are shown in Table 7.1. These vehicles have been registered on the data platform for no more than 13 years, of which the accumulated mileage ranges from 20,000 km to 599,076 km.



(a)



(b)

Figure 7.5: Distribution of age and driving experience (Nanjing participants)

Table 7.1: Vehicle information for Nanjing trial

Brand and model	Vehicle emission	Vehicle weight	Number of seats	Exhaust gas treatment	Type of gearbox	Emission standard
Yutong ZK6859HA	6500	11300	35	No	Manual	China III
Higher KLQ6856AE3	5200	11000	35	No	Manual	China III
Yutong ZK6107H9	7255	15000	47	No	Manual	China III
Yutong ZK6859HE	5200	11300	35	No	Manual	China III
GOLDEN DRAGON XML6127J28	8424	18000	49	Yes	Manual	China IV
Higher KLQ6115HTE40	8270	16000	47	Yes	Manual	China IV
GOLDEN DRAGON XML6113J68	7255	16500	47	Yes	Manual	China IV
Yutong ZK6110HE1A	7140	16000	47	Yes	Manual	China IV
Zhongtong LCK6117HD	6500	15500	47	Yes	Manual	China IV
GOLDEN DRAGON XML6113J68	7255	16500	47	Yes	Manual	China IV
Higher KLQ6115HTAE41	8424	15900	47	Yes	Manual	China IV
GOLDEN DRAGON XML6807J68	5200	11900	33	Yes	Manual	China IV
GOLDEN DRAGON XML6102JEVL0	/	17500	44	No	/	/
Yutong ZK6808BEVQZ52	/	11480	32	No	/	/
Yutong ZK6115BEVZ51	/	17000	44	No	/	/
Yutong ZK6808BEVQZ52	/	11480	32	No	/	/
Higher KLQ6115HTAE51	8424	15900	48	Yes	Manual	China IV
Nanjing Golden Dragon NJL6806EV1	/	9000	26	No	/	/
Zhongtong LCK6920D5ZC	4088	12000	38	Yes	Manual	China IV
Yutong ZK6119H5Z	8424	16400	48	Yes	Manual	China V
King Long XMQ6112AYD5C	7470	15900	48	Yes	Manual	China V
Yutong ZK6137H16QY1	9500	20000	56	Yes	Manual	China VI
GOLDEN DRAGON XML6601J16	2360	6000	19	Yes	Manual	China VI

7.2.2 Selection of drivers and vehicles

The selected vehicles should meet the requirements of balanced coverage of accumulated mileage and completeness of the recorded data of the vehicles. Following these requirements, the selected vehicles are vehicles equipped with exhaust treatment devices, vehicles with China IV emission standards and above, and vehicles that have been registered in the OBD heavy-duty diesel vehicle remote online monitoring platform. The selected drivers, on the other hand, should meet the requirements of balanced data in terms of sex, education, age, and driving experience. As a result of the selection process, a total of 30 drivers were identified for low emission driving training.

7.2.3 Low emission driving behaviour training

Over 30 selected coach drivers participated in a face-to-face and interactive low-emissions training session. Prior to the training, a baseline questionnaire was given to the drivers and their responses were collected. To deliver an effective training, it included an introduction to low-emission driving and a detailed explanation of the guidelines, combined with watching a low-emissions driving training video created in the project specifically for these HDV drivers, followed by an interactive discussion. Through the face-to-face discussions with the managers and drivers from the company, more informative responses regarding low-emissions driving were received.

7.3 Analysis of changes in driver behaviour before and after low-emissions training

7.3.1 Analysis of questionnaire data

As mentioned previously, two questionnaires were distributed to the drivers before and after the training. A baseline questionnaire conducted prior to the training not only allows us to get a general knowledge of the status of driver behaviour and attitudes towards low-emission driving, but also serves as a reference point against which we can measure and evaluate progress after the low-emission training. Therefore, it was distributed to drivers who were eligible for the training and those who were not. Of the 70 coach drivers who responded to the baseline questionnaire (see Annex A), only 20 received training, as only 30 eligible drivers were able to participate in the Nanjing trial after the driver and vehicle selection process described above, and 10 of those selected were unable to attend the training course. The post-training questionnaire (see Annex B) was only given to drivers who attended the training. The analysis included general driving behaviours and attitudes toward low-emissions driving from the baseline questionnaire data, followed by an assessment of the effectiveness of the low-emissions training among those who attended the training course by comparing the baseline and post-training questionnaire data.

7.3.1.1 Driver and vehicle characteristics and driver behaviour

The baseline questionnaire was designed to cover most of the training material as defined in WP5. Driver characteristics and behaviour were analysed looking at driver training experience, vehicle capacity, tyre usage in specific environments, Handling of special situations while driving, Inspection frequency and records, and route planning, etc. Descriptive statistics for some multiple and single response results are shown in Table 7.2 and Table 7.3, respectively. Filtering of obvious answers was done to deal with situations where respondents' answers contradicted their other choices. For example, when a multiple-choice question regarding driver training experience was given, if someone selected no training experience while at the same time selecting multiple training courses, in this case the option of no training was filtered out.

Table 7.2: Descriptive statistics analysis of baseline data from Nanjing with multiple responses

Item (N= 70)	Variable	Responses		Percentage of Cases
		Frequency	Percentage	
Driver training experience	No standard training and self-learning	9	5.30%	12.90%
	Self-learning	30	17.60%	42.90%
	Driving course for specific conditions	42	24.70%	60.00%
	Eco driving course	28	16.50%	40.00%
	Driving course for specific vehicle	53	31.20%	75.70%
	Retraining for traffic violations	8	4.70%	11.40%
	Total	170	100.00%	242.90%
Driving with number of passengers	More than specified passengers	0	0	0.00
	Almost full (80%-100% passengers)	35	50.0%	50.0%
	Less than half empty (50%-80% passengers)	29	41.4%	41.4%
	More than half empty passengers	6	8.6%	8.6%
	Total	70	100.0%	100.0%
Change in speed when go uphill	Reduce speed when go uphill	58	82.9%	82.9%
	Maintain speed when go uphill	6	8.6%	8.6%
	Gradually Increase speed when go uphill	6	8.6%	8.6%
	Total	70	100.0%	100.0%
Address warning light	Ignore warning light	0	0%	0%
	Address it later when having time	1	1%	1%
	Park vehicle in a safe place & turn off engine	36	51%	51%
	Call dealer or fleet maintenance person	33	47%	47%
	Total	70	100%	100%
Frequency of vehicle maintenance	Maintenance once a year	2	2.9%	2.9%
	Maintenance once two years	3	4.3%	4.3%
	Maintenance when engine failure	2	2.9%	2.9%
	Maintenance required by state	47	67.1%	67.1%
	Maintenance required by manufacturer	16	22.9%	22.9%
		70	100.0%	100.0%
Frequency of tyre pressure checks	Check tyre pressure once a week	33	47.10%	47.1%
	Check tyre pressure once a month	9	12.9%	12.9%
	Check tyre pressure once a year	0	0.0%	0.0%
	Check tyre pressure when significantly low	9	12.90%	12.9%
	Check tyre pressure before a longer trip	0	0.0%	0.0%
	Check tyre pressure when stopping for gas	19	27.10%	27.1%
	Total	70	100%	100%
Select a route when driving	Route is fixed and no choice can be made	28	18.40%	43.10%
	Choose the fastest route	23	15.10%	35.40%
	Choose the shortest route	21	13.80%	32.30%
	Choose route with more straight lines	8	5.30%	12.30%
	Choose route with fewer urban areas	12	7.90%	18.50%
	Choose route with more expressways	11	7.20%	16.90%
	Choose route with less traffic	24	15.80%	36.90%
	Choose route with well-maintained roads	25	16.40%	38.50%
	Total	152	100.00%	233.80%
Select an Eco Mode when driving	Eco Mode every time I drive	23	32.9%	32.9%
	Eco Mode when think of it	2	2.9%	2.9%
	Eco Mode occasionally	8	11.4%	11.4%
	Eco Mode never use	37	52.9%	52.9%
	Total	70	100.0%	100.0%

Table 7.3: Descriptive statistics analysis of baseline data from Nanjing

Item (N= 70)	Variable	Responses	
		Frequency	Percentage
Change summer and winter tyres	Yes, change winter and summer tyres	18	25.7%
	No, use the same tyres all year round	16	22.9%
	Only put on winter tyres when needed	4	5.7%
	Only switch to winter tyres when requested by the fleet company	32	45.7%
Speed change in windy weather	Drive at a lower speed than usual	65	92.9%
	Drive faster than usual	2	2.9%
	No difference from your usual driving speed	3	4.3%
Vehicle maintenance record	No	3	4.3%
	Yes	67	95.7%
Vehicle with Eco-mode	Yes, it is in default mode (turn it off when not in use)	19	27.1%
	Yes, but it is not in the default mode (turn it on when using it)	15	21.4%
	NO, it is not available in my car	36	51.4%

Driver and vehicle characteristics

Over 87% of drivers have attended one or more types of training or have enriched their specific driving knowledge through self-learning, and over 75% have participated in vehicle-specific driving training courses; about 60% have taken courses for specific environments, which ensures that drivers are familiar with the vehicles they drive and can effectively improve their ability to handle emergencies during driving and strengthen the safety of the trial.

In general, there was no overloading when driving, which helps to keep the trial safe. Only 8.6% of the vehicles carried less than 50% of the passengers, indicating a considerable efficiency in vehicle transport. Still over 41% of the vehicles carried between 50% and 80% of the passengers, which means that the route arrangement or model selection of these vehicles might be further optimized.

Driver behaviour

Tyres are designed to meet specific weather conditions, especially for heavy duty vehicles, requiring drivers to use different tyres between spring and summer, as well as between autumn and winter, to ensure the safety of the vehicle on the road, tyre durability and reduced emission. Of the 70 coach drivers who responded to the questionnaire, about 16% of them didn't change their winter and summer tyres at all; over 50% switched to their winter tyres as needed or at the fleet company's request. Only 26% drivers switched to winter and summer tyres in winter and the summer, respectively, meaning It might be necessary to inform drivers of the importance of changing the appropriate tyres in specific weather conditions to lower emissions while improving the tyre durability, and safety.

About 93% of drivers in windy weather and 83% of drivers driving uphill would reduce their speed to ensure safety; only 3% of drivers drove faster than usual in windy weather and 4.3% drove the same as usual. Less than 9% of drivers would maintain the same speed and gradually increase their speed, when driving uphill, respectively. The results showed that most drivers handled well in windy weather and uphill, but for some drivers, effective training is still needed to deal with these situations to improve safety while reducing emissions.

When the vehicle fault light comes on, over 98% of drivers would immediately take appropriate measures for the problem, either by parking the vehicle in a safe place, turning off the engine, and checking the manual, or by calling a dealer or fleet service for further instructions.

Regarding the maintenance of vehicles, about 90% of the drivers would regularly check the vehicles to meet the requirements of the national regulations or vehicle manufacturers and at the same time keep the maintenance records. More than 27% of drivers checked the tyre pressure every time they refuel, and nearly 48% of drivers checked their tyres every week. However, there were still about 10% of drivers whose vehicle maintenance frequency did not meet national standards or simply did not carry out vehicle maintenance, and less than 5% of drivers did not keep maintenance records.

Except for over 43% cases where the route was fixed and the driver was not free to choose, most drivers would choose the route with short time (over 35%), short distance (over 32%), low traffic flow (about 37%) and good road conditions (about 39%), while giving less consideration to routes with more straight lines (over 12%), urban areas (about 19%), and the expressways (about 17%).

Less than 50% of drivers had eco-driving mode in their vehicles, with more than 27% having it set as the default mode; more than 21% of drivers had to turn it on when using it, of these, about 67% believed it would affect the performance of the car if turned on, while about 27% chose not to turn it on because they did not understand the significance of eco-driving features. This could potentially be improved through the offering of training or other forms of awareness-raising activities.

In general, most drivers seem to follow some low-emissions guidelines, largely as a result of safety awareness or regulations. There may be some measures, such as low-emissions training, that have the potential to encourage more drivers to adhere to the guidelines.

