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METHODOLOGY FOR SUBJECTIVE DRIVEABILITY CALIBRATION OF A PASSENGER VEHICLE USING A DRIVE-IN-MOTION (DIM) SIMULATOR

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Abstract.
Engine design and calibration phases are challenging tasks that involve the development of engines, considering the significant time and investment required by the manufacturer companies. Drive-in-motion (DiM) simulators aim to replicate the most reliable driver experience, meeting the demanded accuracy level for predicting vehicle response to dynamics and driving sensations. This work proposes a methodology to evaluate vehicle driveability through subjective analysis, utilizing a Drive-in-motion simulator and a previously developed engine model in AVL Boost. Initially, a 0D/1D (zero-dimensional/ unidimensional) engine model was created to predict the response of a 1.6-liter engine. In the DiM simulator model, the original pedal slope was replaced with different accelerator pedal maps. Also, engine maps were developed using AVL Boost and recalibrated on-board. Several drivers participated in blind tests, evaluating the three proposed models based on aspects of fun-to-drive and comfort. The results showed a high level of agreement among the drivers, indicating that it is possible to pre-develop vehicle driveability calibration using a Drive-in-motion simulator, thereby reducing the time and costs associated with vehicle development for manufacturers.
Keywords: *Drive-in-motion, Driveability, Vehicle calibration, Internal Combustion Engine simulation, vehicle simulation*

1. INTRODUCTION

Although sales of hybrid and electric vehicles in Brazil are in constant growth, for the next decade, internal combustion engines continue with high demand and will be the main powertrain for at least another decade. (ANFAVEA 2022; ABVE 2020; Mito et al. 2012).

Engine calibration for driveability and comfort is carried out in the last phase of vehicle development. In some cases, the actual behavior of the coupling among engine, powertrain, and vehicle is only known once the engine is installed in the vehicle and tested on the road. Some simulation software tries to predict performance responses, but it is impossible to predict the driver’s feelings about the vehicle. (Wurzenberger et al. 2013)

Vehicle driveability can be defined as the driver's subjective perception of its dynamic response and comfort. A high level of driveability leads the driver to a fun-to-drive experience and increases satisfaction as a customer. It is a relationship among various parameters such as torque, engine speed, throttling, AF ratio (Air-fuel ratio), transient behavior, gear change, acceleration, etc. There are two ways of driveability evaluation: subjective and objective. During vehicle development, the subjective perspective depends on the professional test driver tests, which are expensive and time-consuming. It increased interest in objective evaluation methodology. It generally seeks consistent ratings with no influence of driver feeling, generalization (standardization), benchmarking, and short development time. However, objective evaluation brings performance figures that do not translate entirely drivers' feelings towards their real perception. Therefore, simulation tools that help to predict vehicle handling such as AVLDRIVE™ are developed for the automotive market to indicate the driver's perspective but only with objective figures (Shin et al. 2014; List and Schoeggl 1998). A vehicle development stage when driveability is evaluated occurs late in the development schedule and needs a high number of prototypes, expert human resources, time, and specific test facilities or tracks. To avoid excessive costs, OEMs (Original Equipment Manufacturer) are investing in CAE (Computer Aided Engineering) Simulation tools applied to the vehicle, called HIL (Hardware-in-the-Loop) technique, allowing an early evaluation of driving experience (Liu, Hong, and Ge 2017). Dynamic driving simulators have been used for subjective evaluation of the vehicle in the early stages of the development, simulating various road conditions and traffic, as if the driver were in a real test drive. Vehicle dynamics such as stability, suspension set-up, and steering behavior, engine response, vehicle driveability can be easily felt and evaluated previously. There is an increasing interest by OEMs in simulation technologies that might instantaneously identify and present driver reactions towards vehicle dynamic behavior such as a DiM (Drive-in-Motion) simulator (Baumgartner et al. 2019; Affani et al. 2020).

