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The use of a vehicle simulator for eco-driving research

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The study presents the use of a driving simulator as a tool for evaluating driver behavior in the context of eco-driving. A group of 37 drivers of varying age and experience completed a predefined urban driving scenario under controlled conditions. Based on four operational variables, each weighted by its assumed impact on fuel efficiency, the WEco indicator was developed to enable a quantitative assessment of driving style. Drivers were classified into three groups representing different levels of eco-driving performance. The results showed clear differences in fuel consumption and engine RPM, confirming the validity of the classification model. The proposed indicator offers practical applications in fleet management, driver training, and environmental impact monitoring.

Key words: *eco-driving, vehicle simulator, driving style classification, fuel consumption, driver behavior analysis*

1. Introduction

Due to growing environmental awareness and the constant rise in fuel costs, the search for effective strategies to reduce fuel consumption and greenhouse gas emissions is becoming a priority and an integral part of responsible vehicle use. The search for alternative energy sources to improve efficiency, reduce toxic emissions into the atmosphere, and prevent global warming are currently key areas of development in the energy sector, including the design of internal combustion engines [30]. Road transport accounts for over 85% of total freight transport. In this process, motor vehicles are primarily used for transport operations [33]. Transport accounts for a significant portion of energy consumption and emissions of environmentally harmful dust and gases [22]. Reducing carbon dioxide emissions to mitigate climate change has become a key focus of research and development in the sector in recent years [10, 26, 29]. As a result, the concept of eco-driving, or eco-friendly driving, is gaining in importance and popularity. Eco-driving is not only a way of driving, but also a comprehensive strategy involving the application of special techniques and driving behaviour in order to minimise the vehicle's negative impact on the environment, while at the same time reducing fuel consumption and operating costs. The main principles of eco-driving are based on smooth driving, reducing unnecessary acceleration and braking. The technique involves driving the car in the highest possible gear, at the lowest possible engine speed. It is also important to brake the engine by reducing gears – e.g. when approaching traffic lights (idling) [4]. Eco-driving appears to be an effective way to achieve energy savings and emission reductions in the short term [27]. It is becoming increasingly common and is thought to improve driving behaviour. Research results presented in papers such as [32] show that the use of eco-driving not only has environmental benefits but also reduces operating costs through lower fuel consumption, which is particularly important in this day and age. The issue of eco-driving is currently very popular and is addressed in numerous publications. Researchers have noted the potential impact of eco-driving on improving the safety of transport users. Studies [2, 6, 8, 28] show a link between eco-driving and safe driving, as safe driving includes, among other things, observing speed limits and avoiding rapid acceleration or braking. Many studies on eco-driving have shown potential reductions in fuel consumption and CO_2 emissions ranging from 5% to 40% [2]. The authors focus on the implementation of eco-driving into fleet driver training. They emphasise that eco-driving not only reduces costs and environmental impacts, but also improves driving safety – through smoother driving, reduced speed and earlier response to traffic situations, among other benefits [6]. Deliberate reductions in greenhouse gas and particulate emissions have been shown to contribute to climate change mitigation [7, 8, 11], as well as generating economic benefits through reduced fuel consumption of vehicle engines [8]. Driving according to eco-driving principles can have a significant impact on reducing fuel consumption by up to 10%, thereby reducing CO_2 emissions while driving by the same amount [7]. The concept of eco-driving may be relevant and is often studied and analysed, especially in the context of companies operating large fleets of vehicles [6, 15, 13]. According to research findings, it can be concluded that the application of eco-driving principles brings tangible benefits such as reduced fuel consumption, lower emissions of greenhouse gases and air pollutants, reduced vehicle operating costs, and extended vehicle life [4, 14]. Compared to normal driving, eco-driving resulted in a reduction in fuel consumption of 0.44 dm^3/100 km (–6.6%), while aggressive driving led to an increase of 1.64 dm^3/100 km (+24.6%) [4]. In order to carry out effective research in the context of eco-driving, it is necessary to select appropriate parameters such as road conditions [16], route choice [24], traffic volume, and other relevant factors. It should be noted, not under all conditions will eco-driving principles produce noticeable benefits [5, 9, 23, 24]. In the literature, researchers often mention routes with a high number of intersections with traffic lights because they force the driver to brake, accelerate and idle frequently [17], which provides a realistic context for evaluating the effectiveness of eco-driving strategies.

