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THE IMPACT OF ACCELERATION STYLE ON VEHICLE EMISSIONS AND PERSPECTIVES FOR IMPROVEMENT THROUGH TRANSPORTATION ENGINEERING SOLUTIONS

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Abstract

Road traffic constitutes a key element of modern life, with many individuals being behind the wheel each day. Their driving style, specifically how they accelerate and brake, can significantly influence the emissions of harmful substances and air quality. Despite the presence of modern cars equipped to reduce exhaust gas components and other emissions, driving style continues to have a substantial impact on air pollution. In the case of aggressive driving, the influence on fuel consumption and emission generation is substantial. Another aspect is the safety of road traffic as it has been proven that aggressive driving reduces safety. This article focuses on the results of our recent research regarding vehicle emissions during acceleration. We found that even though modern cars are increasingly environmentally friendly, aggressive driving with them can quickly change the perspective on this issue. While the acceleration of a single vehicle may seem essentially negligible, it is crucial to realize that, especially in urban environments, the

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number of accelerations of road vehicles as a traffic flow is enormous, particularly during peak traffic hours. Furthermore, there are locations where vehicles must decelerate and accelerate consistently, such as certain types of intersections. The goal of the article is to provide an additional viewpoint on monitoring this trend, this time in combination with the road infrastructure itself, with three examples discussed in the article on how these negative trends can be influenced through modifications to the road infrastructure.

Keywords: emissions; road solutions; fuel consumption; acceleration style

1. Introduction

Fuel consumption and the associated efficiency of road vehicles are at the forefront of interest for many research groups because, according to the universally accepted Law of Conservation of Energy, only a portion of fuel energy transforms into motion – other components include noise, vibrations and so forth, with waste heat being the most voluminous part of energy released into the atmosphere without utility.

Our previous research indicates that ground transportation solutions contribute to the generation of undesirable emissions from road traffic. However, "green" policies in the field of road transport predominantly focus on vehicles and their manufacturers, addressing ground transportation sporadically and, when addressed, often through restrictive measures that sometimes border on restricting basic rights [2, 4, 13]. The presented article combines the issues of ground transportation and aggressive driving styles, which may be caused by, among other factors, driver frustration, particularly due to traffic solutions. Some types of traffic solutions also have a negative effect on the rapid passage of vehicles of the integrated rescue system The issue of measuring fuel consumption under various operational conditions or the influence of driver behaviour and driving style on fuel consumption is a widely studied area. Numerous scholarly articles, outputs and research results have already been published. The aim of this article is to present the results of research within a relatively narrow range of speed variation, specifically between the vehicle's stationary state and a speed of 30 km/h. This research area is not uninteresting, considering the frequency of such accelerations, especially during vehicle movement in urban areas. Analysed publications can be divided into three areas:

- Publications dealing with the measurement of fuel consumption under various operational conditions.
- Publications addressing the impact of driver behaviour and driving style on fuel consumption.
- Publications focusing on the impact of aggressive driver behaviour on traffic flow and the overall efficiency of vehicle operation.

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Noteworthy publications include, for example, Szabo [19]. Szabo and his team studied fuel consumption in various types of vehicles whilst considering the human factor, which has a significant impact on consumption. The authors developed a special measuring device that is universally applicable and connected to the vehicle's tachograph which provides relevant data on the current drive. They also placed a sensor on the brake pedal to monitor the frequency of brake pedal depressions. Based on the results, the deceleration due to braking was calculated, and its impact on overall consumption was analysed. The results were intriguing, indicating that the method of braking the vehicle (brake activation versus engine braking) influences overall fuel consumption by up to 20%.

A similar topic is discussed in the article by Rafael [15]. The authors tested the impact of vehicle acceleration during startup on overall consumption. They defined three types of acceleration – aggressive (using maximum power during acceleration), normal (utilising about 60% of the vehicle's power during acceleration), and technical (using about 30% of the vehicle's power during acceleration). In conclusion, the authors state: "The results are qualitatively expected in terms of the relative magnitudes for the three driving styles. However, they show significant quantitative differences in emissions and fuel consumption among the three driving styles, suggesting the modification of the operator's habits if the 'technical' driving could be part of intelligent transportation systems."

