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Experimental evaluation of gear-shift and internal-combustion engine variables on fuel consumption, noise and pollutant emissions

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Abstract

Although variability of noise and pollutant emissions are usually associated with vehicular speed and acceleration, driving style, mainly related to gear-shift and internal engine variables such as revolutions per minute (RPM) or engine load (EL), can also play a key role. Moreover, the contribution of each variable for fuel consumption, noise and pollutant emissions can vary for different vehicle-motorization types. However, the effect of such internal variables on noise and pollutant emissions is not fully exploited in the literature. Thus, this work aims to assess the impact of the gear selection, RPM, and EL on fuel consumption, and carbon dioxide (CO_2), nitrogen oxides (NOx), and noise in terms of sound power level (L_W) emissions for a diesel passenger vehicle. This is focused on a speed and gear-based controlled on-road environment. Internal observable (fuel consumption, RPM, and EL) and kinematic (speed and acceleration) variables were recorded on a second-by-second time basis using an On-Board Diagnostic System, and noise data were recorded with a Sound Level Meter. Pollutant emissions were estimated using the Vehicle Specific Power (VSP) methodology with a 1Hz frequency. In this study, Clustering and Disjoint Principal Component Analysis is applied to find patterns hidden in data. An Ordered Logit model to predict the gear based on exploring kinetic and internal engine variables, that are influenced by driver's driving style, is developed. Preliminary results highlight the potential of the developed model and show the potential influence of gear selection for minimizing fuel consumption, noise and pollutant emissions. These findings establish a foundation for developing a sustainability gear-shift indicator not only focused on minimizing fuel consumption, but also noise and pollutant emissions. These are relevant to understand vehicle performance and alleviate the relative impacts of the driving style if integrated into vehicle engine control units.

Keywords: Gear-shift indicator; Internal observable variables; Kinematic variables; Pollutant emissions; Noise

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1. Introduction

Road transport has been responsible for approximately a quarter of total Greenhouse Gas (GHG) emissions in Europe (European Commission, 2020). The sector is a key source of nitrogen oxides (NOx) and noise emissions, affecting the health and well-being of millions of people. Despite the slight relief in 2020 caused by the lockdown measures, road transport contributes to almost 40% of total NOx emissions and the exposure of 113 million people to day-evening-night noise levels (L_{den}) exceeding 55 dBA (EEA, 2020b, 2020a). Human exposure to noise and pollutant emissions derived from road traffic has been correlated to respiratory, cardiovascular disease, annoyance and sleep disorders, and premature mortality (EEA, 2020b; Lelieveld et al., 2015; Pitchika et al., 2017). Moreover, in Europe, fuel consumption (petrol and diesel) in the transport sector worsened in the last few years, surpassing 280000 ktoe in 2018 (European Commission, 2020).

Improving fuel consumption and decreasing carbon dioxide (CO_2), local pollutants (NOx), and traffic noise, which have far-ranging environmental and health effects, should be jointly considered as part of a strategy for a more environmentally friendly transport system (Lozzi et al., 2020). However, such type of integrated green-driving approach can entail trade-offs, and a compromise should be made in some cases (Gao et al., 2019). Despite many improvements in technology, for decades to come, road transport will rely on vehicles with internal combustion engines that use petroleum-based fuels (Leach et al., 2020). This means traffic-related impacts in terms of noise and pollutant emissions will still be a major concern, in which driving behaviour, especially regarding gear shifting style, can play a key role (Beckx et al., 2007; Blagojević, Stamenković, et al., 2017; Blagojević, Vorotović, et al., 2017; Gao et al., 2019; Oglieve et al., 2017).