Vehicle simulators offer the possibility of programming routes in such a way that consistent and repeatable measurement conditions, e.g. the number of intersections with traffic lights, environmental conditions, and traffic behaviour, remain consistent across all test drives. Achieving such standardisation in actual road tests would be extremely difficult. Therefore, the use of driving simulators allows controlled experimentation with identical traffic scenarios, enabling analysis and comparison of driver performance under repeatable conditions. According to the literature, the greatest environmental and economic benefits of eco-driving are observed in urban and suburban traffic (e.g. on national, regional, and local roads), while the least benefits are reported for driving on motorways and expressways due to the relatively smooth flow of traffic and fewer stops [5, 9, 23, 24]. This article presents potential applications of vehicle simulators in eco-driving-related research. By discussing various aspects of eco-driving and presenting research results, the aim is to highlight the importance of this concept as an effective strategy to reduce fuel consumption and greenhouse gas emissions in the context of modern road transport. The article presents selected aspects of measurement methodologies in the field of eco-driving using a vehicle simulator. Simulators play a key role and are frequently used tools in many studies [18, 21, 24]. Simulators provide a safe, controlled and precise environment for testing and improving driving techniques [19, 21]. They enable not only the collection of research data, but also the effective training of drivers [25] and the testing of new technologies to support sustainable transport development. They also provide reproducible and safe testing conditions. This allows testing under controlled conditions and strict traffic scenarios, eliminating the risks associated with real-world traffic. This makes it possible to test different driving situations and techniques without endangering drivers. Simulators also offer highly precise data acquisition capabilities. They are equipped with advanced measurement systems that enable detailed tracking of vehicle dynamics and parameters characterising driving behaviour, such as acceleration, braking, gear changes, engine revolutions, and fuel consumption. This data is essential for analysing the effectiveness of various eco-driving techniques. One of the biggest advantages of simulators is the ability to reproduce identical test conditions for different drivers. Through the use of simulators, the same route and driving conditions can be accurately reproduced for each participant, allowing reliable comparisons and evaluation of the impact of different factors on eco-driving efficiency. This approach eliminates potential errors due to route variability or changing road conditions. Simulators are also widely used in driver training. Through practical exercises, drivers can learn and improve their eco-driving techniques, which then directly translates into improved driving behaviour in real-world conditions. Testing in a vehicle simulator also allows new technologies to be tested, including driver assistance systems and systems that support eco-driving, such as fuel-optimised navigation, intelligent speed management systems and different engine modes. In addition, simulators facilitate the study of the behavioural aspects of driving. They allow researchers to analyse how factors such as stress or fatigue, for example, affect driver behaviour and the ability to apply eco-driving techniques effectively. The aim of this study is to develop indicators to analyse driver behaviour and to investigate selected eco-driving techniques using a vehicle simulator. The study also focuses on developing and testing an indicator-based model to classify drivers' driving styles according to eco-driving principles. This research responds to current socio-economic needs related to reducing transport emissions, promoting fuel efficiency, and improving drivers' technical competence. The importance of sustainability in the transport sector is constantly growing and requires effective tools to assess and influence driver behaviour. The classification model proposed in this thesis is practical and flexible, making it potentially useful both in training processes (e.g. for professional drivers) and in monitoring fleet performance. Basing the analysis on real measurement data collected from the simulator increases the reliability of the results and opens up prospects for further research and implementation of solutions in practice.

2. Methods

2.1. Research equipment

The research was conducted using the Oktal™ driving simulator, located at the Laboratory of Vehicles and Tractors of the Kielce University of Technology (Fig. 1).

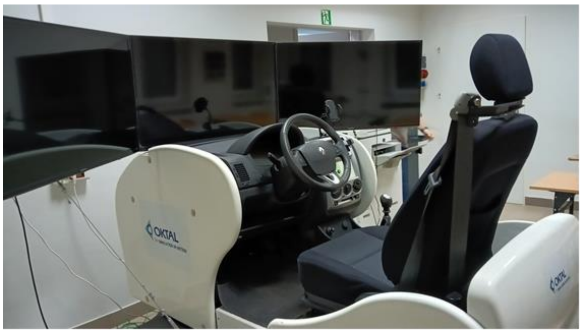

Fig. 1. Oktal™ Vehicle Simulator

The simulator's motion system platform has six degrees of freedom and is driven by six electric actuators, working in conjunction with electronically controlled gear systems. It allows angular oscillations of up to ±10° and linear displacements of up to ±50 mm. The simulator cab is a section of the actual vehicle cab. It is equipped with all the necessary components for driving. It includes a steering wheel with an angle sensor and active force feedback up to 15 Nm, capable of ±540° rotation and simulating uneven road surfaces. The accelerator, brake, and clutch pedals feature passive force feedback, which mimics real pedal resistance, and are equipped with pressure and position sensors. The manual gearshift lever includes a gear position sensor (supporting up to five or six forward and reverse gears), passive resistance, and a mechanical function that simulates clutch engagement by locking the gear when disengaged. Additional cabin features include a keyed ignition, manual parking brake, indicator lever, light switches, hazard warning button, horn, and programmable dashboard. The dashboard can display parameters such as vehicle speed, engine crankshaft speed, fuel consumption, brake pedal pressure, steering angle, and more. The cabin is equipped with an adjustable driver's seat, seat belts, and an audio system that generates dynamic vehicle sounds (such as engine operation, tyre-road interaction, and skidding), as well as ambient sounds [20]. The simulator allows customised measurement routes to be programmed to suit research needs. It also allows full control over environmental conditions, including time of day, weather, and traffic volume. During the experiments, the system records hundreds of parameters such as vehicle speed, position, acceleration, fuel consumption, gear selection, crankshaft speed, accelerator and brake pedal pressure, clutch engagement, and total simulation time. The ability to record and analyse these parameters under reproducible and controlled conditions enables a comprehensive assessment of driver behaviour, particularly in relation to eco-driving practices. For the purpose of the study, a route was chosen that represented driving conditions typical of an urban environment. The total length of the route was 2.5 km. It was programmed to allow repeated testing of driver behaviour under identical environmental conditions. Each driver had to drive the exact same route. The route included, among other things, intersections with traffic lights, which required drivers to stop and start frequently, creating convenient conditions for assessing driver behaviour in terms of eco-driving efficiency. The choice of a relatively short test route (2.5 km) was dictated by the need to ensure consistent, controlled, and repeatable experimental conditions. The main objective of the study was to compare driver behaviour in well-defined and repeatable urban traffic scenarios, which required minimising the variability of external factors such as traffic volumes, signalling patterns, and road infrastructure layout. The limited distance also facilitated the efficient conduct of multiple repetitions of the test within a limited time and under stable environmental conditions, thus increasing the reliability and comparability of the results obtained by the participants. Nevertheless, the authors recognise the limitations of the short route length. Therefore, future research will consider implementing longer and more varied routes that more accurately reflect the complexity of real traffic conditions and allow for more precise statistical averaging of driver behaviour indicators. The programmed route is shown in Fig. 2.