This study proposes an approach to a new methodology for a subjective evaluation of vehicle driveability and driving comfort in terms of onboard engine calibration using a DiM simulator. As a default setup, the DiM simulator is configured with a standard torque curve and a simple acc pedal similar to a ramp function independent of engine load and speed. A 0D/1D (zero-dimensional/ unidimensional) engine model is developed based on real engine data to reconfigure the DiM Simulator. Also, a realistic pedal set-up based on an actual vehicle model was used and their behavior was observed.

This work is relevant to the automotive industry once on-board engine calibration is very expensive and time-consuming. In this way, from the new methodology herein proposed, it will be possible to reduce engineering costs and reduce vehicle development schedule time if a DiM simulator could be used to obtain a driver's impression of the vehicle/engine coupling. Also, pre-calibrations could be evaluated subjectively with no need for a vehicle prototype in such a previous development stage, only using a DiM simulator to test a diverse range of proposed vehicle behaviors towards performance, drivability, and driving comfort, reducing considerably the alternatives that would be tested further in a real prototype.

In section 2, called Development, the proposed methodology is presented including the equipment used in this work. Firstly, it is explained how subject driveability evaluation is carried out. Then, the engine model simulation development is described. DiM simulator engine set-ups were explained for the 3 stages of the work. Finally, the method for the subject evaluation using the DiM simulator was presented. In section 3, it is possible to find the study results and result analysis. Section 4 presents the work Conclusion and Section 5 suggests Future Works.

2. DEVELOPMENT

2.1 Driveability

The driveability of a vehicle is a subjective and complex perception of its performance, either dynamic or comfort, according to the driver's reaction. It became a relevant factor for the customer's final decision to buy a car in a market that increases its competitiveness year by year. For its availability, during a test drive, some criteria such as torque, acceleration, pedal response, continuity of engine speed increase, and gear shift, among others, are well observed. Some objective criteria can be measured directly, such as acceleration time from 0 to 100 km/h or reacceleration time from 60 to 100 km/h. Other are estimated through on-board measurement and further statistical evaluation such as noise, vibration, surge, and acceleration instability. (Shin et al. 2014; List and Schoeggl 1998; Wei and Rizzoni 2004).

However, driveability is hard to evaluate in an objective evaluation only, since subjective aspects of driveability are connected to drivers' sensations, comfort, and experiences. For example, it is not possible to say if vehicle acceleration is exactly what a driver senses and if other drivers have the same feeling. In this case, a subjective analysis of its driveability would indicate a more expressive response. (Wi, Park, and Lee 2018). For the analysis, it is proposed to collect driver opinions and evaluate them with simple statistical concepts such as average and standard deviation.

In this work, driveability was evaluated through a subjective perspective by comparing drivers' answers to predefined criteria. The proposed criteria were as follows:

Acceleration: Feeling of acceleration during partial load:

Progressivity: The sensation of engine torque progressivity.

Aggressivity: Felling of torque variability when acceleration is changed.

Gear Shift: If the gear change is smooth or abrupt.

Speed sensation: Perception of speed while driving.

The arithmetic average provides a representative value for the data obtained from the work, and it can be calculated by:

$$\bar{x} = 1/n \sum_{i=1}^{n} x_i \quad (1)$$

Where $\bar{x}$ is the average, n is number of samples and x_i one sample value.