Interesting results are presented in the study by Yang [21], which examines the correlation between driving style, fuel consumption, and overall emissions. The authors conducted extensive research and practical measurements in real traffic conditions. The results are more than intriguing. The driving style itself does not have a significant correlation with CO or HC emissions, but it has a strong correlation with fuel consumption, NO_x and CO_2 emissions. Moreover, the influence of driving style on fuel consumption and NO_x and CO_2 emissions is related to parameters such as total acceleration time, total deceleration time, average acceleration and average deceleration. Aggressive acceleration of the accelerator pedal caused an additional increase in consumption and emissions by 3%.

Authors such as Dia et al. [3] and Zheng [22] discuss aggressive driving styles and their impact on safety, traffic flow and overall fuel consumption in their articles. Dia et al. state in their article: "...it was found that aggressive drivers are thirty-five times more likely to be involved in highway accidents and twice as likely to be involved in accidents in built-up areas (cities, towns, etc.). The results of highway simulations also showed that aggressive drivers achieved only a 3.8% reduction in travel time (62 seconds on a 26-minute journey) at the expense of driving safety (85% more lane changes than in standard driving) and at the expense of consumption. The reduction in travel time in urban conditions was lower, approximately 1.6% (7 seconds on a 434-second journey), at the expense of safety and driving efficiency (300% increase in lane changes and 138% increase in fuel consumption and CO_2 emissions)." The results showed that the negative impacts of aggressive driving behaviour outweigh the benefits which can be achieved by reducing travel time.

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Similar results are reported in the study by Shahariar et al. [17]. The research revealed that driving style strongly influences emissions. With aggressive driving, a slight increase in CO_2 and NO_x emissions (up to 37% and 38%, respectively) and a high increase in CO emissions (up to 88%) were observed. Particulate emissions increased significantly (up to 112% and 538%, respectively).

Further analysis of publications such as Szumska et Jurecki [20] and Hobeika et al. [6], which deal with aggressive driving behaviour, reveals additional interesting findings. Aggressive driving is not only fast driving with frequent lane changes but can also be excessively slow driving by inexperienced drivers. The results suggest that even slow driving can lead to increased emissions and fuel consumption. Additionally, they are a frequent source of congestion and disrupt traffic flow [7, 8, 18]. This behaviour can subsequently increase the aggressiveness of other drivers, leading to further increases in emissions and fuel consumption. Aggressive driving style causes a significant increase in both fuel consumption and pollutant emissions into the air, especially in urban conditions, where aggressive driving leads to higher average fuel consumption and pollutant emissions by 30% to 40% compared to calm driving. However, "slow" drivers create more problems than aggressive drivers [11, 12, 14].

The analysis of published articles demonstrated the comprehensiveness of the examined issues and their ongoing relevance. The presented article, however, is considered interesting and beneficial by the authors. In the context of the obtained data, which confirm the measured data from other publications and research, the article concludes by discussing the relationship with the longitudinal terrain profile of roadways and its impact on the efficiency of vehicle operation.

From the conducted literature review, it is evident that driving style has an impact on the generation of emissions and fuel consumption. The human factor can thus be considered a potential creator of undesirable emissions, classifying it into the category of risk factors such as the technical condition of the vehicle and similar factors. Furthermore, we believe that the frequent need to change driving speeds or come to a complete stop and restart, especially in traffic jams resulting from permanent traffic engineering measures, may contribute to the development of road rage, exacerbating emissions and fuel consumption.