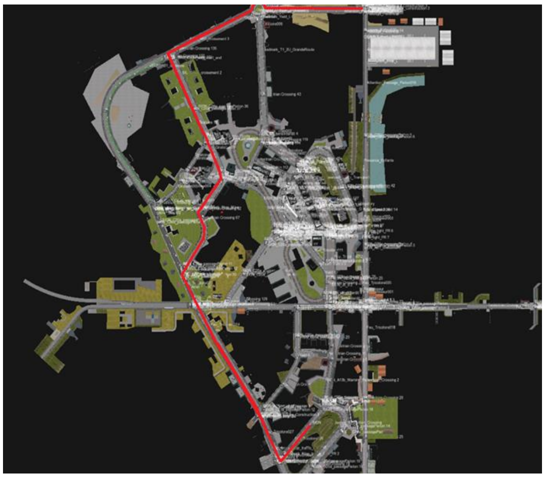

Fig. 2. Route map of the driving simulation

2.2. Participants

A total of 37 drivers aged between 21 and 67 years participated in the study. The age of the drivers averaged 28.22 years (standard deviation = 9.54), and the median age was 25 years. Table 1 shows the characteristics of the study group.

Table 1. Characteristics of the driver study group

Length of holding a driving licence				
Up to a single year	1–5 years	6–10	> 10	
2.70%	35.14%	32.43%	29.73%	
Frequency of vehicle use				
Daily	Several times a week	Several times a month		
72.97%	21.62%	5.41%		
Distance travelled per month				
Up to 100 km	101–300 km	301–1000 km	1001–3000	Up to 100 km
8.11%	5.41%	43.24%	35.14%	8.11%
Total distance travelled				
5–50 thousand kilometres	50–150 thousand kilometres	150–300 thousand kilometres	> 300 thousand kilometres	
16.22%	37.84%	24.32%	21.62%	
Is their work related to driving a vehicle?				
Yes	No			
24.32%	75.68%			

The results indicate that the group of drivers participating in the study was diverse in terms of age and driving experience, as measured by monthly driving distance and time since obtaining their licence. The task assigned to each participant was to drive a designated, pre-programmed route in a driving simulator. The route was designed to elicit various driving behaviours typical of urban traffic, such as stopping at intersections.

2.3 Parameters for eco-driving analysis

Tests carried out using the Oktal™ vehicle simulator allowed data to be collected that could be used to assess driving style. During the experiment, participants were asked to drive through urban areas at a speed typical of urban traffic, while choosing a pace they considered safe. Participants were first given a test drive to familiarise themselves with the simulator and the route. While driving, participants had to remain alert to their surroundings, including other road users. The route included intersections with traffic lights, intersections without traffic lights, and roundabouts. Figure 3 shows a screenshot of a sample simulation drive.

The figures below show examples of the characteristics that can be obtained during simulation studies. These example profiles illustrate the measurement capabilities of the simulator in eco-driving research and demonstrate its potential for use in larger-scale statistical analyses.

Fig. 3. Screenshot of a representative location during the simulation drive

The following variables were analyzed:

– Vehicle velocity [km/h] (Fig. 4a)
– Selected gear [-] (Fig. 4b)
– Engine crankshaft speed [rpm] (Fig. 4c)
– Fuel consumption [l/s] (Fig. 5).