Standard deviation (s) accounts for the variability of the figures around the arithmetic average, and it is calculated by:

$$s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / n} \quad (2)$$

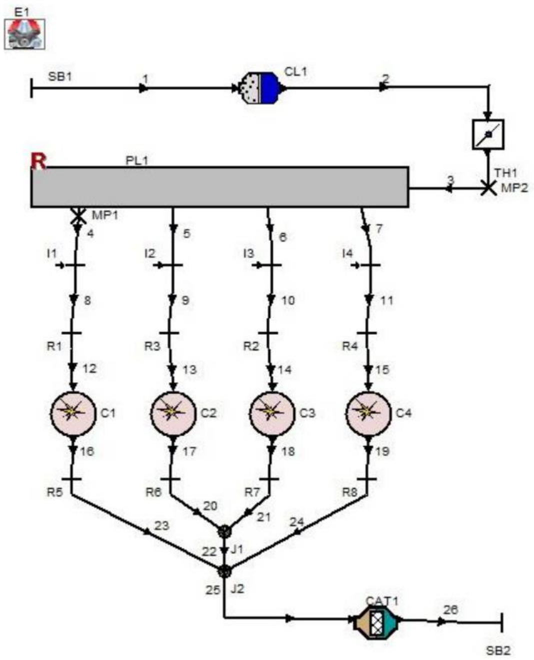
Where $\bar{x}$ is the average, n is number of samples and x_i one sample value.

2.2 Engine Simulation

AVL Boost was used to develop a 0D/1D engine model based on an aspirated, 1.6 liter, 16 valve, 4-cylinder engine. The simulation was an adapted version of the engine model developed by Felisberto (2019), and base engine data was extracted from it.

Figure 1 presents the AVL Boost engine model. In the software, the engine system is modeled as a block diagram in which each block represents one subsystem, and the connectors represent the air ducts. Each subsystem is configured separately, allowing choosing of various models for physical mechanisms such as pressure loss, heat transfer, combustion process, etc. Their theory is described in detail in AVL GMbh (2019a, 2019b). In

Figure 1, the legend shows the meaning of each acronym used in the model.



a) *Engine* – E
b) *System Boundary* – SB
c) *Air Cleaner* – CL
d) *Throttle* – TH
e) *Measure Point* – MP
f) *Plenum* – PL
g) *Fuel injector* – I
h) *Restriction* – R
i) *Engine cylinders* – C
j) *Junction* – J
k) *Catalyst* – CAT
l) *Pipes* – Numbers 1 to 26

Figure 1. AVL Boost Engine Model

For the engine simulation, the chosen physical models that were used in this work are shown in Table 1.

Object	**Process**	**Model**
Pipes	Pressure loss	Darcy-Weissbach / Colebrook
	Heat Transfer	Reynolds Analogy
Cylinder	Heat Transfer	AVL 2000
	Combustion	Wiebe 2 zone
	Knocking	Knock model
Engine	Friction	Experimental table values

Table 1. AVL Boost Models used in engine simulation.

The engine map is determined for a range of engine speed and load. In this work, engine operation speed was set as the chosen maximum speed, at which the ECU (Engine Central Unit) cuts injection. Additionally, the engine load was determined by torque and power demand, controlled by throttle position, ranging from 0% to 100%.

For each operating point, the combustion model must be configured. Wiebe 2-zone requires mainly SoC (Start of Combustion), and CD (Combustion Duration). Those values for WOT (Wide Open Throttle) were initially extracted from Felisberto (2019) and later adapted to partial load. Since the engine map was simulated for the highest torque, the AVL Boost Knock model indicated the possible knock occurrence. In case of knock, SoC was delayed until the model did not indicate any knocking.

2.3 Drive-in-motion simulator

A Drive-in-Motion (DiM) simulator consists of a robot installed on a base plate supported by airpads. The robot is a set of 3 actuators (tripod) connected to a frame where a mechanism with a set of other 6 actuators (hexapod) support a vehicle cabin, resulting in a simulation system with 9 degrees of freedom. The 3 actuators control longitudinal, lateral, and yaw rotational movements. The set of 6 actuators is responsible for pitch rotation, roll, vertical, and smaller movements of the cabins. This work was carried out at SIMCenter, a Simulation Research Center that is a partnership between PUC Minas and Stellantis. It used a DiM®150 developed by VI-Grade.