2. Materials and Methods

The aim of this paper is to determine the change in emissions and the associated fuel consumption in the case of smooth and aggressive accelerations. Additionally, it explores possibilities for partially eliminating emissions through traffic solutions. The efficiency of cars during acceleration pertains to how efficiently a vehicle utilizes its energy and engine power during the acceleration process. This efficiency can be important for several reasons:

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- Fuel Consumption: Acceleration efficiency directly influences a vehicle's fuel consumption. Cars that accelerate more efficiently may have lower fuel consumption, which is crucial for economical operation and reducing greenhouse gas emissions.
- Performance: More efficient acceleration can mean better vehicle performance. This is important for safe overtaking, quick responses in emergency situations, and an overall improved driving experience.
- Component Wear: Rapid and inefficient acceleration can increase the wear on various vehicle components, such as brakes, the engine, transmission, etc. Efficient acceleration can reduce the rate of wear and maintenance costs.
- Environment: Reducing the load on the engine and lower fuel consumption can contribute to emission reduction and have a positive impact on the environment.

The theoretical calculation of fuel consumption is based on the energy required for a change in speed, fuel calorific value, and the overall efficiency of the propulsion system, with manufacturers stating the efficiency of typical road vehicles to be at around (30–40)%. We have opted for data collection through field measurements, selecting a Kia Ceed vehicle (shoen on Figure 1, parameters below in Table 1), which we consider representative considering the age of the vehicle fleet in the Czech Republic (16.2 years) [1] and in the Slovak Republic (14.3 years) [2].

Fig. 1. Testing

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Tab. 1. Personal Vehicle Kia Ceed – Technical Data of the Measurement Laboratory Vehicle.

Commercial Name of Vehicle	Kia Ceed	Engine Code	G4FC
Engine displacement	1591 cm^3	Length	4265 mm
Fuel	gasoline	Width	1790 mm
Number of cylinders	4	Height	1480 mm
Max. power	90 k/6200 rpm	Allowed weight	1163 kg
Max. torque	154 Nm/4200 rpm	Total weight	1710 kg
Max. speed	192 km/h	Year of Manufacture	2014

The basic outputs from the measurements for individual elevation profiles of the road are presented in the following section "Results", and the derived outputs are discussed in the "Discussion" section of this article.

Our vehicle underwent a comprehensive comparison of exhaust gas emissions during two different acceleration modes. The first was 'normal acceleration', in which the vehicle was started and accelerated with an emphasis on fuel efficiency and minimal emissions. The second mode was aggressive acceleration, in which the vehicle was accelerated dynamically and intensively, applying the principle of using sufficient power but avoiding wheel spin.

The speed range for measurement was set between (0–30) km/h. While this acceleration speed range can be considered common in traffic flow and sufficient for level intersections in cities, where 30 km/h is a typical passing speed (e.g. in accordance with the recommendations of TP 135 of the Ministry of Transport of the Czech Republic [13], acceleration measurements at different speed ranges (e.g. (30–50) km/h or (50–90) km/h) will be the subject of our further investigation.

During normal acceleration, the behaviour of the exhaust system was monitored and emissions of harmful substances were measured. This mode emphasises optimisation of the combustion process in order to minimise negative impacts on the environment [9, 15, 16].

By contrast, aggressive acceleration was focused on maximising the vehicle's performance and speed. As cited sources indicate, this mode may result in higher emissions, especially if there is imperfect fuel combustion during rapid acceleration.

3. Results

The results of this experiment have provided crucial insights into the impact of driving style on fuel consumption and exhaust gas emissions. A total of thirty accelerations were conducted (twenty smooth and ten aggressive), along with ten emission measurements (five during smooth accelerations and five during aggressive accelerations). Table 2 reveals that

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both fuel consumption and emissions increase during aggressive driving, as logically anticipated. However, individual emission gases do not increase proportionally. In the third part of Table 2, the percentage increase in emissions and fuel consumption during aggressive driving is presented. The fuel consumption, on average, increases by 54.5% during aggressive driving. Interestingly, CO_2 increases by only 34.9%, while other gases experience increases in the order of hundreds of percent. In the case of NO_x, its production increases by 247.3%, and for HC, it is 361.8%. A substantial increase is observed in CO, averaging up to 1034.6%. Figure 2 provides a visual representation of the changes in these values for different acceleration modes.