Currently, vehicles are equipped with a fuel consumption meter (FCM) and onboard gear-shift indicators (GSI). It was shown that combining a GSI and an FCM may lead to larger positive effects in terms of fuel consumption, but their impact on pollutant emissions is not completely clear, since a GSI can increase NOx and an FCM can reduce it (De Goede et al., 2010), and obviously, it depends on the driver decision to behave rationally. Gear-shifting assistance systems can be valuable tools, but a wrong or non-optimized gear-shift strategy (e.g., not optimal speed set-point and gear shifting) can lead to disastrous fuel consumption and performance, resulting in a waste of energy and increased tailpipe emissions (D'Amato et al., 2017). The GSI are conceived based on the lowest attainable fuel consumption, which related improvements depend on the vehicle motorization, driver behaviour, and traffic conditions (D'Amato et al., 2017; Oglieve et al., 2017; Saboohi and Farzaneh, 2009; Vagg et al., 2012). However, in practice, under different driving style conditions, the indicated gear seems to be focused on the best performance for a particular driving style: in smooth driving, gear indication allows to save fuel by suggesting gear-shift at medium revolutions per minute (RPM), while for heavy driving conditions, the indicator allows to attain high RPM. In this latter case, fuel consumption is shown to be very high, with a consequent impact on pollutant emissions. The majority of literature on GSI strategies is based on controllers (models or algorithms) for estimating the optimal speed set-point to indicate the correct gear based on minimizing fuel consumption. It was shown that an optimal driving strategy based on a combination of RPM and gear ratio through engine load (EL) can lead to a minimization of fuel consumption (Saboohi and Farzaneh, 2009). In (Orfila et al., 2012), a model to describe the gear-shift behaviour was proposed to better understand eco-driving through experimental data based on the maximum engine speed between the second and third gear, and the slope representing the variation of engine speed according to the engaged gear. A fuel-optimal gear shift algorithm based on dynamic programming was suggested in (Ngo et al., 2013) and it reveals significant savings in fuel consumption. More recently, a smart shifting strategy designed for minimizing fuel consumption was developed by considering the road load and the engine speed in its maximum efficiency (D'Amato et al., 2017). Results focus on heavy-duty trucks and were evaluated in terms of both fuel consumption and travel time, yielding savings around 3 and 1.5%, respectively. Studies have been mainly focused on either exploring improvements in fuel consumption or pollutant emissions, but balances between both are scarce (Gao et al., 2019). However, no research seems to address noise, which is known to have significant impacts on human health (Héroux et al., 2018).

The main goal of this paper is to present a gear-shift model for a diesel vehicle based not on an explicit speed factor, but on VSP, RPM, and EL. The purpose of this research is threefold: i) to explore the relative contribution of different variables for a diesel vehicle; ii) to assess the influence of gear choice and internal engine variables on fuel consumption, pollutant, and noise emissions; and iii) to develop a model to predict gear selection based on internal variables.

2. Methodology

Figure 1 illustrates the steps followed in the methodological approach of this study.