Figure 2. SIMCENTER DiM®150 Simulator at PUC-Minas

DiM®150 simulator works together with VI-CarRealTime® and VI-MotionCueing® softwares. VI-CarRealTime® is a virtual environment that allows modeling and simulating a vehicle model. It is possible to model various vehicle subsystems in detail such as front and rear suspension, steering, vehicle body, tires, brakes, gearbox, and IC and electrical powertrains. On the other hand, VI-MotionCueing® translates subsystem data into movement, making it possible for the driver to feel as if he/she were in a real vehicle, with a very realistic dynamic response.

The vehicle set-up that is configured on the VI-CarRealTime® is completely independent of the cabin installed on the DiM. This work was developed based on a small SUV (Sport Utility Vehicle) type of vehicle currently in production for the Brazilian market powered by an IC (Internal Combustion) engine. The only subsystem used was the subsystem Powertrain, which includes the accelerator pedal (Acc pedal). There are 3 different possible setups for the powertrain: Simple pre-define max torque curve; Max Torque curve and Engine Map (Throttle x Engine Speed x Torque). Also, the Acc pedal can be set in 3 different set-ups: a ramp curve, Torque x Acc pedal curve, Acc pedal map (Torque x Acc pedal x engine speed). Generally, when the objective is evaluating vehicle dynamics and handling, (e.g.: front and rear suspension configuration) a simplified powertrain subsystem is set. There would be no need for a very complex powertrain subsystem configuration but, in this case, driveability and driving comfort in terms of engine response would be neglected.

Since the objective of this work goes towards driveability, it was chosen to work with Engine Map and Acc Pedal Map. It allows the simulation to cross both map data to give a powertrain response more realistic in terms of Torque demand and engine transient behavior.

This work aims to subjectively compare firstly the default simulator engine set-up (Simple pre-define max torque and Acc ramp curve) with a complex powertrain subsystem configuration (Engine map and Acc pedal map). Figure 3 presents a flowchart of the approach for the methodology proposed in this work for complete driveability with no need for a physical prototype.