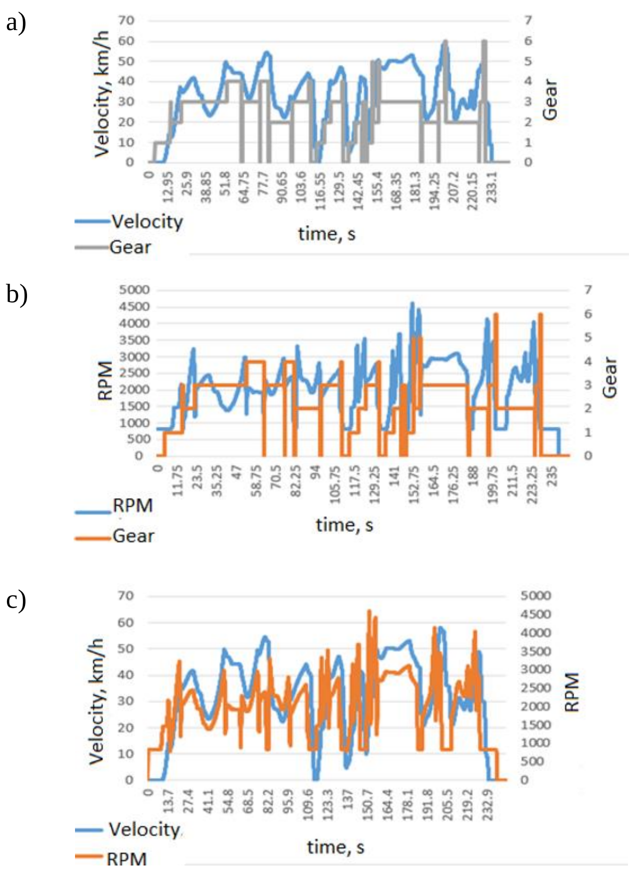

Fig. 4. Sample profiles obtained during the simulation drive: a) vehicle velocity and gear selection during the drive, b) engine crankshaft rotational velocity and corresponding gear, c) engine crankshaft rotational velocity and the vehicle velocity at the given moment

Analysis of the graphs above indicates that the test route was relatively dynamic and required frequent speed changes. In eco-driving, the optimal approach is to maintain a smooth and steady driving style that minimises the need for frequent gear changes. It is generally recommended to keep the vehicle speed as constant as possible, to avoid rapid acceleration or braking, and to select gears that keep the engine crankshaft speed within the optimum operating range. Interpreting these profiles makes it possible to assess whether the driver has chosen the right gears in relation to the vehicle speed. A common problem among drivers is keeping the engine speed excessively high or too low, which is inefficient in terms of fuel consumption and mechanical performance. The sample profiles allow the driver's behaviour to be assessed in the context of eco-driving principles, particularly in terms of gear selection on a specific test route. The data reveal moments when the driver failed to reduce gears in a timely manner – particularly in situations where he or she continued to drive in a higher gear despite a significant drop in vehicle speed and engine speed.

Figure 5 shows the vehicle speed profile in combination with engine crankshaft speed and fuel consumption during the simulation drive.

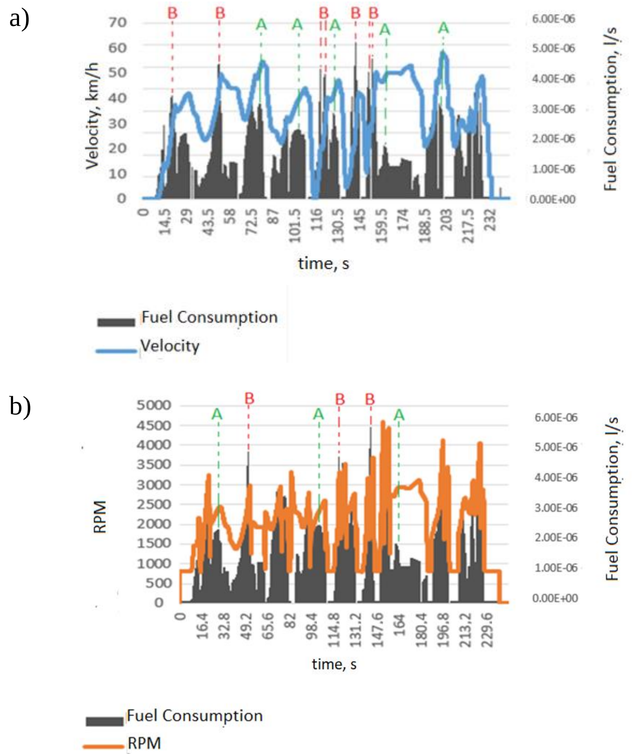

Fig. 5. Fuel consumption during the simulation drive: a) in relation to vehicle velocity, b) in relation to engine crankshaft rotational velocity

Analysis of the vehicle speed profile (Fig. 5a) identifies points where fuel consumption was particularly high (labelled point A), and points where it remained relatively low despite maintaining adequate vehicle speed and crankshaft speed (labelled point B). Dynamic changes in engine speed are associated with an increase in fuel consumption. Any rapid acceleration results in a sharp increase in fuel consumption. By analysing the engine crankshaft speed profile (Fig. 5b), it is possible to identify periods when fuel consumption remained relatively low under relatively stable revving conditions. To assess drivers from an eco-driving perspective, the following indicators were defined (Fig. 6).