Table 2. Fuel consumption and emissions

Type of acceleration		Minimum	Maximum	Mean	Std. Error	Std. Deviation	Range
smooth	CO cumulative [g]	0.149	0.287	0.21435	0.013450	0.042534	0.138
	CO_2 cumulative [g]	20.116	25.545	22.63014	0.529642	1.674875	5.429
	HC cumulative [g]	0.001	0.002	0.00102	0.000094	0.000298	0.001
	NO_x [g]	0.017	0.027	0.02197	0.001098	0.003472	0.010
	fuel consumption [ml]	8.19	9.29	8.5460	0.10728	0.33925	1.10
agressive	CO cumulative [g]	1.821	2.947	2.43197	0.195963	0.554268	1.126
	CO_2 cumulative [g]	27.873	34.287	30.52377	0.949711	2.686187	6.414
	HC cumulative [g]	0.003	0.006	0.00471	0.000483	0.001367	0.003
	NO_x [g]	0.059	0.091	0.07629	0.004500	0.012728	0.033
	fuel consumption [ml]	11.89	13.99	13.2038	0.27167	0.76841	2.10
difference of measured values (smooth – aggressive) in %	CO cumulative [g]	1122.15	926.83	1034.58	1356.97	1203.12	715.94
	CO_2 cumulative [g]	38.56	34.22	34.88	79.31	60.38	18.14
	HC cumulative [g]	200,00	200.00	361.76	413.83	358.72	200.00
	NO_x [g]	247.06	237.04	247.25	309.84	266.59	230.00
	fuel consumption [ml]	45.18	50.59	54.50	153.23	126.50	90.91

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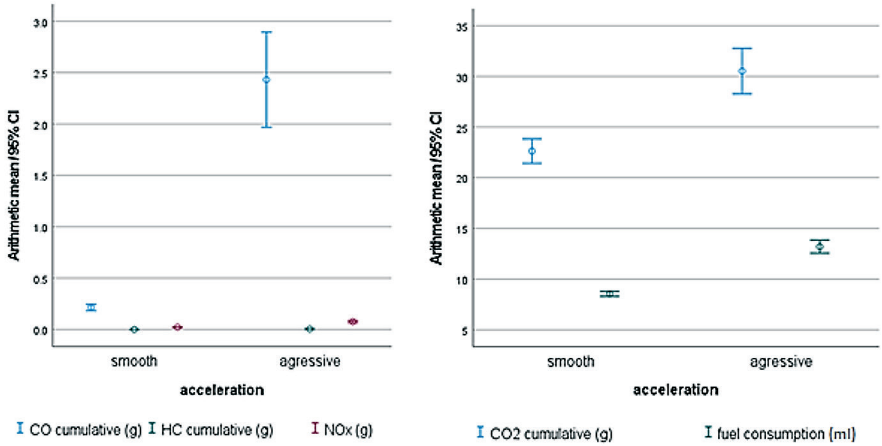

Fig. 2. Visual representation

Table 3 provides information on the results of the Student's t-test, indicating that the values of gas emissions and fuel consumption undergo statistically significant changes at the 1% significance level. It is therefore possible to conclude that the measured values can be generalised within the limits of the research.