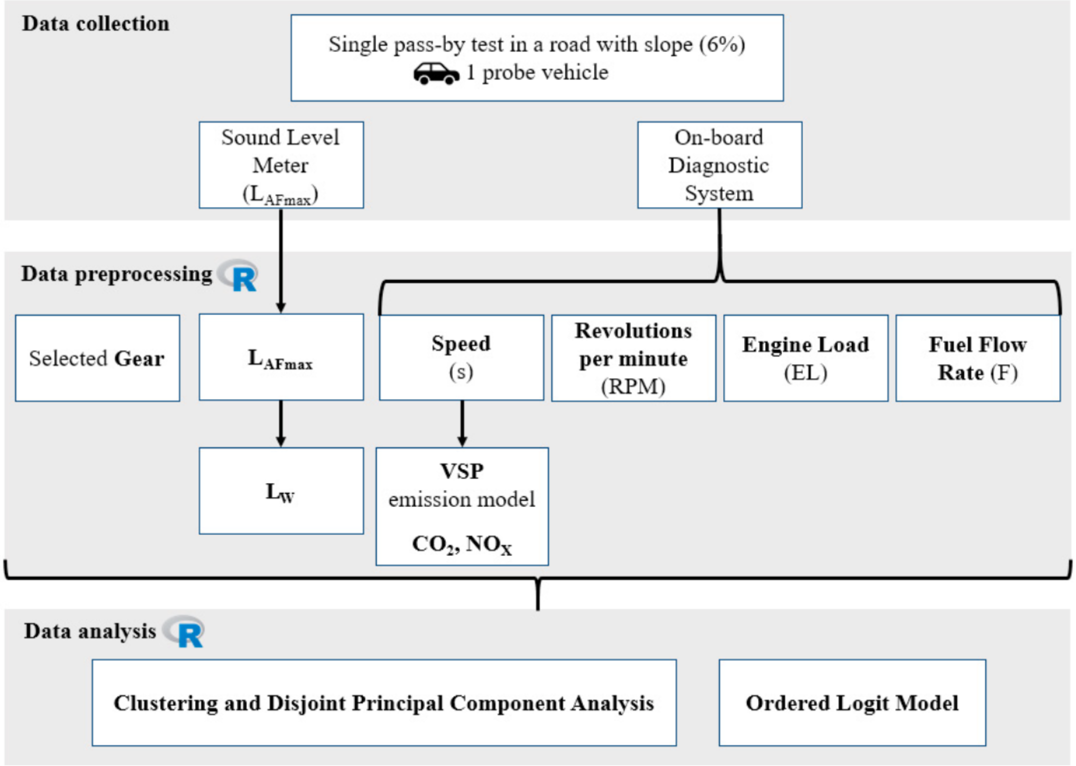

Fig. 1. Methodology overview.

Following the work of Pascale et al. (2020), where the influence of gear choice at a certain speed on the noise was evaluated, empirical data from a diesel-powertrain vehicle were collected on a gear and speed-based controlled on-road environment experiment. The probe vehicle was equipped with an OBD-II ELM 327 and GPS, allowing it to acquire accurate engine activity information regarding speed, RPM, EL, and Fuel Flow Rate. Table 1 presents the test vehicle and engine characteristics (five-speed manual transmission).

Table 1. Vehicle and engine specifications considered for this study.

Parameter		Value
Vehicle	Mass/Fuel type	1200 kg / Diesel
	Radius of the tires	0.381 m
	Aerodynamic frontal Area	~2.1 m^2
	Category/Emission standard/Model year	B / Euro 6b / 2017
Engine	Cylinders/Volume	4 / 1.3 l
	Maximum/Idle engine speed	4600 RPM / 800 RPM
	Maximum Torque	190 Nm at 1750 RPM

All instruments were properly calibrated and synchronized before the data collection (Pascale et al., 2020). The experimental setup occurred in the outskirts of the city of Aveiro (Portugal). It consisted of pass-by tests performed by the probe vehicle running at a constant speed and without changing the gear, in a road of approximately 0.5 km, without any traffic or buildings nearby, under good meteorological conditions. Since the road slope can strongly affect the motive energy, the selected case study consists of a road at a 6% ruling grade. The maximum A-weighted sound pressure levels (L_{AFmax}), recorded with a Sound Level Meter (RION-NL-52), were used to estimate the sound power level (L_w) values through the sound propagation formula (Pascale et al., 2020). It should be mentioned that the vehicle was considered as a point-like source and the road surface completely absorbent.

2.1. Noise Estimation

In (Pascale et al., 2020), a nonlinear regression was suggested to obtain L_w by considering the vehicle speed as input, inspired by the CNOSSOS model (Kephalopoulos et al., 2012), which can be given by the following formula:

$$L_w = 10 \log\left[10^{0.1\left(A+B\frac{s-s_{ref}}{s_{ref}}\right)} + 10^{0.1\left[C+D\,Log\left(\frac{s}{s_{ref}}\right)\right]}\right],$$

where s is the vehicle speed (km/h); s_{ref} is the reference speed (70 km/h); A, B, C, and D are estimated parameters.

It was shown through the ANOVA test that noise is in general, not affected by gear selection for speeds higher than 30 km/h (Pascale et al., 2020). Thus, the methodology for estimating L_w was updated to better reflect the gear choice at lower speeds, and the data for different gears were fitted through nonlinear least-squares regression ending up with the following function of vehicle operating speed and gear split into three branches as reported in Table 2.

Table 2. Nonlinear regression results.

Speed range (km/h)	Gear	A	B	C	D	R^2 (%)
10-20	1	125.9	47.1	-6325.8	7924.2	91
15-30	2	115.7	40.1	54.6	215.6	84
>30	-	93.7	17.1	103.8	33.3	98

2.2. Emission Estimation

The microscopic Vehicle Specific Power (VSP) methodology (US EPA., 2002) was applied to estimate pollutant emissions in terms of CO_2 and NOx. The VSP is a representative variable of the traction power and it is a function of the vehicle instantaneous speed, acceleration, and road grade. The second-by-second VSP can be calculated by:

$$VSP = s[1.1a + 9.81\sin(\arctan(grade)) + 0.132] + 0.000302s^3,$$

where VSP is the vehicle specific power (kW/ton), s and a represent the instantaneous speed (m/s) and acceleration (m/s^2), respectively, and $grade$ is the terrain gradient (decimal fraction). For a diesel passenger vehicle, the VSP values are grouped into 14 VSP-based operating mode bins, that in turn correspond to specific emission rates (Coelho et al., 2009). In fact, real-world emissions data (obtained using Portable Emissions Measurement Systems) were combined with the VSP methodology and specific emission factors for the probe vehicle were used (Fernandes et al., 2019).