7.3.1.1 Analysis of the effectiveness of low emission training based on questionnaire data

The quantitative analysis of the effect of low-emissions training was conducted by comparing whether there are certain changes in vehicle energy consumption, tyre use in special environments, driving handling in special situations, frequency and records of maintenance, vehicle modification, route selection, and low emission driving awareness of drivers before and after training. Comparisons were made with drivers who responded to pre- and post-training questionnaires and also received low-emissions training.

Driver behaviour changes

As for fuel consumption, more than 85% of the drivers who participated in the training said there was a notable reduction in vehicle fuel consumption after the low-emissions driving training.

For driving behaviour in long idling situations, less than 37% of drivers turned off their engines prior to training to avoid potentially long periods of idling, and these drivers continued to remain the same after training. Others kept the engine on to ensure that the vehicle is able to move in the first place. However, this behaviour can, to some extent, lead to unnecessary vehicle emissions and fuel consumption. After the training, more than 63% of drivers chose to turn off their engines, which means 26% of them modified this driving behaviour. Only about 37% of the drivers kept their engines on after the training, as shown in Figure 7.6.

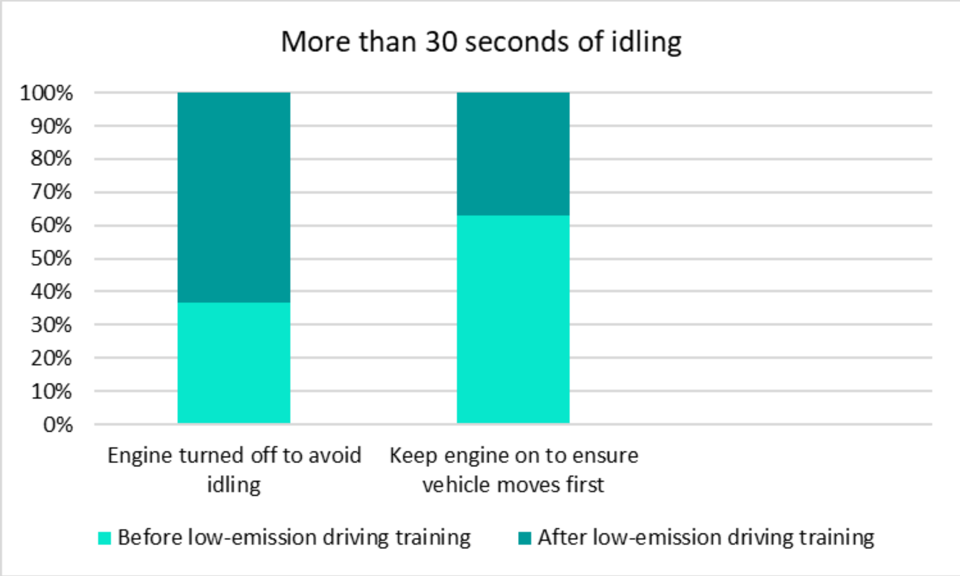


Figure 7.6: Driver response when idling time exceeds 30 seconds before and after training in Nanjing

With regard to the use of tyres in special weather conditions, prior to the low-emissions driving behaviour training, only about 20 percent of drivers changed their winter and summer tyres. About 55% of drivers changed their tyres as required by the company, and the rest never changed their summer and winter tyres at all. As a result of the training, the percentage of drivers willing to change their tyres rose to 25 percent, while the percentage of drivers who chose never to change their tyres dropped from 25 percent to 0 percent, as shown in Figure 7.7.

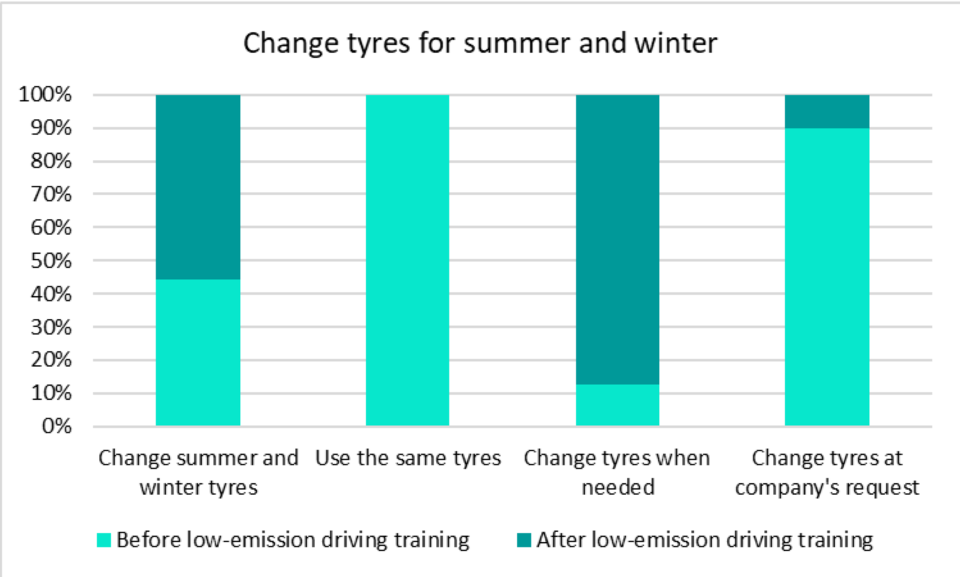


Figure 7.7: Change tyres in summer and winter before and after training in Nanjing

As for the maintenance, prior to the training, only 5% of drivers did not meet state requirements for maintenance or did not perform vehicle maintenance at all, and about 10% of drivers were not keeping maintenance records. After the training, almost all drivers agreed to comply with the respective requirements. As prior to training, about 10% of drivers did not keep maintenance records.

Regarding route selection, before the training, drivers focused more on time efficiency and driving comfort but less on fuel consumption when choosing routes, with the exception of situations where routes were fixed and drivers were not free to choose. After the training, about 35% of the drivers included the gradient and slope conditions of the route in their route selection, which was 10% more than before the training, as shown in Figure 7.8. Due to the time-sensitive nature of public transportation, drivers have limitations in route selection, and the effect of low-emissions driving behaviour training on route selection was not significant.

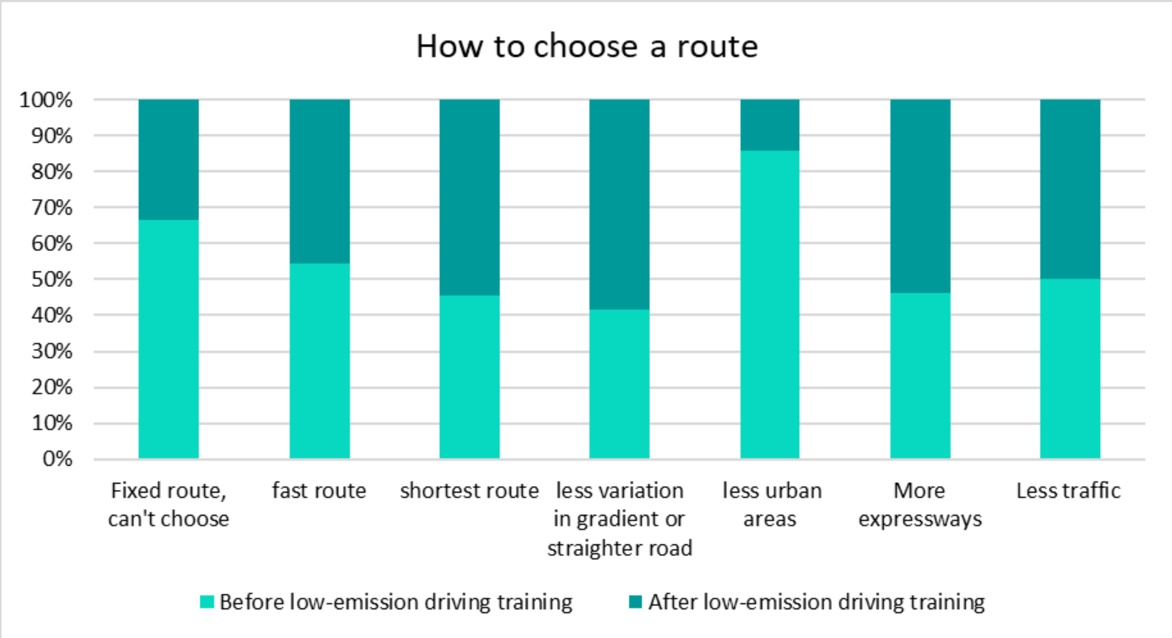


Figure 7.8: Route selection before and after training in Nanjing

Regarding acceleration and deceleration, during the low-emissions driving training, 95% of respondents before training and almost all of them after training claimed that they would try to minimize acceleration and deceleration to keep the vehicle moving at a steady speed.

As for the use of eco-driving mode and attitude towards low-emission driving, about 45% of drivers would use the vehicle's eco-driving mode when driving before the training, rising to 60% after the training. About 30% of respondents had never used it at all before the training. This situation has improved after the training, dropping to 15%. In general, drivers believed that high fuel consumption is highly related to frequent acceleration and deceleration, frequent lane changes and speeding, etc. More than 90% of drivers agreed with the importance of fuel-efficient driving and paid attention to information about vehicle emissions, but there were still about 10% of drivers who were not concerned about the vehicle emissions.

7.3.1.2 Conclusions

Through the analysis of questionnaires before and after the low-emissions driving training, the results showed that the drivers who received the training made more significant progress in tyre use, vehicle maintenance, idle speed handling, and use of eco-driving modes, indicating a positive impact on their daily low-emissions driving. On the other hand, however, given the characteristics of coach drivers, who have years of experience and have developed their own strong driving behaviours, it will take time to modify to low-emissions driving. After training, improvements in route selection, acceleration and deceleration habits are not significant, and further optimization of training methods and focus is needed, specifically for coach drivers.

7.3.2 Analysis of real-world driving data

Following the driver/vehicle selection process, the first phase of data (baseline data) collection began on 16 December 2022 and was collected from the data platform system described above for 2 months until February 17, 2023, when drivers received low-emissions training. On average, the total driving distance for Phase 1 was approximately 10,895 km per driver.

After the training, the second phase of real-world driving data collection began in February 18, 2023 and lasts for 2 months until April 18, 2023. The average total driving distance for Phase 2 was approximately 10,368 km per driver.

7.3.2.1 Method of CO_2 and NO_x emission factors

Based on the real driving data collected by the data platform, the CO_2 and NO_X emissions from the exhaust and their emission factors can be generated as follows:

According to the formula for calculating the total vehicle engine exhaust flow (Equation 7.1) and the formula for calculating the intake air flow (Equation 7.2), the second-by-second NO_X emissions of the vehicle can be calculated from Equation 7.3:

$$n_{\text{exhaust}} = \frac{m_{\text{intake}}}{M_{air}} + \frac{L_f \cdot \rho_f \cdot k}{4(M_C + k \cdot M_H)} \tag{7.1}$$

$$m_{NOx} = n_{\text{exhaust}} \cdot \Phi_{NOx} \cdot M_{NOx} \cdot \frac{1000}{3600} \tag{7.2}$$

$$m_{NOx} = \left(0.25346 \cdot L_f + 0.30532 \cdot m_{\text{intake}}\right) \cdot \Phi_{NOx} \times 10^{-6} \tag{7.3}$$

where $\mathrm{n_{exhaust}}$ is the total material flow rate of vehicle engine exhaust; $\mathrm{m_{intake}}$ is the engine intake air flow rate (kg/h); $\mathrm{M_{air}}$, $\mathrm{M_C}$, $\mathrm{M_H}$ are the molecular weight of air, element H, and element C, respectively (kg/kmol); $\mathrm{L_f}$ is the engine fuel flow rate (L/h); ρ_f is the average density of fuel; k is the H:C molar ratio; $\mathrm{m_{NOx}}$ is the NO_X emission per second of the vehicle (g/s); $\mathrm{M_{NOx}}$ is the average molecular weight of NO_X (g/mol).

From the analysis of diesel density, the density of diesel in this report is 0.825 kg/L, and k is 1.95. Also, according to the vehicle information, the volume ratio of NO in NO_X of diesel engine is 90% and NO_2 is 10%, which results in $\mathrm{M_{NOx}}$ of 31.6 g/mol in this report.