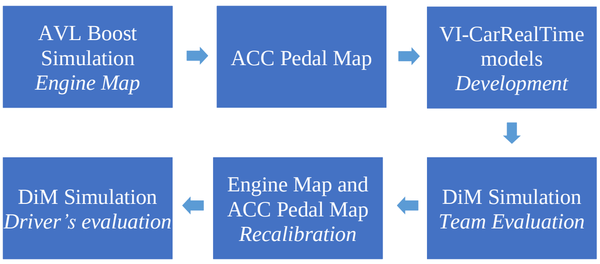


Figure 3. Methodology flowchart

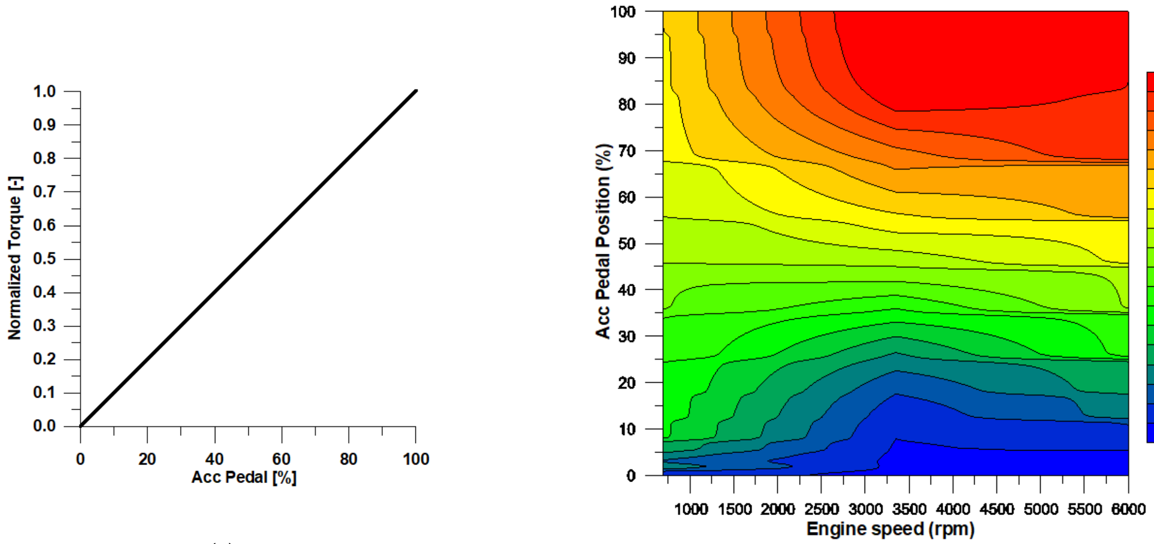
Based on the base engine, an AVL Boost simulation was conducted to obtain the engine map. The 0D/1D model intends to work as a base engine calibration, that is the engine calibration was carried out on a bench dynamometer trying to obtain the higher torque allowed for each load and engine speed tested. The higher torque can be determined by MBT (Maximum Advance for Best Torque) or LKL (Lower Knocking Limit) (Heywood 2018; Baeta et al. 2004). In sequence, from the base vehicle, it was extracted the ACC Pedal Map. Then, the vehicle models were created and transferred to VI-CarRealTime to be compiled and used by the simulator with VI-MotionCueing®. At this moment, basic problems with the model can be detected to avoid unexpected and undesired behavior in the DiM. After, the working team drives the DiM simulator to make it evaluation of the model. The working team should be composed of expert drivers with long-time experience in on-board vehicle calibration. The suggestions and opportunities to enhance the model are listed and the actions planned for the next step: Recalibration. The Recalibration stage should work as an on-board vehicle calibration to enhance driving comfort with progressiveness and no jolts.

For the study, 3 vehicle models were created and evaluated according to their powertrain set-up, presented in the test plan in Table 2. Model 1 is the default configuration of the DiM that is commonly used for dynamics and handling vehicle applications. Model 2 is a set-up similar to a base engine calibration that is generally carried out in a test cell using a pedal map that is commonly found in passenger small vehicles. Model 3 is a recalibrated engine map and acc pedal map for the proposed vehicle that is a modification of the base engine map (Model).

Table 2. Characteristics of Vehicle Models according to Powertrain Subsystem Configuration

Model	Description	Engine	ACC Pedal
1	Default	Max Torque Curve	Ramp
2	Base Calibration	AVL Boost Engine Map	Acc Pedal map
3	On-board Calibration	Recalibrated Engine Map	Recalibrated Acc Pedal map

Figure 4 (a) and (b) show the Acc Pedal setup for models 1 and 2, respectively. Figure 4 (a) is a simplified ramp with slope 1 that converts directly acc pedal percentage to engine torque. It does not consider engine speed and driver torque demand. Figure 4 (b) is the Acc Pedal map presented as a map contour graph. For each engine speed, there is a different relation between acc pedal position and torque, improving vehicle control and comfort. A real vehicle Acc Pedal map was used for its setup. Model 3 was utilized for the recalibration of the accelerator (Acc) pedal map. However, this paper does not present it since a contour map lacks sufficient precision to differentiate between them.



(a) (b)

Figure 4. Acc pedal ramp (a) and Acc pedal map for model 2 (b)

2.4 Driveability evaluation procedure

The subjective evaluation is based not on performance results but on opinions taken from the drivers after a test drive in the DiM simulator. There is a pre-loaded track where the driver can drive freely. In this work, the track is a virtual version of the Hockenheim racing circuit. A *n* number of drivers were invited to join the Driver's Evaluation Group in which some aspects should be observed:

- The driver must have a driver's license.

- The driver should be an experienced driver.
- It is not a video game, and it is not a pilot test.
- It should not be his/her 1st experience in the DiM simulator. It is very common for a 1st-time driver to feel dizzy and suffer from some nausea and headache.