Over-speed indicator (W1): expressed as a percentage of the total driving time in which the vehicle exceeded the speed limit. This indicator provides information on whether a driver complies with traffic regulations and how often and to what extent he or she exceeds the speed limit. Exceeding the speed limit not only constitutes a legal offence but can also lead to increased fuel consumption.

High Engine RPM Indicator (W2): expressed as a percentage of the time that the engine crankshaft speed exceeded 3,000 revolutions per minute (rpm). High engine speeds, especially in the context of unreasonably aggressive driving, lead to higher fuel consumption and increased emissions. A well-defined indicator makes it possible to assess how often the engine operates in the excessive rev range, which is a key aspect of driving style analysis in the context of eco-driving principles.

Engine Idling Time Indicator (W3): expressed as a percentage of the total time the vehicle remains idling (e.g. during traffic jams or stopping at traffic lights). Longer engine idling results in unnecessary fuel consumption and increased CO_2 emissions. While this may be due to factors beyond the driver's control – such as road infrastructure – it can be remedied by implementing Intelligent Transport Systems (ITS), which improve traffic flow, and by equipping vehicles with Start-Stop systems. Reducing this rate is a key element in improving economic driving performance.

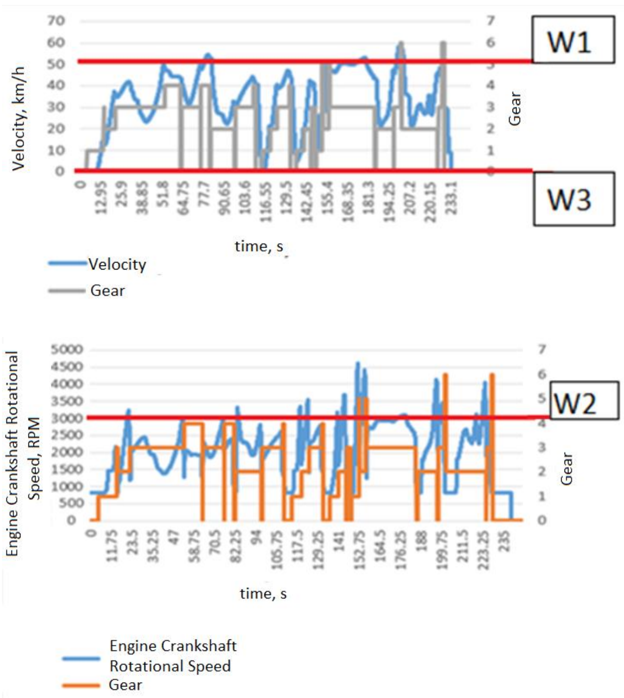

Fig. 6. Diagram of the applied indicators

Fuel Consumption Indicator (W4) is a direct measure of driving efficiency, representing the amount of fuel consumed relative to the distance travelled. Analysis of this indicator makes it possible to assess the impact of driver behaviour on vehicle fuel efficiency. These indicators make it possible to identify common mistakes made by drivers that can lead to increased fuel consumption. As part of the study conducted, each participant drove in urban conditions using a driving simulator, covering the same route. The following parameters were recorded for each participant during the drive: instantaneous speed, selected gear, engine crankshaft speed and instantaneous fuel consumption. Indicators W1 to W4 were calculated from the collected data. Weights were then assigned to each of these indicators, allowing the WEco index to be calculated for each driver. Based on the WEco index value, participants were classified into one of three driver profile groups.

3. Results

3.1. Characterisation of driving sessions in terms of eco-driving

In order to initially characterise the data used to calculate the WEco index, an analysis of the distribution of the four operational variables was carried out. For this purpose, box plots were used to graphically assess the dispersion, asymmetry and presence of outliers in the data set.

Figure 7 shows the distributions of the previously mentioned parameters.

The first variable analysed, representing the percentage of time driving at speeds exceeding 50 km/h (Fig. 7a), had a median of 12.48%.

The interquartile range was from 9.11% to 18.5%, with non-outliers ranging from 1.44% to 32.26%.

Numerous outliers were observed, indicating significant variation in driving speed among drivers, with some participants displaying a much more dynamic driving style.

The second variable, illustrating the percentage of time driving with an engine crankshaft speed above 3000 rpm (Fig. 7b), had a median of 16.54% and an interquartile range from 5.95% to 24.29%.

Nevertheless, the presence of outliers suggests significant differences in acceleration techniques and gear selection strategies, which have a direct impact on fuel economy.

The third variable, the proportion of idling time (Fig. 7c), showed a median of 7.1%.

Most observations fell between 3.36% and 11.38%, while non-outlier values ranged from 0.64% to 18.5%.

This distribution may reflect differences in driving smoothness and frequency of stops – such as during traffic congestion or while waiting at signalized intersections.

Extended engine idling is an undesirable phenomenon from an energy efficiency perspective.

The last analyzed variable – fuel consumption in liters per 100 km (Fig. 7d) – had a median value of 12.63 l/100 km, with quartiles ranging from 12.03 to 13.95 l/100 km.

Numerous outlier observations were recorded, reaching up to 22–25 l/100 km.