Based on these emission model and related information, the calculation of NO_X emission factor per unit mileage can be obtained from Equation 7.4.

$$EF^D_{NOx} = \frac{3600 \cdot \sum_{t=1}^{T} m_{NOx}}{\sum_{t=1}^{T} v} \tag{7.4}$$

In a similar way to the NO_X emission factor calculation, the CO_2 emission factor calculation can be obtained from Equation 7.5.

$$EF^{D}_{CO2} = \frac{3600 \cdot \sum_{t=1}^{T} m_{CO2}}{\sum_{t=1}^{T} v} \quad (7.5)$$

7.3.2.2 Changes in CO_2 and NO_x emission before and after training

Changes in emissions by road type and traffic conditions

After the driver/vehicle selection process, a total of six coaches were selected for this study based on the balance of data and the completeness of the corresponding vehicles on the Nanjing Truck OBD platform, all of which were equipped with exhaust gas treatment devices and all of which were 48-seat China V diesel coaches， as shown in Figure 7.9: Image of the coach used in the Nanjing trial.

Figure 7.9: Image of the coach used in the Nanjing trial

Based on different road types and traffic characteristics, each trip was categorized into six driving scenarios for each vehicle, namely, highway-peak hour, highway-off peak hour, primary road - peak hour, primary road – off peak hour, secondary road - peak hour, and secondary road – off peak hour. Mileage based $CO_2$and NO_X emissions are therefore calculated for each vehicle per trip category. Table 7.4 shows the changes in CO_2 and NO_X emission before and after training with the subjects. The conclusions are based on observed data only, as the sample of data tested was too small to allow statistical testing. No statistical interpretation of significance was given.

Table 7.4: CO_2 and NO_X before- and after-training in Nanjing

Road/traffic	CO_2 (g/km)						NO_X (g/km)					
	Before-training			After-training			Before-training			After-training		
	Mean	S.D.	S.E	Mean	S.D.	S.E	Mean	S.D.	S.E	Mean	S.D.	S.E
Exp-peak	590.39	89.07	36.36	646.62	161.68	66.01	2.69	1.62	0.66	2.78	1.61	0.66
Exp-off-peak	533.42	68.32	30.55	568.42	73.25	32.76	2.61	0.94	0.42	3.01	0.87	0.39
Pri-peak	833.81	198.32	80.97	916.00	164.76	67.26	4.41	1.35	0.55	4.78	2.81	1.15
Pri-off-peak	703.69	153.81	62.79	717.66	164.08	73.38	3.36	1.30	0.53	3.36	3.18	1.42
Sec-peak	1035.84	816.36	333.28	761.41	142.18	58.04	3.14	1.92	0.78	3.00	2.20	0.90
Sec-off-peak	926.41	758.60	309.70	976.23	748.56	334.76	6.20	8.76	3.57	10.15	14.25	6.37

Note: Exp-peak, Exp-off-peak, Pri-peak, Pri-off-peak, Sec-peak, Sec-off-peak refer to peak hour expressway, off-peak expressway, peak hour primary road, off-peak primary road, peak hour secondary road and off-peak secondary road, respectively.

In Figure 7.10, for the same road type, the peak hour CO_2 emissions for both expressways and primary roads before and after the training were much higher than the off-peak hour CO_2 emissions. Similar results were found for CO_2 emissions on secondary roads before training. Before and after the training, there was hardly any change in the primary roads and the expressways during the off-peak hours. However, CO_2 emissions from secondary roads increased by about 5.3% during off-peak hours; primary roads increased by 9.9% and freeways by 9.5%, both of which are peak hours. The effects of the low-emission training intervention on CO_2 emissions were particularly significant on secondary roads during off-peak hours, with a reduction of more than 26% after the training.

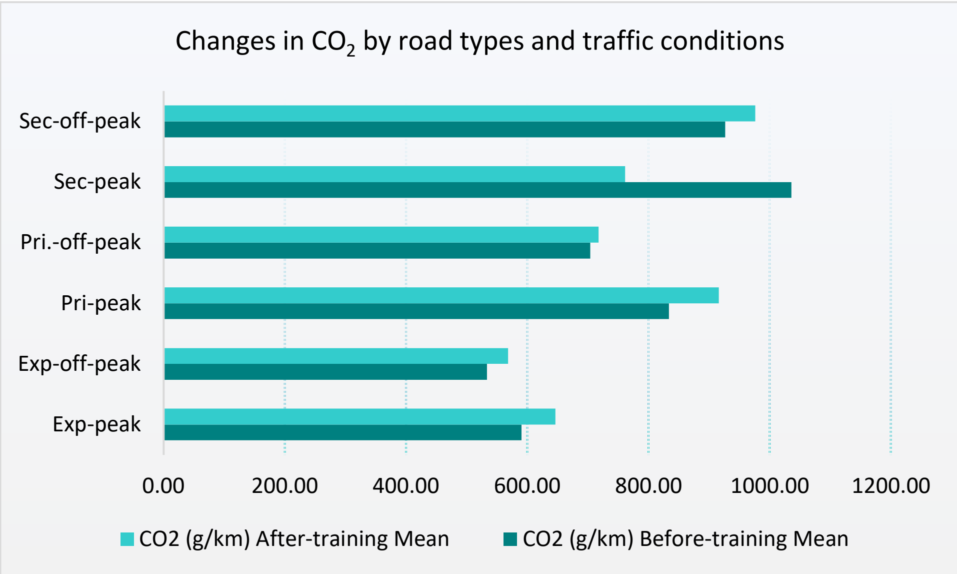


Figure 7.10: Changes in CO_2 before and after training in Nanjing under different road types and traffic conditions

In Figure 7.11, similar to CO_2 emissions, NO_x emissions from vehicles on expressways are lowest before and after eco-driving training. Before and after the training, there was hardly any change in the primary roads during the off-peak hours and the expressways during the peak hours. However, NO_x emissions from secondary roads increased significantly by about 63.9% during off-peak hours; primary roads increased by 8.5% during peak hours and expressway by 15.3% during off-peak hours. On secondary roads, low-emission training interventions had only a small impact on NO_X emissions, with a reduction of more than 4.4% after the training.

The results for changes in CO_2 and NO_X emissions were consistent, with reductions in both CO_2 and NO_x emissions after training under the same traffic conditions and on the same roads. This may be because of lower traffic volumes on secondary roads during off-peak hours, when drivers can focus more on low-emission driving techniques.

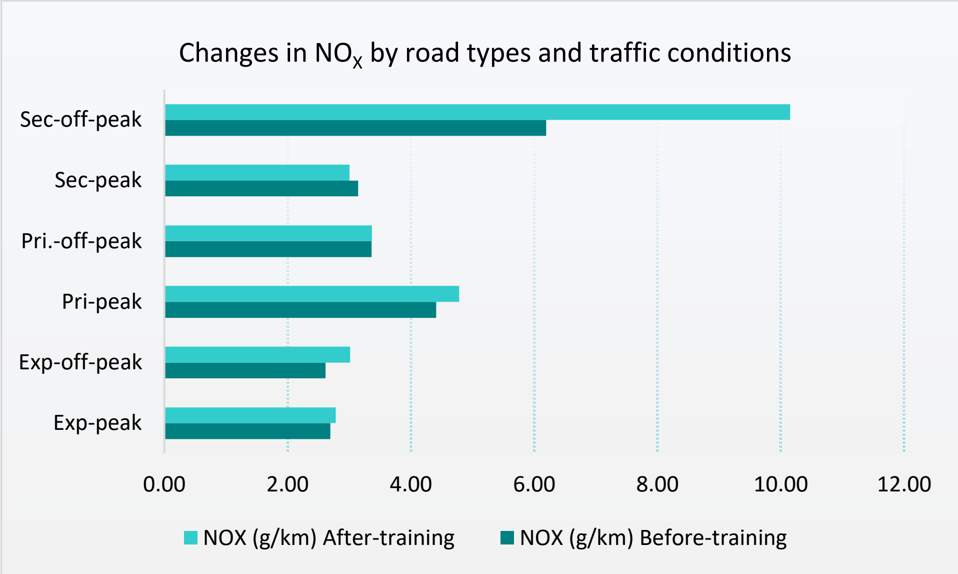


Figure 7.11: Changes in NO_X before and after training in Nanjing under different road types & traffic conditions

7.3.2.3 Changes in speed before and after training

In Figure 7.12, the average speed of vehicles was lower after the training than before it, during the off-peak hours of secondary roads, off-peak hours of primary roads, peak hours of primary roads, peak hours of expressways, and off-peak hours of expressways; however, an opposite trend is observed in the speed change before and after driver training during the peak hours of secondary roads.

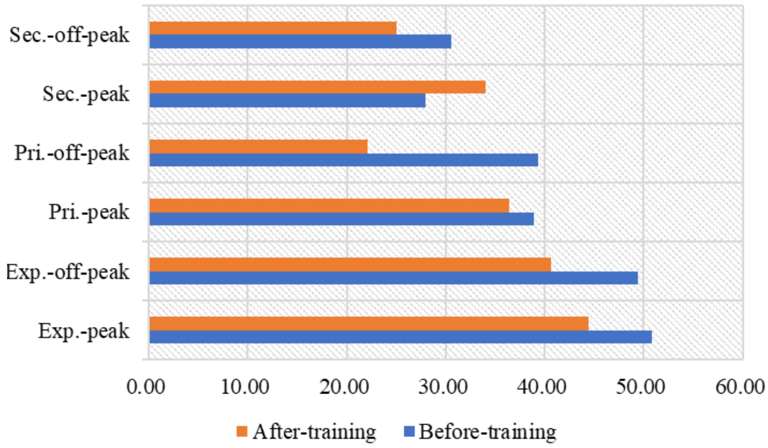


Figure 7.12: Speed changes before and after driver training in Nanjing by road types and traffic conditions

7.3.2.4 Changes in CO_2 and NO_x emission by age groups before and after training

Combining the questionnaire data and the trucking platform OBD data, the age of drivers was divided into three categories: 45 to 50 years old, 50 to 55 years old, and 55 to 60 years old, from which drivers of different age groups were selected for analysis based on the completeness of the data. The changes in their CO_2 and NOx emissions before and after the low-emission driving training are shown in Figure 7.13.

The figure shows the changes of average CO_2 and NO_X emissions on weekdays under different road type and traffic condition categories before and after the training for drivers of different age groups. There was no significant difference in CO_2 emissions between drivers of different ages, where CO_2 emissions were highest during peak hours on primary roads and during peak hours on secondary roads. The highest CO_2 emissions were found during the peak hours of the primary roads and the peak hours of the secondary roads, while the CO_2 emissions of drivers aged 50-55 were significantly higher during the peak and non-peak hours of the secondary roads. In terms of low-emission driving training effect, drivers aged 45-50, 50-55, and 55-60 had lower CO_2 emissions during the off-peak hours on primary roads, the peak and off-peak hours on secondary roads, and the peak hours on secondary roads, respectively.