2.3. Data Analysis Methods

After proper data cleansing and integration, data were aggregated into a single database. Exploratory analysis was performed and then, the CDPCA-Clustering and Disjoint Principal Component Analysis (Macedo and Freitas, 2015) visualization technique was employed to analyse patterns hidden on data. This technique allows clustering and dimensionality reduction of data with nonoverlapping homogeneous clusters and, simultaneously, disjoint components with maximum variance, such that the between cluster deviance is maximized. The Two-Step-SDP version of CDPCA suggested in (Macedo, 2015) was applied, since it reveals better true clustering recovering property (Freitas et al., 2020). The algorithm is based on Semidefinite Programming (SDP) models for clustering both objects and variables and approximation algorithms that use Singular Value Decomposition and K-means procedure on the reduced space of the components. The advantage of the Two-Step-SDP over PCA or Sparse PCA is to provide disjoint components with nonnegative loadings and simultaneously, clustering of the object space, which ease data interpretation. Considering the objective of this study and harnessing the information obtained by the CDPCA, an Ordered Logit

(OL) model was developed based on internal variables influence on the gear, which represents the response variable, while VSP, engine RPM, and EL are the independent variables. The OL is a regression model for an ordinal response variable (selected gear obeys a natural order) and the cumulative probabilities are related to a linear predictor through the logit function. Computations are made using the open-source software R.

3. Results and Discussion

Considering the case study conditions, it was not reasonable to use the 5th gear in an urban environment. Figure 2 presents the class-specific boxplots for all variables for the different selected gear, providing graphical information on the location, the dispersion, and the skewness of the dataset.