Tab. 3 Statistical results

Independent Samples Test							
Variable / Equal variances assumed		Levene's Test		Independent Samples Test			
					Significance	95% Confidence Interval of the Difference	
		F	Sig.	t	Two-Sided p	Lower	Upper
CO cumulative [g]	assumed	388.369	<.001	-12.704	<.001	-2.587666	-1.847577
	not assumed			-11.290	<.001	-2.681213	-1.754030
CO_2 cumulative [g]	assumed	3.541	.078	-7.648	<.001	-10.081679	-5.705587
	not assumed			-7.259	<.001	-10.282081	-5.505185
HC cumulative [g]	assumed	44.969	<.001	-8.339	<.001	-.004622	-.002748
	not assumed			-7.482	<.001	-.004833	-.002537
NO_x [g]	assumed	11.189	.004	-12.995	<.001	-.063182	-.045459
	not assumed			-11.727	<.001	-.065041	-.043599
fuel consumption [ml]	assumed	4.276	.055	-17.276	<.001	-5.22930	-4.08620
	not assumed			-15.946	<.001	-5.31654	-3.99896

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Equally important as the increase in fuel consumption is the rise in greenhouse gas emissions during aggressive acceleration. This phenomenon demonstrates that the choice of driving style has a direct impact on the environmental footprint of the vehicle. It follows from this that optimizing acceleration and managing driving style can be a key factor in reducing greenhouse gas emissions.

4. Discussion

We consider the vehicle with which we conducted the measurements to be representative of an average vehicle in the Czech and Slovak Republics. The presented measured values represent only a part of the obtained data. It can be assumed that even newer vehicles without additional electric propulsion are not significantly better at managing emissions during acceleration. Although it involves a relatively small amount of emissions per vehicle, considering the number of such accelerations, especially in urban environments, we believe it is necessary to explore possibilities for their reduction.

At this point, we will discuss our assumption in connection with traffic engineering solutions of roadways using several examples:

1. Intersection of a local road in České Budějovice and road No. II/156 (Figure 3).

Fig. 3. Traffic solution [10]

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The traffic intensity on road No. II/156 in one direction is approximately 2960 vehicles per day at this location (source: https://scitani.rsd.cz/CSD_2020/pages/map/default.aspx). About 1410 vehicles connect from the local road to road No. II/156 daily, with the traffic connection equipped with a "STOP" sign for safety. Therefore, drivers are obliged to stop their vehicles and then proceed again, which can be considered a model situation for our measurements. It is necessary to emphasise the obligation to stop in front of the "STOP" sign every time. Given the relatively low traffic intensity (traffic survey results indicate that road No. II/156, especially in peak hours, has low traffic intensity), there is an opportunity to explore measures to improve this situation. Our measurement calculation or conducting additional measurements can serve as a basis for motivation in this regard.

In the absence of traffic restrictions, the intersection can be traversed at a speed of 30 km/h. In this case, the "STOP" sign limitation serves as a reference location for our measurements.

In the case of using our results and the observed driver composition ratio of approximately 80% smooth acceleration and 20% aggressive acceleration, using the average of our measured values, the following results for fuel consumption and CO_2 emissions can be obtained for 1000 reference vehicles (i.e. assuming a critical situation with 410 vehicles with completely different parameters):

	1 day	**100 days**
Fuel [l]	9.52	952
CO_2 [kg]	24.5182	2451.820

From the provided values, it follows that the mentioned traffic engineering solution, in the case of the daily passage of 1000 vehicles like our reference, requires 952 litres of fuel and 2.4 tons of CO_2 over 100 days. These simplistically interpreted results can serve as a basis, for example, in decision-making at the municipal policy level or when deciding on the implementation of another traffic engineering measure, such as an intelligent traffic light system. It is evident that a better solution cannot completely eliminate the emission generation but may contribute to its reduction.

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2. Poor Technical Condition of the Road Surface (Figure 4).