The test drive is a blind test. The driver does not know which model he/she will be driving. For each driving test, there would be 2 people, the controllers, in the DiM control room, that are responsible for managing the data for each driver. The driver only knows he/she is driving a different set-up called A, B, or C. It is allowed for the driver to ask the controllers to change the models any time he/she wants to make it easy for him/her to compare.

After leaving the DiM cabin, the invited driver fills out a question form on his/her feelings about the different models (Table 3). The grade starts from 1 (poor) to 5 (excellent).

Table 3: Subjective evaluation form

Parameter	A	B	C	
Acceleration				
Progressivity				
Aggressivity				
Gear Shift				
Speed Sensation				
Name				
1 – Poor	2 – Fair	3 – Regular	4 – Good	5 – Excellent

3. RESULTS AND ANALYSIS

After collecting all information on the driver's perception, the results were analyzed to a better understanding of the proposed methodology for objective evaluation.

3.1 AVL Boost Engine Simulation

The AVL Boost simulation was intended to reproduce the engine torque curve at WOT and extend to partial load, creating a simulated engine map. In Figure 5, the graph shows the real engine curve (red dot-dash line) for comparison. The Default setup uses only a Max Torque curve that limits torque for each engine speed. The one used in this work for the Default set-up is represented by the black continuous line.

For this work, an engine map was first developed in AVL Boost. The orange dashed line (Model 1) is only the maximum torque curve (at WOT). However, the AVL Boost simulation started with WOT but was extended to partial loads in other to create an engine map that is not represented here. In some points, Torque was obtained by MBT or LKL. But in some cases, the Torque value was manipulated to try to reproduce a real engine curve profile.

Model 2 engine map was recalibrated based on Model 1. Model 2 torque curves can be seen in the graph by the grey dotted line. Here, it is possible to observe that the Torque curve was recalibrated to obtain a less irregular profile. Partial loads were also "recalibrated" (recalculated) to reduce some slopes in the middle of the map. Those slopes and irregular points could harm the progressiveness during transient operation.

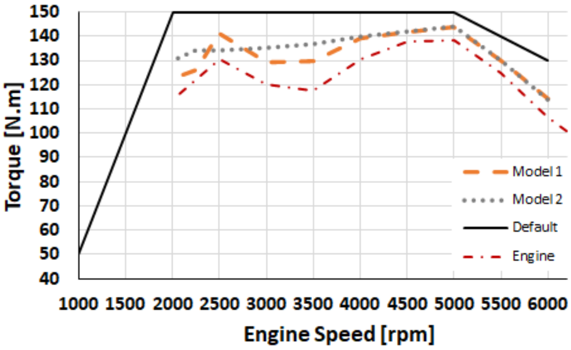


Figure 5. Torque curve at WOT for the different models and the real engine.

Observing these results, it was determined that the AVL Boost simulation provided an engine map that was consistent with the objectives of this work. As a result, an objective evaluation could be conducted.

3.2 Objective Evaluation

Based on the interviews, subjective results and their standard deviation are presented in Figure 6 (a) and (b), respectively. The Default setup is the blue continuous line. The dashed orange line corresponds to Model 1 while the dotted grey line is for Model 2. At first, it is possible to observe that the results for the Default set-up diverge more from models 1 and 2 than they diverge from each other.

Model 1 presented an enhanced perspective from the Default setup. The perception of the Progressivity and Gear shift with a higher grade reveals the smoother behavior of the vehicle during the test drive. The acc pedal map allows the simulator to have a soother path when engine speed changes, mainly when it changes significantly during a gear shift. Speed sensation did not change substantially although the standard deviation shows that probably opinions were not very convergent. The same occurs with Acceleration however with lower standard deviation. Aggressivity was the only parameter with a higher grade for the Default setup. Aggressivity was a concept that was perceived with a bad connotation, probably more associated with the lack of perspective of control and irregular, unexpected, and non-progressive acceleration behavior.