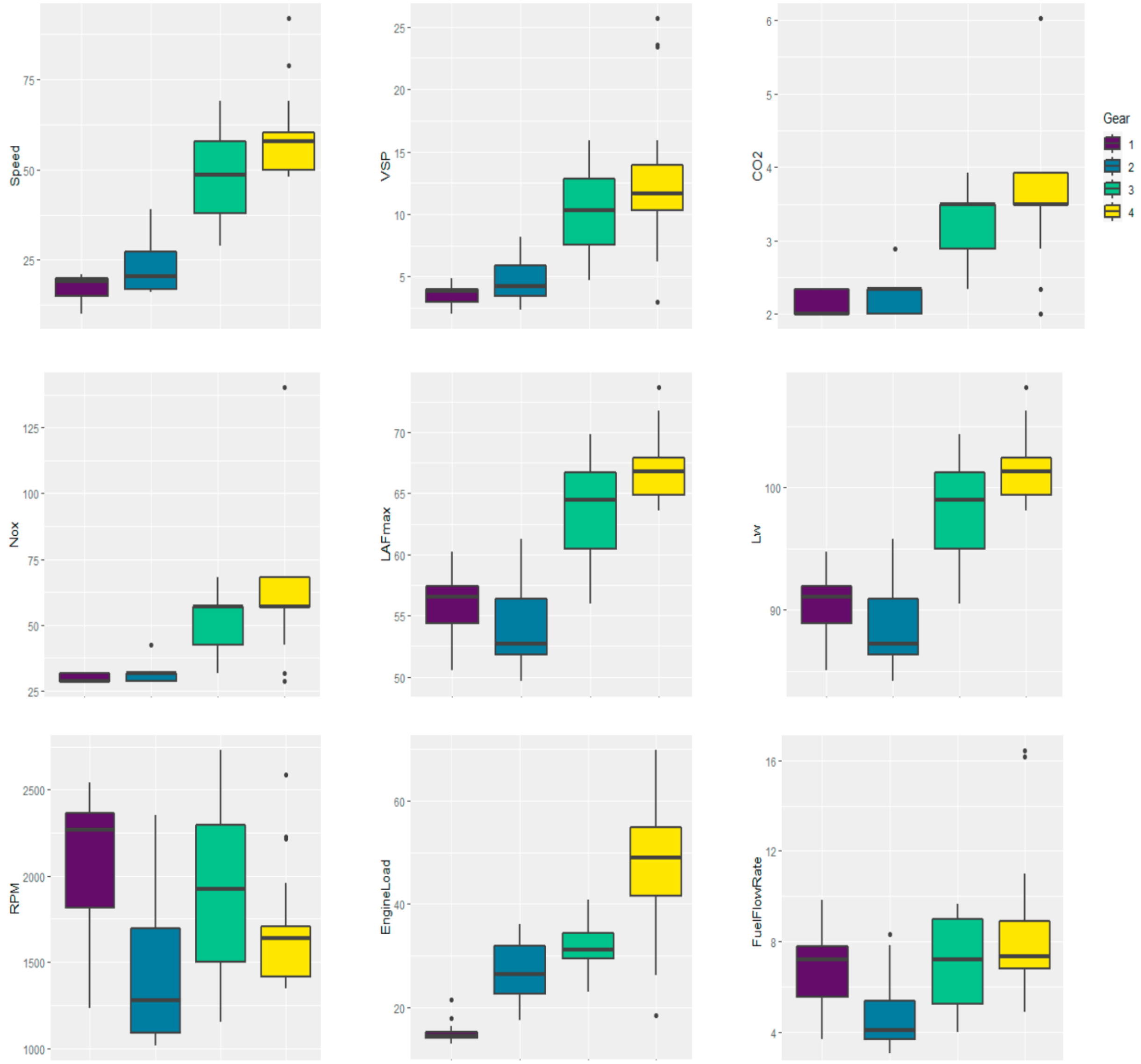

Fig. 2. Exploratory analysis results - boxplot.

Results highlight different levels of noise and pollutant emissions and fuel consumption for different combinations of gear selection. In general, for a particular gear, speed and VSP trends are similar. The same happens for the pollutant emissions, although the skewness at the 4th gear is the opposite. More variability is found to be associated with RPM, independently of the gear, and with EL, for the highest gear. Fuel Flow Rate variability taking into account the engaged gear shows similar skewness trends to RPM, except for the 4th gear. In general, significant differences are observed comparing a smooth (low gear, RPM, and EL) and heavy (high RPM and EL) driving style.

Examining the strength of association between the variables considered in this study, a Pearson's correlation analysis was performed. Figure 3 shows noise variables seem to be highly correlated with speed and VSP; pollutant emissions are strongly related to VSP; and engaged gear seems to be highly correlated with speed and EL. Fuel Flow Rate presents a relatively strong association with RPM, VSP, and noise and pollutant emissions. As expected, speed and VSP are correlated. Results also show significant linear relationships between all pairs of variables, except for the RPM – Gear pair, at a 95% confidence level.

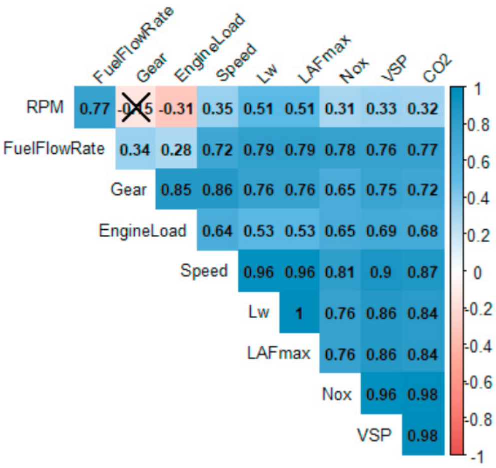

Fig. 3. Correlation results.

The CDPCA was applied to the dataset that comprises 109 observations, by choosing four clusters of objects (four levels for the gear) and three subsets of variables (expected to be related to noise, pollutant emissions, and fuel consumption). Table 3 reports the component loadings obtained with the CDPCA.

Table 3. Component loadings for CDPCA.