Fig. 4. Wrong road condition [10]

The picture is taken from a publicly accessible road with a traffic intensity of approximately 1400 vehicles daily in both directions (determined based on daily observations). Although the issue of poor road surface conditions may seem trivial, it also influences the generation of emissions. Common measures taken by the road administration include speed restrictions (usually 30 km/h) and the "uneven road" sign, which are often installed for years in these locations. Our model data are flexible, and partial speed regimes, such as the calculation for acceleration from 15 km/h to 30 km/h, can be derived from them, as in this case. We explored this through on-site observations and monitoring the speeds of passing vehicles. After overcoming the damaged section of the road, vehicles accelerated to the permitted speed of 30 km/h. Recalculating for 100 days and considering the observed ratio of 50% smooth accelerations and 50% aggressive accelerations (the road is damaged in a section of approximately 180 metres, likely causing drivers to feel the need to accelerate), this results in:

	1 day	100 days
Fuel [l]	6.804	680.4
CO_2 [kg]	16.1816	1618.16

From the above, it can be stated, for example, that due to the neglect of maintenance in this specific section of the road, approximately 1.6 tons of CO_2 are generated unnecessarily every 100 days.

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3. Roundabout and traffic jam in front of it.

It is important to note at the outset that the topic of roundabouts (especially those in rural areas) is interesting in different speed regimes to the one that we are investigating. As an example, we mention a roundabout built on the international road E55 in the years 2017–2019 on the outskirts of Benešov u Prahy (Figure 5).

Fig. 5. Roundabout near the city of Benešov u Prahy [5]

The previous traffic solution, namely a level intersection with priority adjustment markings, was inadequate due to the traffic flow (approximately 25,000 vehicles per day), especially due to the crossing of the E55 road. The implementation of a roundabout was most likely aimed at addressing this issue. The fact that the roundabout is located on a highly congested road, where approximately 25,000 vehicles are forced to decelerate from the allowed 90 km/h to about 30 km/h every day without exception and then accelerate again after passing through the roundabout, is at least concerning in terms of the generation of unwanted emissions. Simultaneously, we believe it may lead to an increased risk of aggressive and, therefore, dangerous driving, which, as stated in the literature review, poses a much greater risk when moving in rural areas (as is the case with the E55 road). However, such traffic situations will be the subject of further investigation in our research. In connection with our current research, we present data on the acceleration of vehicles in the queue before the roundabout. This time, we consider 20,000 vehicle accelerations with characteristics similar to our reference vehicle. We neglect the influence of the longitudinal terrain profile and provide only an indicative overview assuming five accelerations of the vehicle starting from a stationary state at a speed of 10 km/h, considering an 80% smooth acceleration and 20% aggressive acceleration ratio.

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	1 day	100 days
Fuel [l]	56.933	5693.3
CO_2 [kg]	110.6938	11069.380

The provided numbers are not the final quantity that the existence of the roundabout on the E55 road causes; they are merely indicative results illustrating the fuel consumption and emissions during the movement of cars in the queue before this roundabout. An interesting and concerning aspect of the traffic engineering measure in the form of a roundabout is also the passage of vehicles from the Integrated Rescue System, as these vehicles are also forced to significantly change their passage speed.

5. Conclusions

The measured values may not have a significant impact on individuals, but they hold particular importance for the overall context. Understanding that traffic solutions can be a significant contributor to emissions is deemed crucial. Based on our results, we can recommend the implementation of strategies that support more economical and environmentally friendly driving behaviour. These strategies need not necessarily involve technical or technological interventions in vehicle construction but can be explored in other areas, such as the design of road infrastructure and traffic solutions, or through educational campaigns highlighting the benefits of eco-friendly driving for drivers. Our measurements essentially confirmed the research presented in the literature review. The limitations of our measurements lie mainly in their quantity and the inability to conduct a more comprehensive statistical evaluation. However, for orientation in the given issue, we consider them to be sufficient. Additionally, we present our findings regarding the impact of road infrastructure and traffic engineering measures, which we perceive as potential contributors to road transport emissions. We are intensifying our investigation into the extent of the influence of these factors on emissions. It can already be assumed that under certain conditions, road infrastructure and its traffic engineering solutions have a significant impact on the generation of emissions and increased fuel consumption of vehicles. As mentioned earlier, in the subsequent parts of the research, we will focus on further exploration.

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7. Nomenclature

CO carbon monoxide
CO_2 carbon dioxide
NO_x shorthand for nitrogen oxides
HC carbohydrates

8. References

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