Model 2 results are the consequences of "on-board" calibration. In general, subjective result figures showed drivers perceived Model 2 driveability as more refined than the others. The fine adjustment of the Engine map and Acc Pedal Map helped the drivers feel the ride was smoother. It can be seen when observing the great difference obtained by Model 2 in Gear Shift.

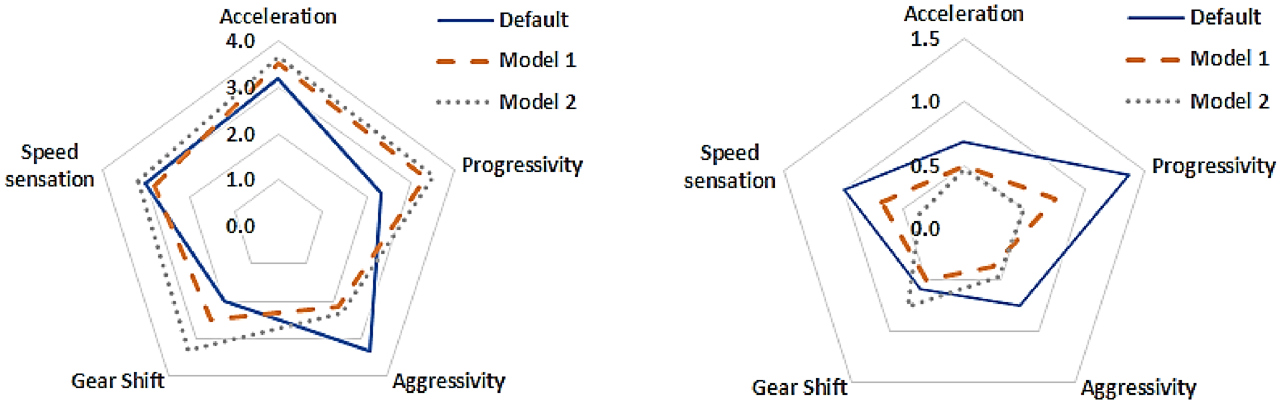


Figure 6. Subjective results from the test drive

The results showed that from the driver's perspective, model 1 and model 2 presented an enhanced feeling of vehicle driveability. Also, it was possible to perform a fine adjustment to improve the driver's perception of quality. Moreover, it is possible to observe that the methodology proposed for a subjective evaluation of driveability showed coherent results, going toward the objective. This methodology for driveability work in a DiM simulator could be used in vehicle development previous to the onboard engine calibration on the road, reducing time and cost to the project development.

4. CONCLUSIONS

This work proposes an approach for a new methodology to evaluate vehicle driveability using an engine simulated in a 0D/1D simulation software and a DiM simulator.

Based on the results, some conclusions can be drawn:

a) AVL boost is a feasible tool to generate an engine map to be used in the DiM simulator.
b) With an engine map and an Acc pedal map it is possible to improve the engine response in the DiM simulator.
c) The Dim simulator proved useful in suggesting improvements in engine and pedal calibration, enabling virtual on-board calibration.
d) The objective evaluation of vehicle driveability presented encouraging results. The drivers' opinions from the blind test showed an expected enhancement in their perception of the models that used more complex tools for engine and pedal calibration. Moreover, the objective evaluation demonstrated that drivers were able to notice different behaviors among the models, indicating that the objective evaluation can be applied to the driveability calibration of a virtual vehicle using a DiM simulator.

5. FUTURE WORKS

Observing this study's results and the potential of the DiM simulator, some works are suggested:

- Development of a Methodology to predict Vehicle fuel consumption and emissions for a Driving Cycle using a DiM simulator.
- Development of a Methodology for On-board Engine Calibration using a DiM simulator.
- Development of a Hybrid Powertrain system model in the DiM simulator.

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