This highlights significant variation in vehicle operating intensity, resulting from factors such as driving dynamics, acceleration behavior, and engine RPM usage.

The relatively high median confirms that urban conditions – combined with certain driving styles – can lead to substantial fuel consumption.

In summary, the analysis of the four partial indicators revealed notable variability in driver behavior, with the presence of both typical and outlier values.

Particularly pronounced variation was observed in indicators W2 and W4, confirming their critical role in constructing the WEco indicator and in the overall assessment of eco-driving performance.

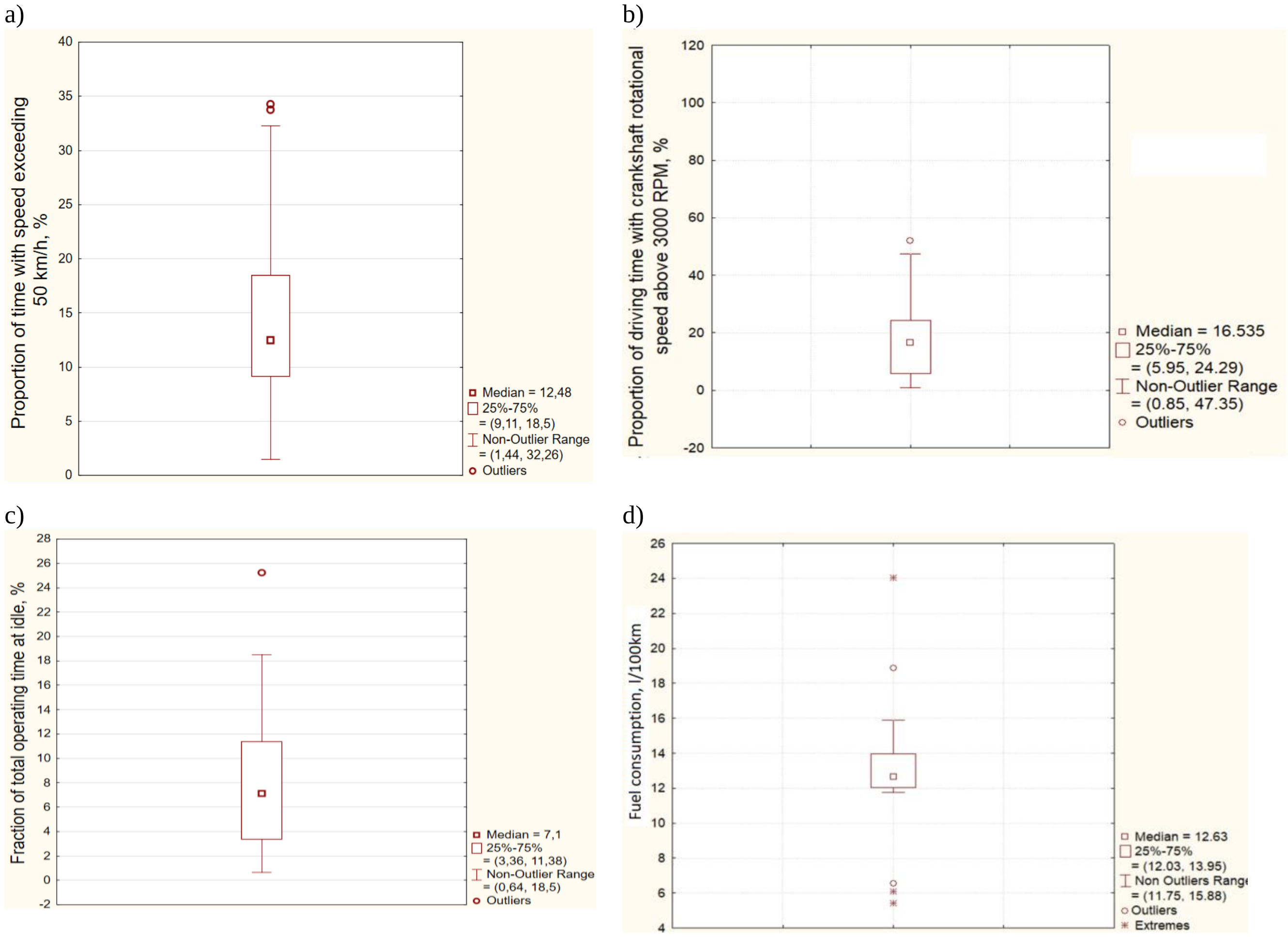

Fig. 7. Indicator values: a) W1 – proportion of time with speed exceeding 50 km/h, b) W2 – proportion of driving time with crankshaft rotational speed above 3000 rpm, %, c) W3 – fraction of total operating time at idle, %, d) W4 – fuel consumption, dm^3/100 km

3.2. Indicator-based assessment of driving style

The presented driver classification model is a proposal and can be modified according to research and practical needs. Four key eco-driving indicators, defined in Chapter 2.3, were analyzed. To construct a synthetic WEco index that takes into account various aspects of driver driving style, each indicator was assigned a weight corresponding to its potential impact on economic and environmental performance. By multiplying the indicator values by the weights, adjusted values were obtained, reflecting the importance of a given parameter in the overall assessment of driving style. The choice of weights presented in this article is a proposal and can be modified depending on the adopted methodology, available data, or the purpose of the analysis. Different scenarios may place greater emphasis on, for example, CO_2 emissions, fuel consumption, or acceleration intensity. The presented classification method is open-ended and can be modified depending on the specifics of the case study, research assumptions, or practical requirements—for example, in the context of specific vehicle fleet types or training systems. The choice of weights was based on the assumption that individual indicators differ in their importance in terms of their impact on economic and environmental performance. A high WEco value, according to the adopted criteria, may indicate a less economical/ecological driving style, while a lower value may indicate a smoother and more economical driving style.