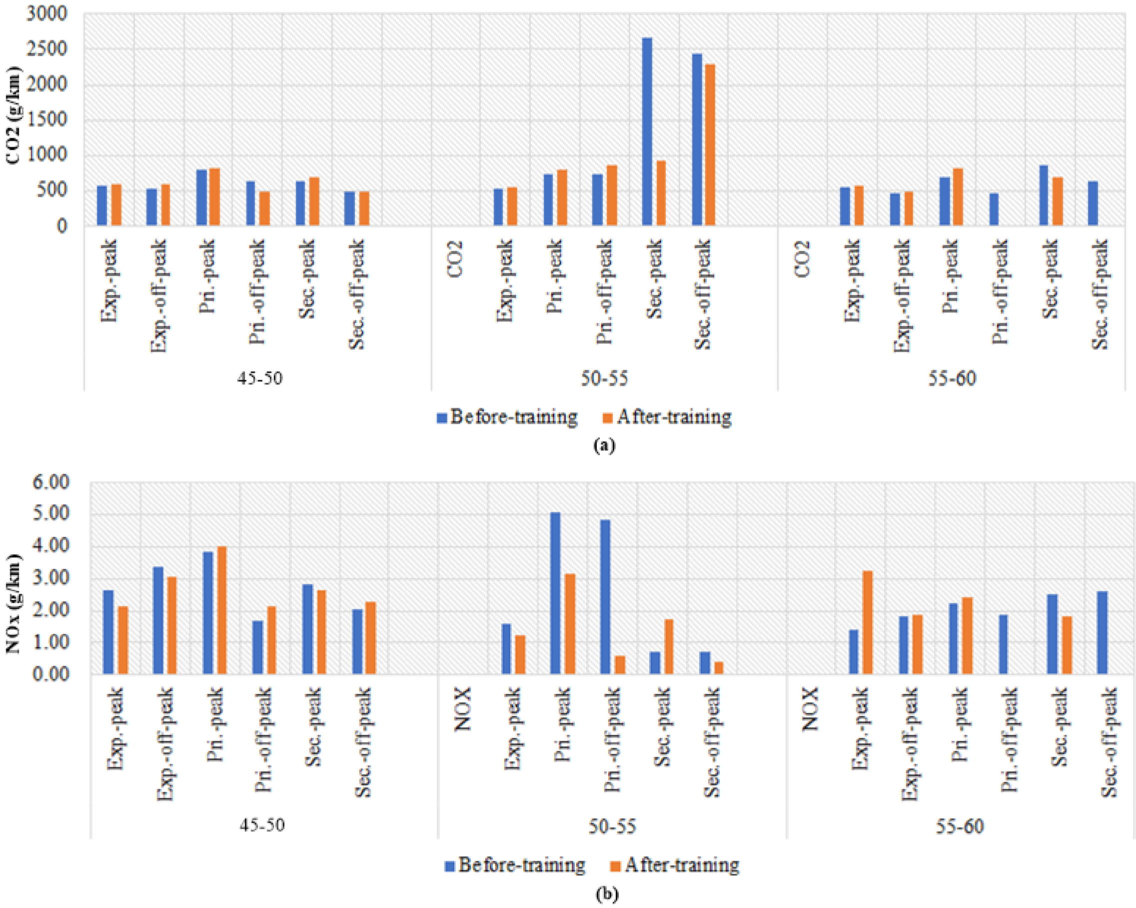


Figure 7.13: Changes in CO_2 and NO_X before and after training in Nanjing by age groups

In terms of NO_X emissions, drivers aged 50-55 had significantly higher NO_X emissions during peak hours and off-peak hours on primary roads. In terms of the effect of the training, NO_X emissions from vehicles of drivers aged 45-50 decreased during peak hours on expressways, off-peak hours on expressways, and peak hours on secondary roads. The NO_X emissions of vehicles of drivers aged 55-60 decreased significantly only during the peak hours of secondary roads.

7.3.2.5 Changes in CO_2 and NO_x emission by gender

Figure 7.14 shows the changes of CO_2 and NO_X emissions of drivers of different genders before and after the training. In general, for different genders, CO_2 emissions are distributed differently across different road and traffic conditions. For female drivers, the higher CO_2 emissions are mainly on primary and secondary roads during peak hours while the CO_2 emissions of male drivers are higher on primary roads during both peak and off-peak hours. In terms of training effects, CO_2 emissions were reduced only during peak hours on secondary roads, regardless of the gender of the driver, by 19% for women and 5% for men.

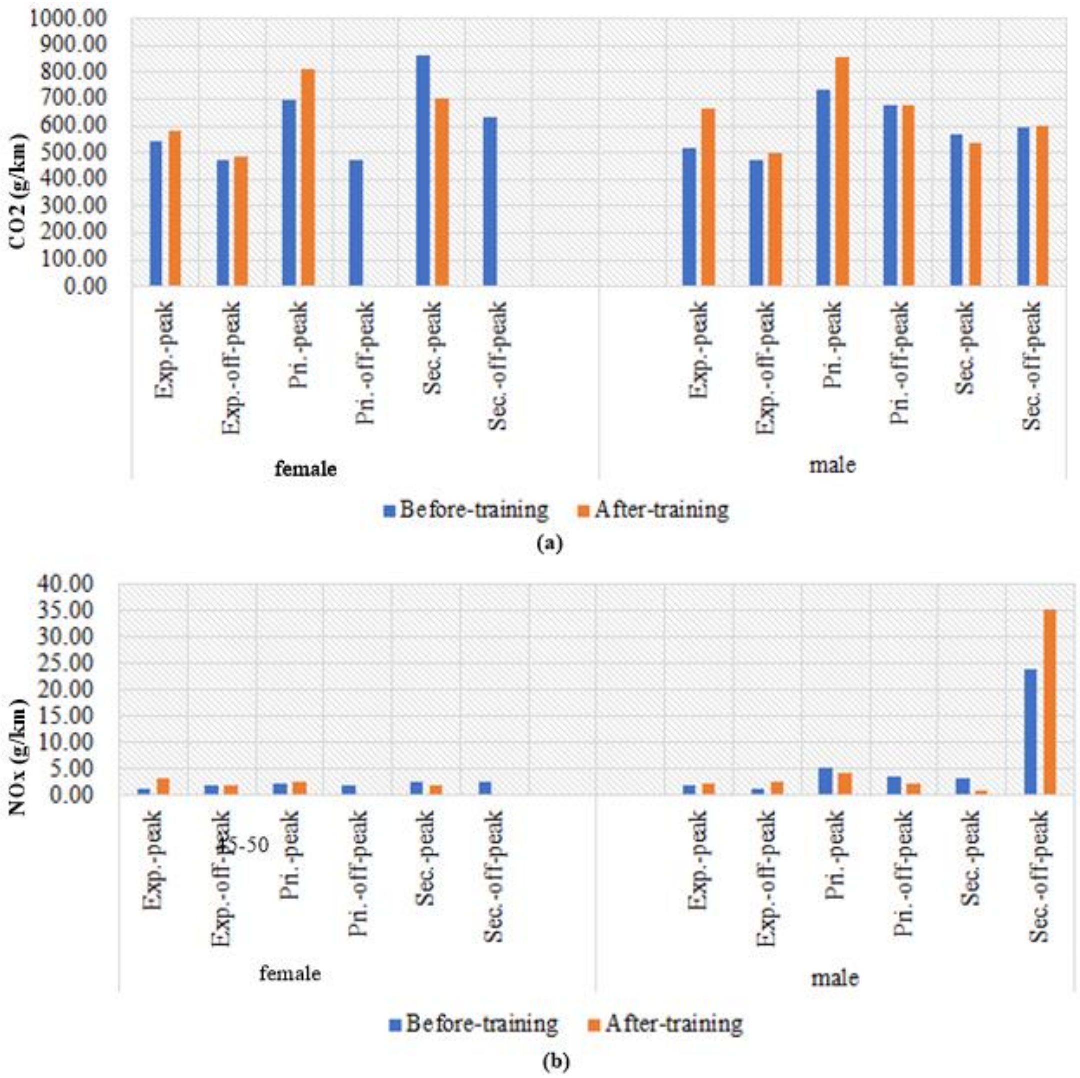


Figure 7.14: Changes in CO_2 and NO_X before and after training in Nanjing by gender

For male drivers, NO_X emissions in general were significantly higher than those from females, In terms of the effect of the training, the intervention worked better for male drivers than for female drivers, with female drivers experiencing a 27% reduction in NOx emissions during peak hours on secondary roads, and male drivers experiencing a 20%, 41%, and 70% reduction in NOx emissions during peak hours on primary roads, off-peak hours on primary roads, and peak hours on secondary roads, respectively.

7.3.2.6 Changes in CO_2 and NO_x emission by driving experience

Figure 7.15 shows the changes of CO_2 and NO_X emissions before and after the training for drivers of different driving experience. The CO_2 emissions for drivers of different driving ages varied, especially for drivers with 20-25 years of driving experience, compared to other driving age groups. Emissions on secondary roads for drivers with 20-25 years of driving experience, both during peak and off-peak periods, were much higher than for drivers in other driving experience groups; for those with 25-30 and 30-40 years of driving experience, CO_2 emissions were highest during peak hours on primary roads and during peak hours on secondary roads.

In terms of the training effects, the higher the driving experience, the less likely drivers were to be affected by the intervention. Those with 20-25 years of driving experience had significant lower CO_2 emissions on secondary roads during peak and off-peak hours, with decreases of 66% and 6%, respectively, while those with 25-30 years of driving experience experienced a reduction in CO_2 emissions during off-peak hours on primary roads, with decreases of 22%; those with 30-40 years of driving experience only experienced a reduction in CO_2 emissions during peak hours on secondary roads, with decreases of 19%.

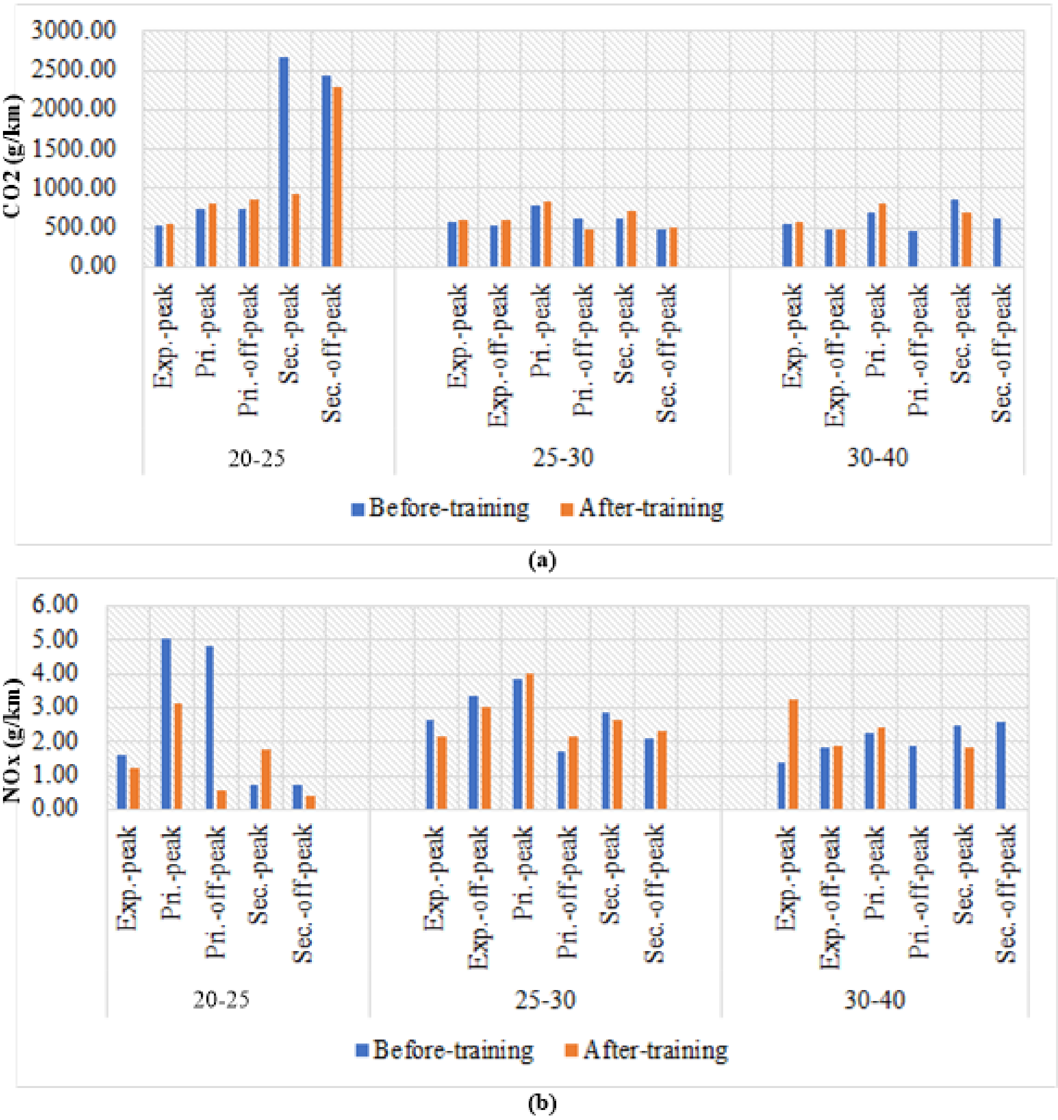


Figure 7.15: Changes in CO_2 and NOx before and after training in Nanjing by driving experience

For NO_X emissions, drivers with 20-25 and 25-30 years of driving experience showed the same trend, i.e., significantly higher emissions during peak hours on primary roads and during peak hours on secondary roads, with the difference that emissions of NOx were extremely high during off-peak hours on primary highways for drivers with 20-25 years of driving experience prior to training. For drivers with 20-25 years of driving experience, NOx emissions were lower for this road type and traffic condition than for peak and off-peak freeways. For drivers with 30-40 years of driving experience, NOx emissions were evenly distributed across all road types and traffic conditions.