	Speed	VSP	CO2	NOx	L_w	L_{AFmax}	RPM	EL	Fuel Flow Rate
PC1	0.0000	0.5251	0.5348	0.5391	0.0000	0.0000	0.0000	0.3842	0.0000
PC2	0.5644	0.0000	0.0000	0.0000	0.5837	0.5837	0.0000	0.0000	0.0000
PC3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6277	0.0000	0.7784

Results show a clear partition of the original variables into meaningful subsets. The first CDPCA component explains 39.09% of the total variance and is mainly characterized by the VSP, CO_2, NOx, and EL, which means these can be grouped in the same partition and related to a pollutant emission component. The second CDPCA component explains 33.01% of the total variance and is characterized by the speed, and noise-based variables, L_{AFmax} and L_{W}., which can form a partition associated with a noise component. The third CDPCA component explains 20% of the total variance and is characterized by RPM and Fuel Flow Rate, which can be associated with a component related to fuel consumption. Since there can be variables with significant weight contributing to more than one principal component, to ease data interpretation, the CDPCA algorithm tries to reveal the partitions of variables so that one variable contributes to a single principal component. The obtained CDPCA between cluster deviance is 82% of the total deviance and the model error is approximately 14%. A representation of the data into the 2-dimensional reduced space of the first two CDPCA components reveals that the positive value for the first CDPCA component tends to be attributed to objects on higher gears (3rd and 4th).

Focusing on variables that are related to the vehicle engine performance, an Ordered Logit model with VSP, RPM, and EL (engine-directed variables at a given time) as explanatory variables was developed to predict the selected gear. Such variables were chosen considering the relationships obtained through the correlation analysis (speed has shown to be highly correlated with VSP) and the results obtained with the CDPCA model, which showed that noise and pollutant emissions, as well as fuel consumption, can be described by one of such variables. Data were split into a training (70%) and a test set (30%). Table 4 reports the results obtained for the Ordered Logit model. For the tested vehicle, in terms of goodness-of-fit, results show the model is adequate, the observed data are consistent with the fitted model at a 95% confidence level. Although RPM showed to be not statistically significant (p-value > 0.05), its incorporation in the model showed to slightly increase the accuracy (85% to 88%) and provide information in the model. The linear predictor has a specific cut-point (intercept), which represents the different thresholds of the gear going from one class to the next, and the model allows to estimate of probabilities for a particular profile.

Table 4. Ordered Logit model coefficients and intercepts, and odds ratio.

coefficients						
Variable	Value	Std. Error	t-value	p-value	confidence interval	
					2.5 %	97.5 %
VSP	0.5696034	0.1766296	3.225	0.00126	0.223415798	0.9157909356
RPM	-0.0007754	0.0006983	-1.110	0.26680	-0.002143938	0.0005931695
EL	0.4193695	0.0464980	9.019	0.00000	0.328235137	0.5105038799
intercepts					odds ratio	
ordered levels	Value	Std. Error	t-value	p-value	Variable	Value
1|2	9.2534	0.0053	1733.8345	0.00000	VSP	1.7675658
2|3	15.2294	1.2921	11.7861	0.00000	RPM	0.9992249
3|4	20.1905	1.7721	11.3936	0.00000	EL	1.5210023

The obtained gear prediction model coupled with the VSP function and the recently proposed VNSP (Pascale et al., 2020) (which allows estimating noise emissions in terms of the L_W for different vehicle motorization), can be considered fundamental for an integrated assessment tool capable of estimating the adequate gear under specific conditions and considering other types of vehicle motorization, i.e., a sustainability gear-shift indicator. With successful validation of the designed assessment framework, this can be replicated for each particular vehicle by car manufacturers to better estimate the related impacts in terms of noise and pollutant emissions, and fuel consumption through incorporation into an onboard GSI, which might likely be conceived in such a way that current in-vehicle electronic control units could be easily updated with the developed functions.

4. Conclusion and Future Research

This study seems to be the first that jointly explores the influence of gear choice and internal engine variables on various components, namely, fuel consumption, and noise and pollutant emissions. Correlation and CDPCA allowed to find that VSP, RPM, and EL can be relevant factors for estimating the gear class, thus, an OL model was developed for predicting the gear based on such variables. Results are promising and provide insights for research improvement. The authors are aware that the obtained results are preliminary, and more experiments should be conducted. Therefore, future work will focus on: i) conducting the same study on a flat road segment; ii) collecting data for various drivers to account for driving variability; iii) exploring the influence of different vehicle motorizations; and iv) developing a sustainability gear-shift indicator that warns the driver about adequate gear selection such that not only fuel consumption is minimized, but also pollutant and noise emissions. Future research is envisaged to develop for diesel, gasoline, and hybrid engines and different gearbox configurations (manual or automatic), for which new gear-shifting strategies can be devised. Going forward, it will be important to have a more holistic view of the driving style, and the proposed future topics can be complemented by including a specific component related to driving comfort.

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