The fuel consumption index (W4) received the highest weight of 0.4 because it was considered the most critical component of the combined score. Fuel consumption is a direct and tangible consequence of inefficient driving, and its impact on the final score was deliberately emphasized [31].

The second most important variable was the percentage of time the engine crankshaft speed exceeded 3000 rpm (W2), which was assigned a weight of 0.3. High engine speeds typically correlate with aggressive acceleration and frequent operation above optimal speeds for a given gear, which negatively impacts fuel economy and exhaust emissions.

The engine idling time index (W3) was assigned a weight of 0.2. This parameter indirectly reflects driving smoothness and the driver's ability to effectively manage idle times – long idling times are associated with lower energy efficiency, especially in urban conditions. This is particularly important for pollutant emissions, and modern vehicles often use start-stop systems to mitigate this issue. The lowest weight, 0.1, was assigned to W1, the percentage of time driving at speeds exceeding 50 km/h. Although this variable relates to road safety and provides information about driver behavior, its direct impact on fuel consumption in an urban environment is relatively limited and more difficult to interpret compared to other indicators.

Based on the calculated WEco values, drivers were divided into three groups. The decision to use a three-level classification was made to ensure transparency and analytical usefulness of the results. This division distinguishes between drivers with low, medium, and high WEco scores, corresponding to three general profiles: eco-driving, average driving, and non-ecological driving. This simplification allows for simple interpretation and facilitates further statistical comparisons between groups.

Classification thresholds were determined based on the empirical distribution of WEco values (i.e. a histogram), taking into account a uniform distribution of participants and the presence of clear natural breakpoints in the data. The aim was to maintain a balanced group size (as far as possible), while reflecting the actual variability in driving behaviour. Interval grouping, based on data-driven cut-off values, is shown in Fig. 8.

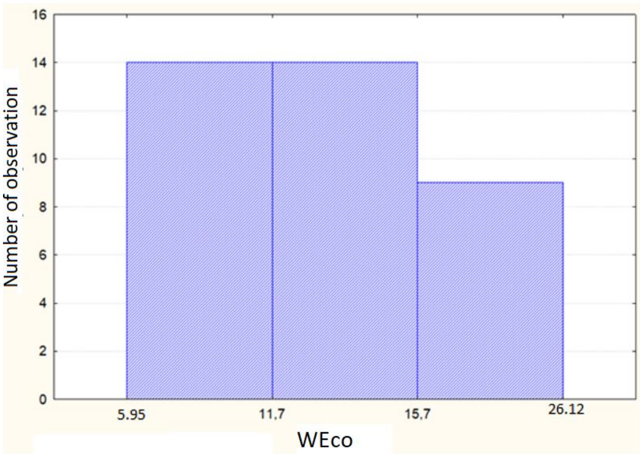

Fig. 8. Histogram of the WEco indicator (sum of operational parameters) divided into 3 classes

Based on the calculated WEco values, drivers were assigned to the appropriate classification group.

Group 1 (n = 14) comprises drivers with the lowest WEco values (≤ 11.7), indicating the relatively most economical and environmentally friendly driving style.

Drivers in this group are characterised by moderate speed, a low proportion of driving at high crankshaft speeds, short idling times, and moderate fuel consumption. Their driving style can be described as smooth, calm and energy-efficient.

Group 2 (n = 14) represents an average level of efficiency, with WEco values ranging from 11.71 to 15.70.

Drivers in this group show an average level of adherence to eco-driving. Their driving behaviour is more variable, which may reflect an inconsistent driving style or a lack of dominance of fuel-saving habits.

Group 3 (n = 9) includes drivers with the highest WEco values (> 15.70), indicating the least economical driving style in the sample. Their driving style was associated with more frequent use of high engine speeds, higher fuel consumption and longer idling periods.

The style of this group can be characterised as more dynamic and potentially less environmentally friendly.

In order to assess the relevance of the classification adopted and the contribution of the individual WEco components, a statistical analysis of the differences between the groups (groups 1–3) was carried out for four sub-indices: W1, W2, W3, and W4.

For this purpose, the non-parametric Kruskal-Wallis test was used.

The analysis confirmed that the WEco indicator was effective in differentiating drivers according to their driving style.

Significant differences, especially at W1 ($H = 13.42$, $p = 0.0012$) and W2 ($H = 28.73$, $p = 0.00000058$), indicate that a more dynamic driving style – characterised by higher speeds and increased engine crankshaft speed – clearly differentiates the classification groups.