In terms of the training effects, the higher the driving experience, the less likely drivers were to be affected by the intervention. Those with 20-25 years of driving experience experienced a significant reduction in NO_X emissions during peak and off-peak hours on primary roads, and off-peak hours on secondary roads, with decreases of 38%, 88% and 42%, respectively, while those with 25-30 years of driving experience experienced a reduction in NO_X emissions during peak and off-peak hours on expressways and during peak hours on secondary roads, with decreases of 18%, 10% and 7%, respectively; those with 30-40 years of driving experience only experienced a reduction in NOx emissions during peak hours on secondary roads, with decreases of 27%.

7.4 Conclusions of the Chinese case study

The analysis of the Nanjing trial used real-world driving data and participant responses to pre- and post-training questionnaires to investigate the effectiveness of MODALES' low-emissions driving training tool by comparing driver behaviour before and after low-emissions driving training.

Analysis of the data from the questionnaire shows that training has a positive impact on driver behaviour such as prolonged idling situations, changing appropriate tyres in special weather conditions, maintenance, use of eco-driving modes while driving, and the degree and frequency of acceleration/deceleration. Because of the time-sensitive nature of public transportation, drivers have limitations in route selection and the impact of low-emissions driving behaviour training on route selection is not significant.

Analysis of real-world driving data showed that the low-emissions training had a positive impact on secondary roads during off-peak hours. Average speeds decreased for all road types and traffic conditions except for peak hour secondary roads. Depending on the type of road and traffic conditions, there were positive effects for each age group. In terms of gender differences, CO_2 emissions decreased during peak hours on secondary roads for both females and males; the training effect was particularly prominent for male drivers compared to females in terms of NO_X emissions reduction during peak hours on primary roads, off-peak hours on primary roads and peak hours on secondary roads. In terms of the training effect with respect to driving experience, the higher the driving experience, the less likely the driver is to be influenced by the training.

From the degree and frequency of acceleration/deceleration in both analyses, it appears that the drivers' behavioural changes were not very consistent, with more positive responses than the real-world results measured. The results of the questionnaire survey indicate that drivers have recognized the importance of reducing the degree and frequency of acceleration/deceleration for low-emissions driving; however, the steady driving habits have not yet been developed and will take time to progressively implement. To further develop low-emission driving habits, monitoring and awareness measures may be needed to reach the goal.

This study was based on a small sample size, and in order to draw reliable conclusions, a larger sample size would need to be gained for further investigation.

8 A case study of hybrid/electric vehicles

The rising concern for environmental sustainability and the need to reduce dependence on fossil fuels have led to significant advancements in the automotive industry. As a result, hybrid and electric vehicles have emerged as promising alternatives to traditional ICE vehicles. This chapter explores the brake wear, tyre wear, and total emission score of hybrid/electric vehicles.

8.1 Brake wear emissions of hybrid/electric vehicles

This section provides a preliminary analysis of the brake wear $PM_{2.5}$ emissions resulting from hybrid/electric vehicles and compares them with those from ICE vehicles. Figure 8.1 presents brake wear $PM_{2.5}$ emissions from hybrid/electric vehicles before and after low-emission driver training programmes. It can be seen that the training exhibited positive effects on brake wear $PM_{2.5}$ emissions from hybrid/electric vehicles. For hybrid vehicles, the mean values of brake wear $PM_{2.5}$ emissions reduced from 9.10 mg/stop to 4.63 mg/stop, with a substantial reduction of 49.1%. In the case of electric vehicles, the corresponding mean value of brake wear $PM_{2.5}$ emissions experienced a significant reduction of 36.2%, with mean values decreasing from 8.24 mg/stop to 5.26 mg/stop.

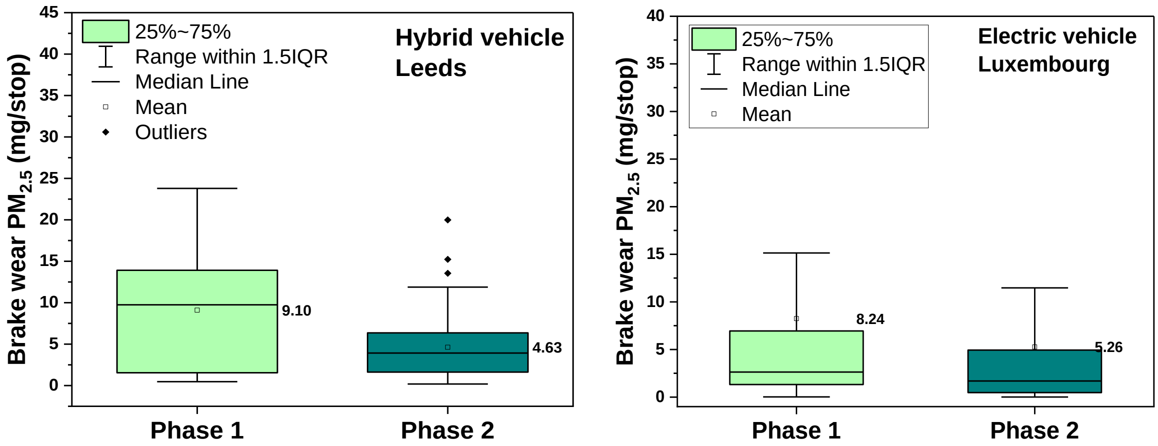


Figure 8.1: Brake wear $PM_{2.5}$ emissions of hybrid/electric vehicles before and after training

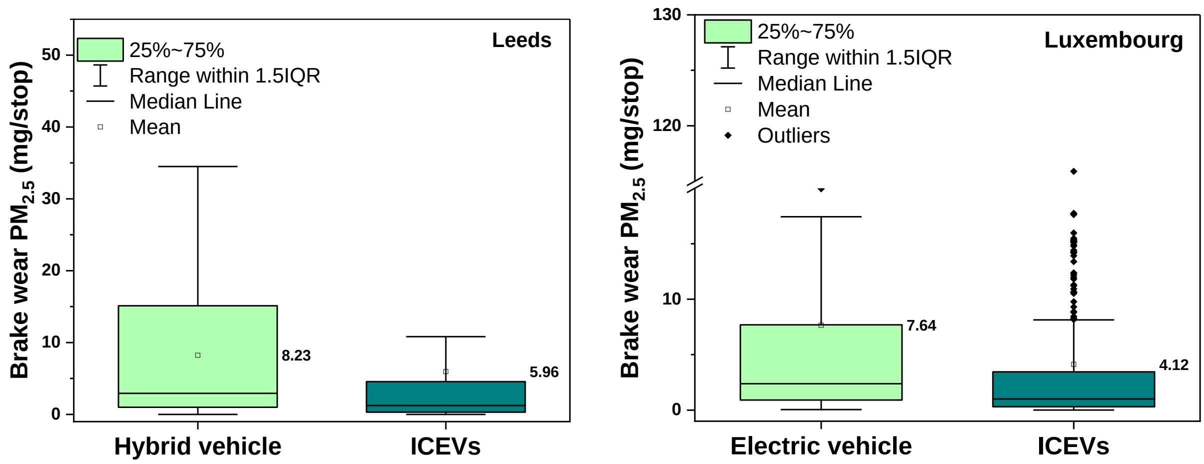


Figure 8.2: Brake wear $PM_{2.5}$ emissions of hybrid/electric vehicles and internal combustion engine vehicles (ICE vehicles).

In addition, we also performed a comparative analysis regarding brake wear $PM_{2.5}$ emissions from hybrid/electric vehicles and ICE vehicles, and the results are shown in Figure 8.2. It can be observed that the mean values of brake wear $PM_{2.5}$ emissions from hybrid/electric vehicles were significantly higher compared to those from ICE vehicles. Specifically, the mean values of brake wear $PM_{2.5}$ emissions from hybrid vehicles were 38.1 higher than those from ICE vehicles. In the case of electric vehicles, the brake wear $PM_{2.5}$ emissions showed an 85.4% increase in mean values.

8.2 Tyre wear emissions of hybrid/electric vehicles

This section offers an initial analysis of the tyre wear emissions generated from hybrid/electric vehicles and compares them to those from ICE vehicles. Figure 8.3 illustrates tyre wear emissions of hybrid/electric vehicles before and after the training. The results from Figure 8.3 indicate that the results indicate that the training had a positive impact on tyre wear emissions from hybrid/electric vehicles. In the case of hybrid vehicles, the mean tyre wear emissions decreased from 93.55 mg/km to 88.36 mg/km, representing a significant reduction of 5.5%. For electric vehicles, there was a decrease of 6.5% in the mean tyre wear emissions, with mean values dropping from 89.35 mg/km to 83.50 mg/km.

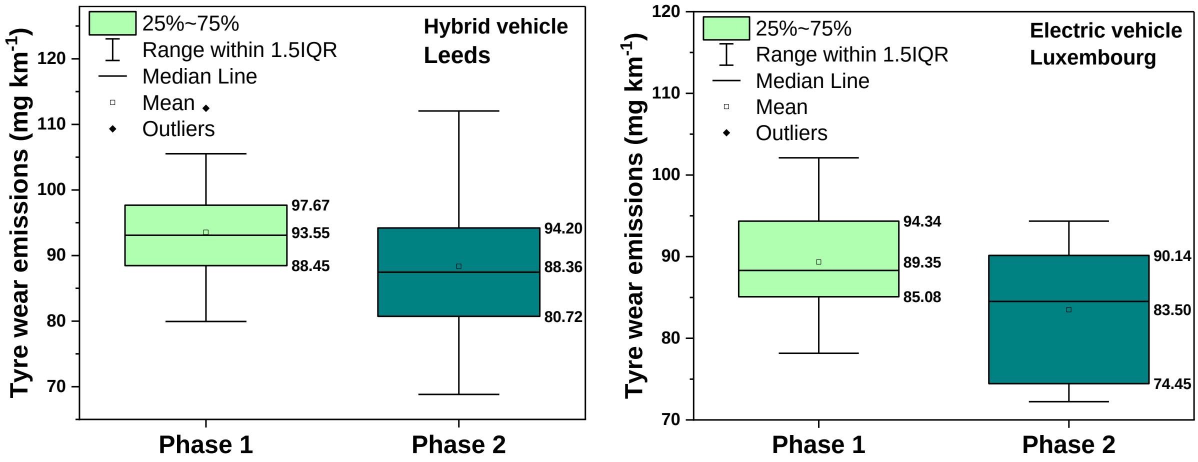


Figure 8.3: Tyre wear emissions of hybrid/electric vehicles before and after training

Furthermore, a comparative analysis of tyre wear emissions between hybrid/electric vehicles and ICE vehicles was performed, and the results are depicted in Figure 8.4. It is evident that the average tyre wear emissions from hybrid/electric vehicles were considerably higher than those from ICE vehicles. More precisely, the mean values of tyre wear emissions from hybrid vehicles were found to be 8.1% higher than those from ICE vehicles. As for electric vehicles, the tyre wear emissions showed a significant increase of 4.6% in average values.

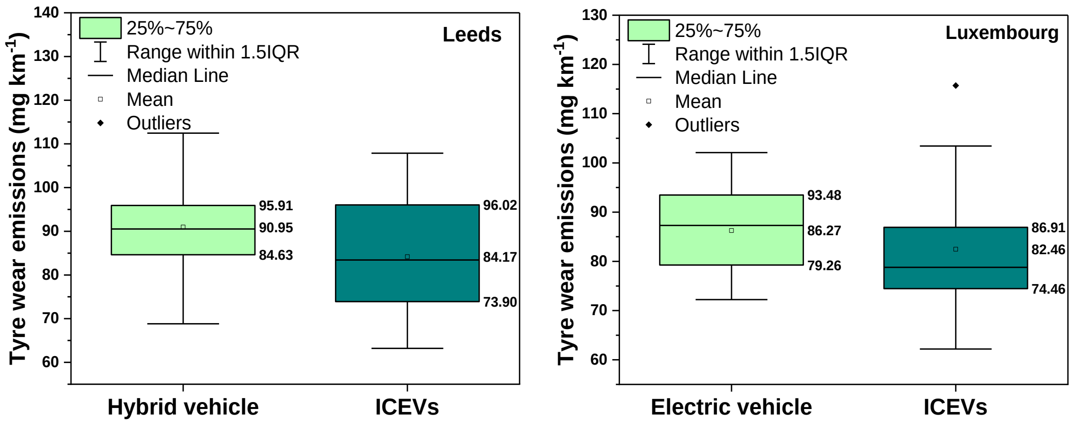


Figure 8.4: Tyre wear emissions of hybrid/electric vehicles and internal combustion engine vehicles (ICE vehicles)

8.3 Total score and fuel consumption electric-and-hybrid vs. other

In this trial drivers were recruited of different gender, age groups and driving different types of vehicles, in terms of fuel types. The main fuel types were: diesel, petrol, electric and hybrid. Data for electric and hybrid vehicles was available only for Leeds, Luxembourg and Thessaloniki (Figure 8.5 and 8.6). Data collected by different type of vehicles has been analysed in chapter 6, section 6.5, here the focus is only on hybrid and electric vehicles. Figure 8.5 shows total scores and Figure 8.6 shows fuel consumption of electric and hybrid fuels vs. other fuels (mainly petrol and diesel). Fuels consumption has a strong positive correlation with PM emission and total emission (section 6.1), therefore no need to analyse all three parameters, and for brevity only fuel consumption is analysed. Firstly, total score is analysed for hybrid vehicles vs. other vehicles using total data (including both phases 1 and 2 data). Total score is higher for hybrid and electric vehicles than other fuel types at Leeds. However, results are different for Thessaloniki and Luxembourg, where the total score is lower for electric vehicle than other vehicle types. The difference between hybrid and other vehicle types at Thessaloniki and Luxembourg is not significant ($p\text{-value} > 0.05$). As said before, fuel consumption is inversely proportion to total score (chapter 6, section 6.1), therefore, the results of fuel consumption are opposite to that of total score at all three sites. Fuel consumption for electric and hybrid vehicles is measured in miles per gallon of gasoline (petrol) equivalent (MPGe) or kilometre per litre gasoline equivalent (KmPLe) as opposed to the standard miles per gallon or kilometre per litre.

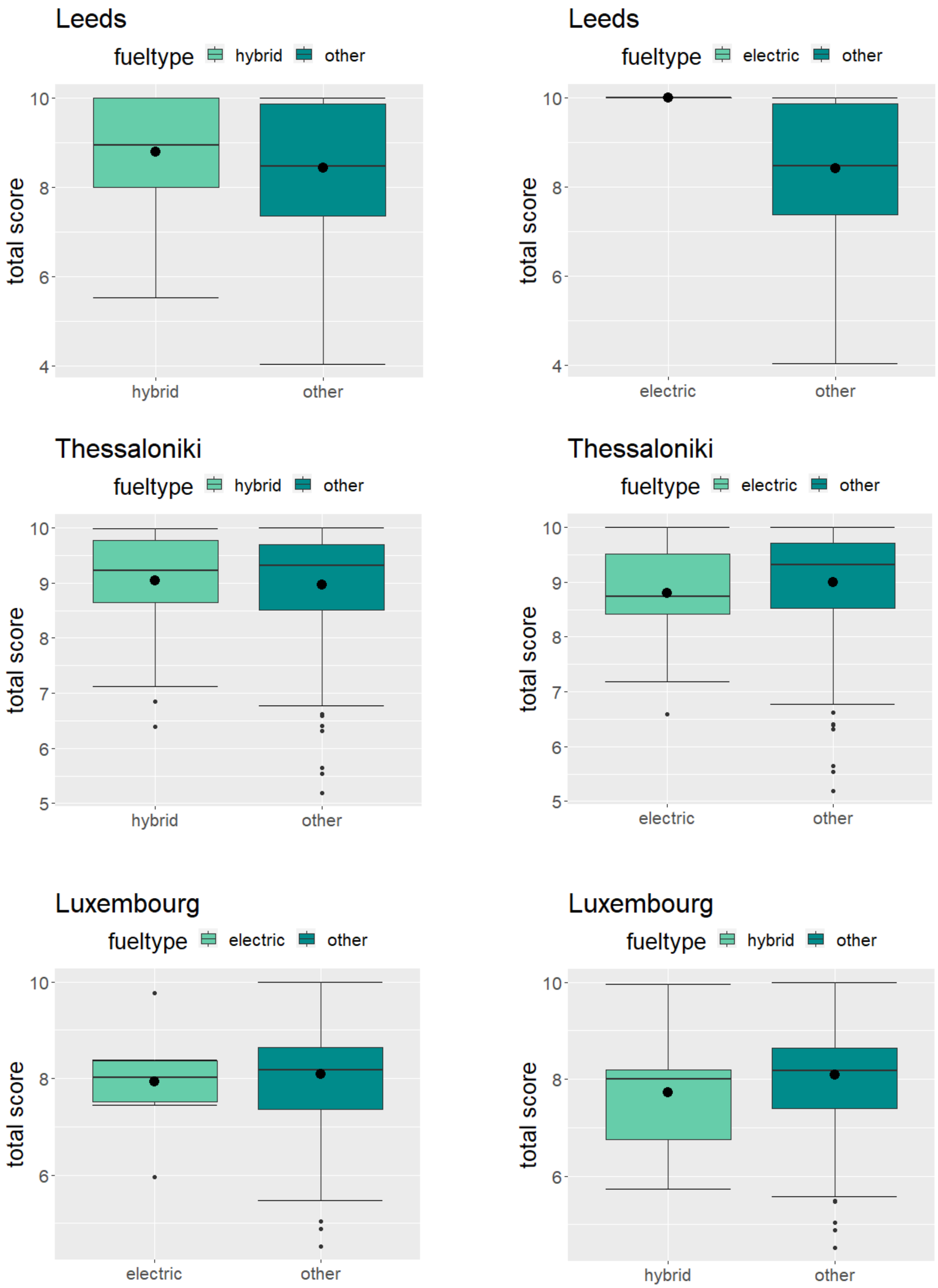


Figure 8.5: Total scores of electric and hybrid vehicles vs. others vehicles (mainly petrol and diesel) for Leeds, Luxembourg, and Thessaloniki

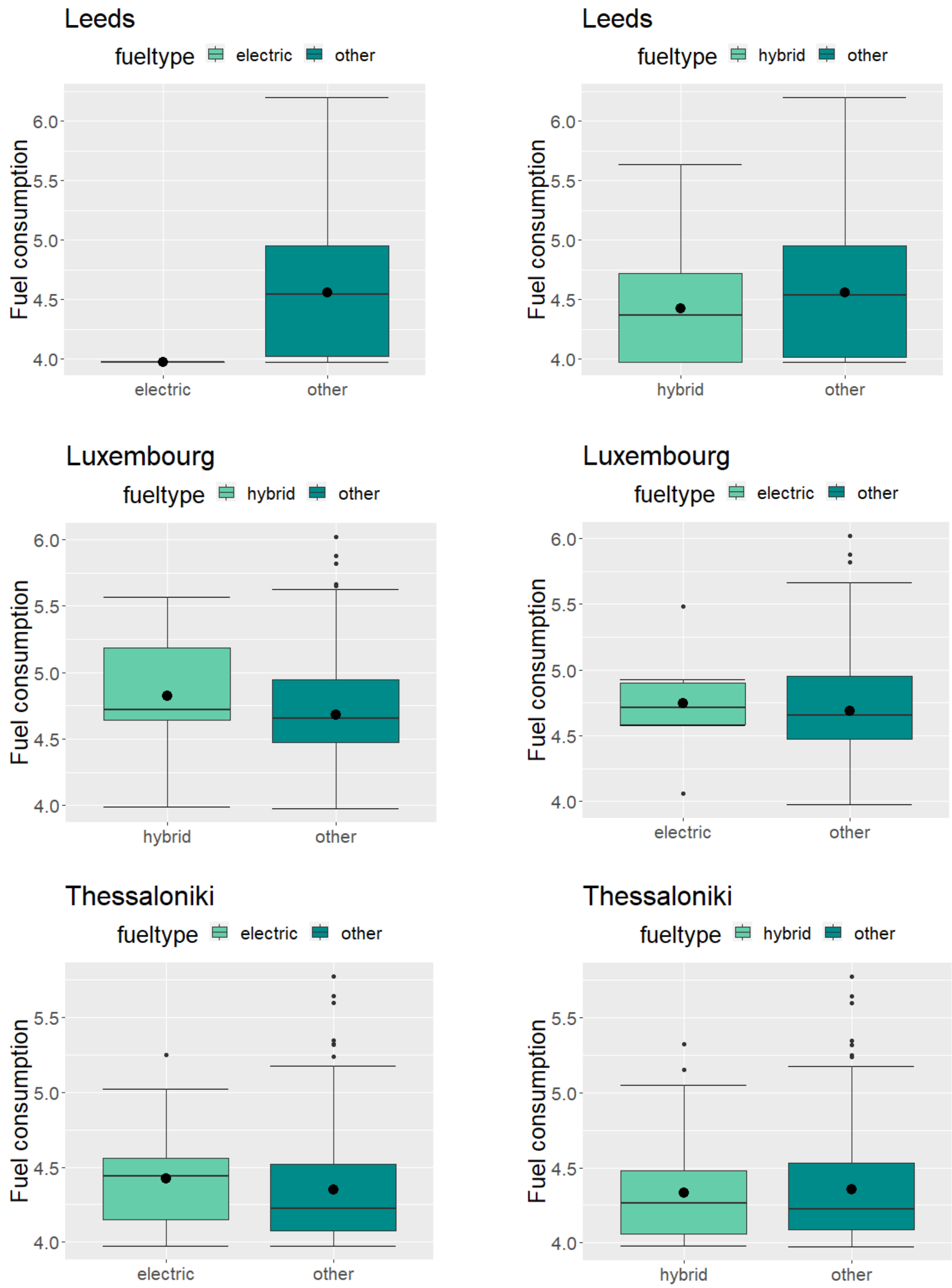
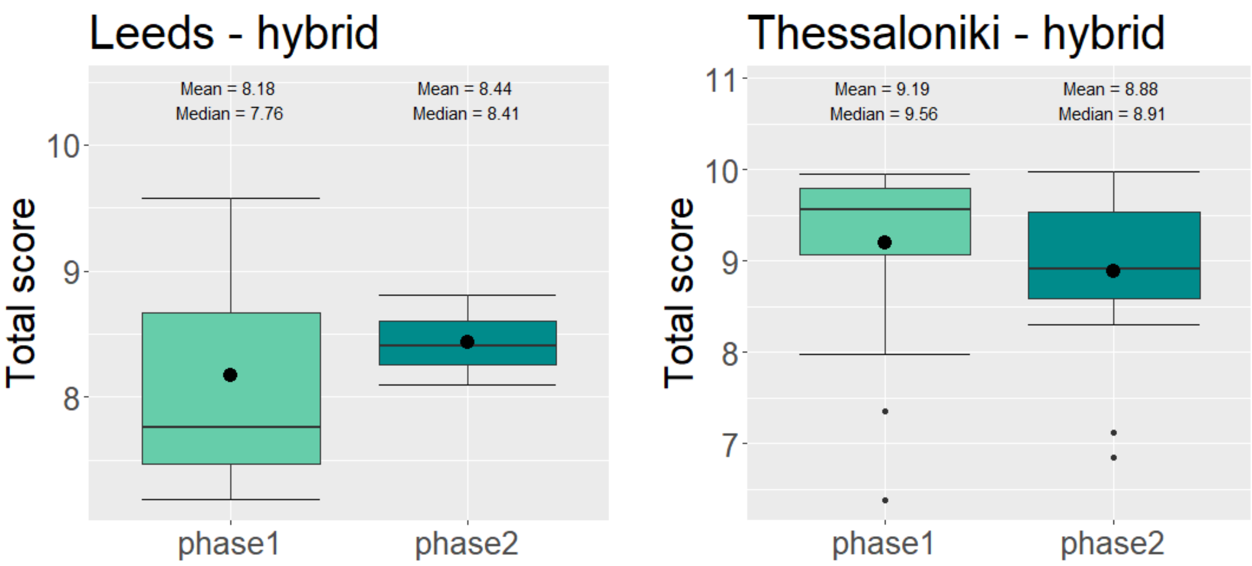


Figure 8.6: Fuel consumption of electric and hybrid vehicles vs. others vehicles (mainly petrol and diesel) for Leeds, Luxembourg, and Thessaloniki

Figure 8.7 depicts total score of hybrid and electric vehicles in Phase 1 and Phase 2 for Leeds, Luxembourg and Thessaloniki. Total score increased in Phase 2 for hybrid vehicles, however, comparison was not possible for electric vehicles in Phase 1 vs. Phase 2 at Leeds due to the absence of electric vehicle data in Phase 2. Hybrid vehicles demonstrated reduction in total score in Phase 2 for Thessaloniki. Data of electric vehicles existed for both Phase 1 and Phase 2 for Luxembourg and Thessaloniki. Average total score for Phase 1 and Phase 2, their difference and percent difference for Leeds, Luxembourg and Thessaloniki are presented in Table 8.1. Highest improvement (29 %) in total score in Phase 2 was demonstrated by electric vehicles at Luxembourg, followed by electric vehicle at Thessaloniki (4.49 %). Total score increased by 3.18 % in Phase 2 at Leeds, whereas the score decreased in Phase 2 at Thessaloniki by 3.40 %.