The results confirm the usefulness of the WEco index as a tool for assessing driving efficiency and further benchmarking.

4. Discussion

The aim of this study was to develop and evaluate an indicator model for classifying driving styles in urban environments, with particular emphasis on eco-driving principles using a vehicle simulator. The study defined four key indicators, which were assigned arbitrarily determined weights based on their assumed impact on eco-driving and environmental friendliness. These values were used to calculate the WEco index, which provided an overall assessment of driver behavior behind the wheel. The WEco index was then used to classify drivers into three groups representing different levels of driving efficiency and eco-friendliness. The obtained values revealed noticeable variation among participants, enabling the identification of both highly efficient and decidedly unsustainable driving styles. The largest number of drivers was recorded in groups 1 and 2, suggesting that a moderate approach to vehicle operation may be the dominant trend among the drivers studied. Although the proposed model is still in development, it demonstrates potential for practical application – for example, in fleet management systems, driver behavior monitoring applications, eco-driving training programs, and in assessing progress in reducing fuel consumption and exhaust emissions. Based on easily measurable vehicle parameters obtained during actual driving using telematics systems, it is possible to identify drivers who effectively employ eco-driving techniques in practice. It should be emphasized, however, that the presented concept remains open to adaptation – both the indicators themselves and the weights assigned to them can be adapted to specific applications, available datasets, or transport policy goals. Further work in this area is planned. Driver classification based on the WEco indicator is consistent with existing literature on eco-driving and driver behavior analysis. Research indicates that variables such as fuel consumption, engine idling time and high-rpm operation are key to assessing energy efficiency and emissions [3, 31]. The literature also highlights the effectiveness of simple standarised indicators as tools for monitoring driving style, especially in the context of vehicle fleets or driver education programmes [1, 12].

Therefore, the WEco indicator proposed in this study is in line with current knowledge and offers a useful analytical tool for future research and practical applications.

5. Conclusions

In this study, a composite WEco index was developed and initially validated to classify drivers' driving style in terms of compliance with eco-driving principles. Analysis of four component indices (W1–W4) enabled effective differentiation of driver behavior in simulated urban traffic conditions. The results confirm the potential of WEco as a tool for assessing the energy efficiency of driving style, with potential applications in driver training and assistance systems. Despite limitations – such as the short test route – the obtained data were consistent and repeatable. Future plans include expanding the study to include longer and more diverse driving scenarios, which will enable a more comprehensive assessment of the stability and usefulness of the WEco index. As a result of the analyses, the WEco index was developed, enabling not only a qualitative but also a quantitative assessment of driving style in relation to eco-driving principles. Based on this index, participants were assigned to three efficiency classes, including drivers with smooth and energetic driving styles, as well as those with a more dynamic and less economical driving style. The Kruskal-Wallis test results confirmed statistically significant differences between the groups, particularly in terms of engine operation at high speed and fuel consumption, which confirms the validity of the proposed classification approach.

The model presented can be applied both in research and in practice – for example, in driver training programmes or fleet management systems. With climate change on the rise, the concept of eco-driving is gaining importance. Eco-driving is a driving style that not only reduces fuel consumption but also reduces the emission of harmful pollutants into the atmosphere, such as carbon dioxide (CO_2) and nitrogen oxides (NO_x). Environmental responsibility in everyday activities, including vehicle operation, is becoming a key factor in the fight against global warming and air pollution. This highlights the importance of promoting appropriate driving behaviour, starting with driver education.

Driving simulators are an innovative tool that plays a significant role in promoting and teaching eco-driving. These technologies make it possible to assess driver behaviour in terms of eco-driving. Thanks to advanced systems, simulators can accurately reflect road conditions and driving dynamics, enabling a detailed analysis of an individual's driving style. They assess aspects such as driving fluidity, use of gears, braking, and acceleration technique. As a result, simulators can effectively identify areas where drivers can improve their habits to become more environmentally responsible behind the wheel.

For young drivers just starting their driving adventure, simulators provide particularly valuable educational support. In a controlled and safe environment, they can learn the principles of eco-driving from the very beginning. Regular simulator training allows them to acquire and reinforce habits that not only reduce their environmental impact but also improve road safety. Young drivers learn how to avoid sudden acceleration and braking, maintain a constant speed, and optimally use gears to reduce fuel consumption.

Eco-driving brings not only environmental but also economic benefits. Reduced fuel consumption translates into savings, providing additional motivation for drivers to implement eco-driving principles in their daily practice. Furthermore, simulators allow drivers to familiarize themselves with various realistic driving scenarios where eco-driving techniques are particularly beneficial – for example, in urban environments, where frequent stop-and-go driving often leads to increased fuel consumption.

In the face of climate challenges, eco-driving education is becoming an essential part of both new driver training and the ongoing development of experienced drivers. Thanks to their advanced capabilities, simulators offer a unique opportunity for both learning and assessment, making them a very valuable tool in promoting sustainable and responsible driving behaviour.

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