Difference and percent difference of fuel consumption and PM emission of Phase 1 and Phase 2 for the Leeds, Luxembourg and Thessaloniki are provided in Table 8.2 for both hybrid and electric vehicles. Fuel consumption and PM emissions for Leeds and Thessaloniki are presented in Figure 8.8 for hybrid vehicles, which in contrast to total score have shown reduction for Leeds and increase for Thessaloniki. Table 8.2 shows that fuel consumption and PM emissions have increased in Phase 2 for hybrid vehicles at Thessaloniki, whereas they decreased for electric vehicles. Also, both fuel consumption and PM emissions have decreased for hybrid vehicle at Leeds and electric vehicles at Luxembourg. Highest percent increase was demonstrated by hybrid vehicle at Thessaloniki (5%) and highest reduction was demonstrated by electric vehicles at Luxembourg (-27%).



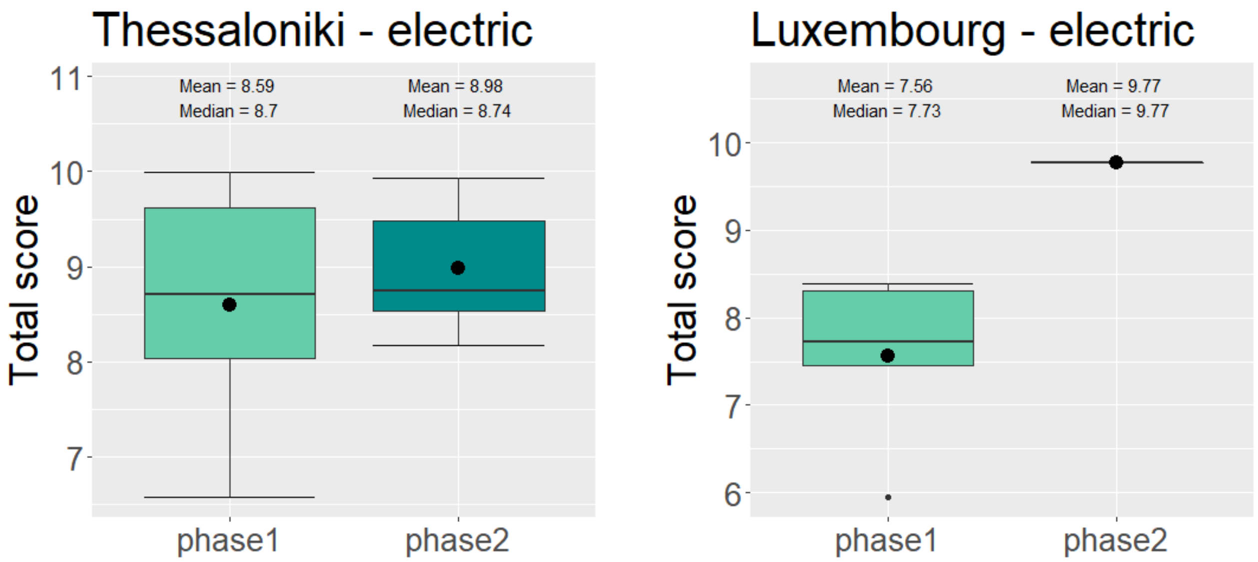


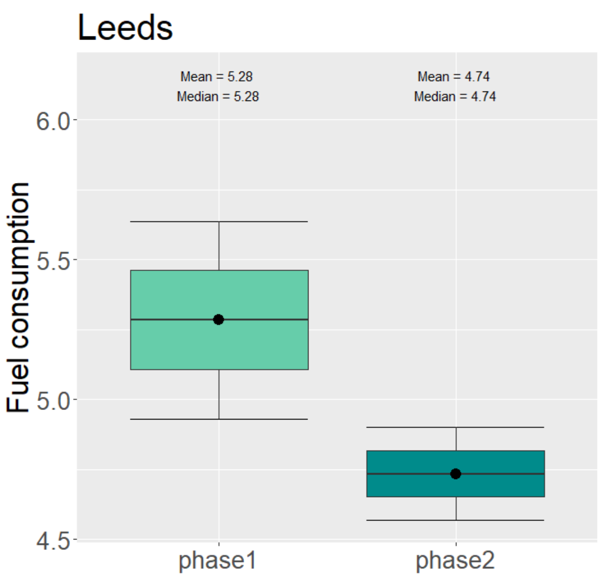
Figure 8.7: Total score of Phase 1 vs. Phase 2 for hybrid and electric vehicles at different sites

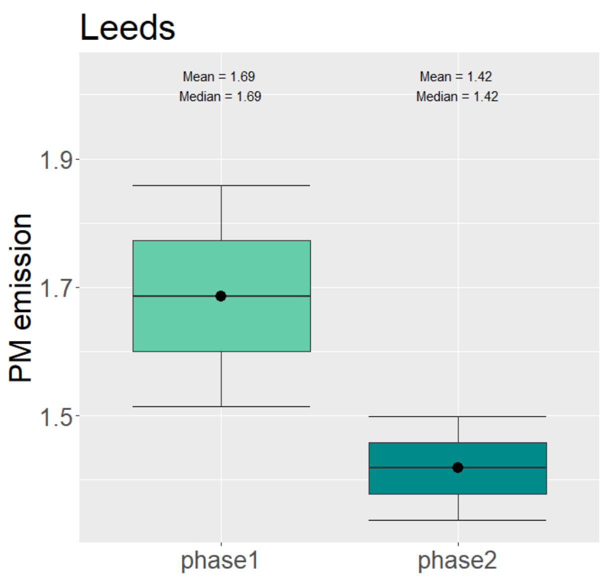
Table 8.1: Difference in total score between Phase 1 and Phase 2 for hybrid and electric vehicles

Site	Fuel type	Phase 1	Phase 2	Difference	% difference
Thessaloniki	Electric	8.59	8.98	0.39	4.49
	Hybrid	9.19	8.88	-0.31	-3.40
Luxembourg	electric	7.56	9.77	2.21	29.16
Leeds	hybrid	8.18	8.44	0.26	3.18

Table 8.2: Difference in fuel consumption and PM emission between Phase 1 and Phase 2 for hybrid and electric vehicles

Site	Fuel type	Phase 1	Phase 2	Difference	% difference
	Fuel consumption				
Thessaloniki	Electric	4.5	4.35	-0.15	-3.33
	Hybrid	4.27	4.39	0.12	2.81
Luxembourg	electric	4.88	4.06	-0.82	-16.80
Leeds	hybrid	5.28	4.74	-0.54	-10.23
	PM emission				
Thessaloniki	Electric	1.3	1.23	-0.07	-5.69
	Hybrid	1.19	1.25	0.06	5.04
Luxembourg	electric	1.49	1.09	-0.40	-26.85
Leeds	hybrid	1.69	1.42	-0.27	-15.98





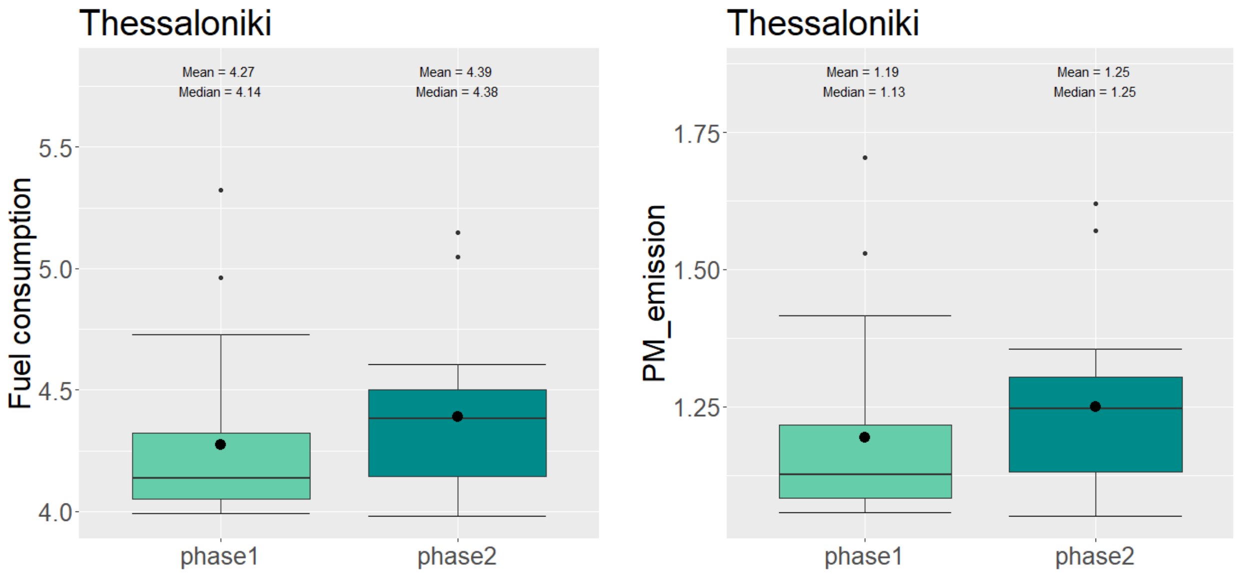


Figure 8.8: Fuel consumption and PM emission Phase 1 vs. Phase 2 for Leeds and Thessaloniki only for hybrid vehicles

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Annex A: Baseline questionnaire in Nanjing Trial

Thank you for participating in this trial. This questionnaire includes 25 questions, most of which are in multiple choices and will only take a few minutes of your time.

This questionnaire is used only to understand your driving habits and attitudes, so please fill it out honestly. For contact purposes, we would like you to provide us with your contact information and will not disclose it to others.

We will delete all data provided by you after the training is completed.

Personal Information

Name: License plate of vehicle driven: Contact information:

Note: The above information will only be used to contact you about the trial and will not be linked to the following information on you as a person, driver, or vehicle type.

Please tick one of the following

1. Have you received any other driver training since passing your driving test? (multiple choices possible)

- ☐ No unified training and no self-study
- ☐ Self-learning through self-media, etc.
- ☐ Took a driving course for specific conditions (e.g. winter driving course)
- ☐ Took an eco-driving or fuel-efficient driving course
- ☐ Attended driving courses or tests for specific vehicles, e.g. heavy trucks, large buses
- ☐ Attended retraining for a traffic violation

2. How do you usually carry passengers in your vehicle? (multiple choices)

- ☐ More than the rated passenger limit of the vehicle with standing passengers
- ☐ About 80%-100% of rated capacity, almost full
- ☐ About 50%-80% of rated capacity, less than half empty seats
- ☐ Less than 50% of rated capacity, with more empty seats

3. How often do you or the fleet manager take vehicles to the garage for maintenance? (multiple choices)

- ☐ Three times a year or more
- ☐ Twice a year
- ☐ Once a year
- ☐ Less often

4. Where do you or the fleet manager perform vehicle maintenance? (multiple choices)

- ☐ Do all maintenance and repair work at the garage
- ☐ Do basic maintenance at work, but go to the garage to complete other projects
- ☐ Do most of the maintenance myself or at the company
- ☐ New car, never serviced.

5. Do you change your tyres between summer and winter? (single choice)

- ☐ Yes, I will actively change summer and winter tyres
- ☐ No, I use the same tyres all year round
- ☐ I only put on winter tyres when I need them (when there is snow, or when the route goes through mountainous areas).
- ☐ I only install winter tyres after a company or fleet request for a tyre change

6. About eco-driving mode (also called city driving mode or fuel saving mode)

a) Does your car have Eco Mode or City Mode? (Single choice)

- ☐ Yes, it is the default mode (I have to turn it off when I don't want to use it)
- ☐ Yes, but it is not the default mode (I have to turn it on when I want to use it)
- ☐ No (please skip directly to question 7)

b) How often do you use eco-drive mode? (Single choice)

- ☐ Use it every time I drive
- ☐ Use it when I think of it
- ☐ Occasionally
- ☐ Never

c) If you have not used Eco Mode, why? (Single choice, please skip this question if you have used eco-drive mode)

- ☐ It affects the performance of the car (too slow, etc.)
- ☐ Don't know how to activate eco-mode
- ☐ Forgot to activate eco mode
- ☐ Don't understand what eco-mode does
- ☐ Other - please specify.

7. How would you choose your route before setting off? (multiple choices possible)

- ☐ Route is fixed and no choice can be made

- Choose the fastest route
- Choose the shortest route
- Choose a route with fewer grade changes and/or more straight lines
- Choose a route with fewer urban areas
- Choose a route with more freeways
- Choose a route with less traffic
- Choose a route with well-maintained roads

8. How often do you check your tyre pressure? (multiple choices)

- Once a week
- Once a month
- Once a year
- When tyre pressure looks significantly low
- Before having a longer trip
- Every time you stop for gas

9. How often do you check your engine and oil trouble lights? (Single choice)

- Before each job
- Weekly
- Monthly
- Annually
- Never

10. How often do you change your engine oil? (Single choice)

- Once a month
- Every six months
- Once a year
- Never

11. How often do you clean the air filter? (Single choice)

- Once a month
- Once every six months
- Once a year

- ☐ Never

12. Does your driving speed change in windy weather? (Single check)

- ☐ Will drive at a lower speed than usual
- ☐ Will drive faster than usual
- ☐ No difference from your usual driving speed

13. Does your driving speed change when you go uphill? (multiple choices)

- ☐ will reduce speed.
- ☐ will maintain the same speed.
- ☐ will gradually increase speed.

14. How often do you or the fleet manager check the vehicle for possible mechanical problems (loose parts, etc.)? (Single choice)

- ☐ Once a week
- ☐ Once a month
- ☐ Once a year
- ☐ Several times a year
- ☐ Never

15. How often do you or the fleet manager take vehicles to the garage for vehicle maintenance? (multiple choices)

- ☐ Once a year
- ☐ Once every two years
- ☐ When there is engine failure
- ☐ In accordance with periodic inspection requirements set by the state
- ☐ In accordance with the periodic vehicle inspection requirements specified by the vehicle manufacturer

16. What do you do when the diagnostic warning light comes on? (multiple choices)

- ☐ Ignore
- ☐ Address it later when you have time
- ☐ Park the vehicle in a safe place, turn off the engine and check the manual
- ☐ Call your dealer or fleet maintenance person for further instructions

17. When purchasing and using vehicle spare parts and consumables, do you prefer? (single choice)

- ☐ Cheaper

- Manufacturer specified
- Any, as long as it is valid

18. Do you keep detailed records of vehicle maintenance, including vehicle mileage? (single choice)

- Yes
- No

19. Do you modify the following parts of your vehicle beyond the manufacturer's standards? (multiple choices)

- Exhaust
- Air filter
- Turbo
- Electronic Control Unit (ECU) reprogramming/chip tuning
- Diesel Particulate Filter (DPF) Removed
- Speed limiter modification
- Tyre size
- Modifications to engine (e.g. intake, exhaust manifold)
- Drivetrain modifications (e.g., transmission)
- Modifications to the chassis (e.g.: suspension, brakes, rims)
- Modifications to the bodywork (e.g., adding a spoiler)
- Other modifications: please specify.
- Have not modified the above parts, but intend to do so
- No modifications have been made, keep the car as standard as possible

20. How often do you use the following types of apps for driving assistance or navigation? (each row is a single choice)

---

21. Usually, how often do you drive your work vehicle on the following roads? (Single choice)

a) Inner city roads

☐ Once a day ☐ Once a week or more ☐ Once a month or more ☐ Less than once a month

b) Major roads outside of urban areas, connecting rural areas or suburban areas

☐ Once a day ☐ Once a week or more ☐ Once a month or more ☐ Less than once a month

c) Secondary roads in rural or suburban areas

☐ Once a day ☐ Once a week or more ☐ Once a month or more ☐ Less than once a month

d) Highways

☐ Once a day ☐ Once a week or more ☐ Once a month or more ☐ Less than once a month

22. When driving, how often do you do the following? (multiple choices)

a) When the engine temperature is low, I tend to drive at normal speed

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) I tend to accelerate quickly to the desired speed to save time.

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

c) I tend to do small accelerations frequently until I reach the desired speed to save time

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

d) While driving, I tend to maintain a steady speed as much as possible

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

e) I tend to accelerate frequently on city streets

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

f) I tend to continue accelerating at higher speeds

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

g) I tend to accelerate suddenly regardless of other conditions

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

23. When the vehicle is going downhill or when a vehicle appears in front of you, how often do you perform the following actions in order to reduce the speed of the vehicle: (single choice)

a) Depress the clutch pedal:

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) By engine braking:

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

24. How often do you perform the following operations while driving in summer: (optional)

a) Turn on the air conditioning system and close the windows

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) Open the windows when the air conditioner is on

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

25. Your attitude toward the following statements is: (select one)

a) It is important to drive in a way that saves fuel

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

b) Whenever possible, try to use public transportation, walk or bike to reduce car use

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

c) There is a health risk from air pollution in my town or city

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

d) I would pay more for this car if it produced less pollution

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

e) My driving style is very cautious

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

f) My driving speed is very fast

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

g) I drive in an energy-efficient way

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

h) I am very relaxed while driving

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

Annex B: Post-training questionnaire in Nanjing Trial

Thank you for participating in this survey, most of the questions in this questionnaire are in multiple-choice and will only take a few minutes of your time. For contact purposes, we would like to ask your contact information, but will not disclose it to others.

Personal Information:

Name: License plate of vehicle driven: Contact information:

Please tick one or more checkboxes or for some options, please fill in the content as required.

1. Has your average fuel consumption decreased after eco-driving training? (multiple choices possible)

- ☐ Average fuel consumption has decreased
- ☐ Average fuel consumption has not changed much
- ☐ Not sure or did not notice the change of average fuel consumption

2. When there is more than 30 seconds of idling (such as when the red light lasts more than 30 seconds or when there is a more serious traffic jam), how did you operate before and after the training?

a) Before eco-driving training:

- ☐ I turn off the engine to avoid idling
- ☐ I keep the engine on to ensure the vehicle moves first
- ☐ Other: ______________________________

b) After eco-driving training:

- ☐ I turn off the engine and avoid idling
- ☐ I keep the engine on to ensure the vehicle moves first
- ☐ Other: ______________________________

3. Do you change your tyres between summer and winter? (Single choice)

- ☐ Yes, I will actively change summer and winter tyres
- ☐ No, I use the same tyres all year round
- ☐ Only put on winter tyres when needed (when there is snow, or when the route goes through mountainous areas).
- ☐ I only install winter tyres after a company or fleet request for a tyre change

4. About eco-driving mode (also called city driving mode or fuel saving mode)

a) Does your car have Eco Mode or City Mode? (Single choice)

- ☐ Yes, it is the default mode (I have to turn it off when I don't want to use it)
- ☐ Yes, but it is not the default mode (I have to turn it on when I want to use it)

- ☐ No (please skip directly to question 6)

b) How often do you use eco-drive mode? (Single check)

- ☐ Use it every time I drive
- ☐ Use it when I think of it
- ☐ Occasionally
- ☐ Never

c) If you have not used Eco Mode, why? (Single choice, please skip this question if you have used eco-drive mode)

- ☐ It affects the performance of the car (too slow, etc.)
- ☐ Don't know how to activate eco-mode
- ☐ Forgot to activate eco mode
- ☐ Don't understand what eco-mode does
- ☐ Other - please specify.

5. How would you choose your route before setting off? (multiple choices possible)

- ☐ The route is fixed and no choice is possible
- ☐ Choose the fastest route
- ☐ Choose the shortest route
- ☐ Choose a route with fewer grade changes and/or more straight lines
- ☐ Choose a route with fewer urban areas
- ☐ Choose a route with more freeways
- ☐ Choose a route with less traffic
- ☐ Choose a route with well-maintained roads

6. How often do you check your tyre pressure? (multiple choices)

- ☐ Once a week
- ☐ Once a month
- ☐ Once a year
- ☐ When tyre pressure looks significantly low
- ☐ Before having a longer trip
- ☐ Every time you stop for gas

7. How often do you check your engine and oil trouble lights? (Single choice)

- ☐ Before each job
- ☐ Weekly
- ☐ Monthly
- ☐ Annually
- ☐ Never

8. How often do you change your engine oil? (Single choice)

- ☐ Once a month
- ☐ Once every six months
- ☐ Once a year
- ☐ Never

9. How often do you clean the air filter? (Single choice)

- ☐ Once a month
- ☐ Once every six months
- ☐ Once a year
- ☐ Never

10. Does your driving speed change in windy weather? (Single choice)

- ☐ Will drive at a lower speed than usual
- ☐ Will drive faster than usual
- ☐ No difference from your usual driving speed

11. Does your driving speed change when you go uphill? (multiple choices)

- ☐ will reduce speed
- ☐ will maintain the same speed
- ☐ will gradually increase speed

12. How often do you (or the fleet manager) check your vehicle for possible mechanical problems (loose parts, etc.)? (single choice)

- ☐ Once a week
- ☐ Once a month
- ☐ Once a year
- ☐ Several times a year
- ☐ Never

13. How often do you (or the fleet manager) take your vehicle to the garage for vehicle maintenance? (single choice)

- ☐ Once a year
- ☐ When there is engine failure
- ☐ As required by state regulations for periodic inspections
- ☐ In accordance with the periodic vehicle inspection requirements specified by the vehicle manufacturer

14. What do you do when the diagnostic warning light comes on? (multiple choices)

- ☐ Ignore
- ☐ Address it later when you have time
- ☐ Park the vehicle in a safe place, turn off the engine and check the manual
- ☐ Call your dealer or fleet maintenance person for further instructions

15. When purchasing and using vehicle spare parts and consumables, do you prefer? (single choice)

- ☐ Cheaper
- ☐ Manufacturer specified
- ☐ Any, as long as it is valid

16. Do you keep detailed records of vehicle maintenance, including vehicle mileage? (single choice)

- ☐ Yes
- ☐ No

17. How often do you use the following types of apps for assisted driving or navigation? (each row is optional)

	Often	Occasionally	Rarely or neve
General navigation apps (e.g., Gaode Maps)			
Company-assigned route navigation apps			
Assisted driving apps (e.g., eco-driving apps that reduce fuel use)			
Other types:____________________			

18. When driving, how often do you perform the following operations? (single choice)

a) When the engine temperature is low, I tend to drive at normal speed

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) I tend to accelerate quickly to the desired speed to save time.

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

c) I tend to do small accelerations frequently until I reach the desired speed to save time

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

d) While driving, I tend to maintain a steady speed as much as possible

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

e) I tend to accelerate frequently on city streets

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

f) I tend to continue accelerating at higher speeds

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

g) I tend to accelerate suddenly regardless of other conditions

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

19. When the vehicle is going downhill or when a vehicle appears in front of you, how often do you perform the following actions in order to reduce the speed of the vehicle: (single choice)

a) Depress the clutch pedal:

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) By engine braking:

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

20. How often do you perform the following actions while driving in summer: (optional)

a) Turn on the air conditioning system and close the windows

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

b) Open the windows when the air conditioner is on

☐ Never ☐ Rarely ☐ Occasionally ☐ Frequently ☐ Always

21. Your attitude toward the following statements is: (single choice)

a) It is important to drive in a way that saves fuel

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

b) Are you concerned about the pollution of the environment from car emissions?

☐ Very concerned ☐ Concerned ☐ Neutral ☐ Occasionally concerned ☐ Not concerned

22. What are your suggestions for implementing low-emissions driving?

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Adapting driver behaviour for lower emissions