APPES Maps as Tools for Quantifying Performance of Truck Drivers

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Abstract— **Understanding and quantifying drivers' influence on fuel consumption is an important and challenging problem. A number of commonly used approaches are based on collection of *Accelerator Pedal Position - Engine Speed* (APPES) maps. Up until now, however, most publicly available results are based on limited amounts of data collected in experiments performed under well-controlled conditions. Before APPES maps can be considered a reliable solution, there is a need to evaluate the usefulness of those models on a larger and more representative data.**

In this paper we present analysis of APPES maps that were collected, under actual operating conditions, on more than 1200 trips performed by a fleet of 5 Volvo trucks owned by a commercial transporter in Europe. We use Gaussian Mixture Models to identify areas of those maps that correspond to different types of driver behaviour, and investigate how the parameters of those models relate to variables of interest such as vehicle weight or fuel consumption.

I. INTRODUCTION

Road transportation is one of the ways most often used to move goods and people from one point to another in Europe. According to [1], almost 75% of all the cargo transported in 2011 in Europe was done with trucks, summing to approximately 520 billion tonne-kilometres. As a consequence the fuel burned by vehicles accounts for around 20% of the CO_2 emissions in the region.

In addition, fuel expense is one of the most important cost factors, accounting for approximately 30% of the total operating expenses of a heavy duty vehicle.Fuel efficiency is very important for modern vehicles for environmental as well as financial reasons.

There are many factors influencing fuel consumption of a vehicle. Some of them the transporters and vehicle manufacturers have little or no control over, such as weather or road topology. However, there are many others that they can affect, for example route planning, aerodynamics or tires. Furthermore, a factor that has been widely recognised as being very important is the driver.

One asset that is recently becoming available are large quantities of data collected over long time under real driving conditions. This data can generally be made available and processes either on-board or off-board the vehicle. Each of these two options have their own advantages and disadvantages. Storage and analysis of high frequency data consisting of hundreds of signals requires large amounts of memory and computation power, neither of which is commonly available or feasible to implement on commercial trucks. On the other hand, data transmission costs are currently too high to justify a fully off-board solution. Therefore, a promising approach is to investigate data representation abstractions that can be easily computed and stored on-board, but which also contain enough information to provide valuable knowledge when analysed off-board.

In order to find opportunities for reducing fuel consumption there is a need to analyse this newly available data. This paper is one step in this direction.

A. Related Work

Fuel consumption for heavy duty vehicles is an issue that affects our daily lives. The recently adopted Euro VI standard exemplifies the importance of fuel consumption reduction, as it directly affects particle emissions. The Euro VI standard enforces reduction of noxious emissions by 66% and of nitrogen oxide emissions (NOx) by 80%, compared to Euro V.

Liimatainen [2] has demonstrated how to use fuel consumption as an incentive for drivers to increase their fuel efficiency. He also points out that that it is difficult to take external factors into account when assessing drivers' performance. Ting et al [3] have, in a simulation study, shown the importance of driver and address the issue of driver fatigue and its effects on driving capabilities. Another study of driver performance and its classification is done in [4].

Rafael-Morales and de Gortar [5] conducted an extensive field study to determine the effects of so called "technical driving" for reducing fuel consumption. Authors investigate several means of using vehicle in an efficient manner looking from various perspectives, including analysis of relation between torque and engine speed.

In this paper we expand on the work of of Guo et al [6], who investigate using *Accelerator Pedal Position - Engine Speed* (APPES) map for evaluating drivers' performance. Guo et al identify different regions of this map that correspond to higher or lower fuel consumption. The weakest point of their work is the limited variety of data used to validate the method: only one vehicle was driven on the same route by the same driver. We show that APPES maps can be correlated with a number of relevant factors not only under controlled experimental conditions, but also during actual commercial operation.

II. DATA

We use two large datasets that have been collected in research and development projects within Volvo Group Trucks

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Technology(VGTT). The first dataset comes from *European Field Operational Test* (EuroFOT) project [7], in which VGTT was a partner with the role of testing *Fuel Efficiency Advisor* functionality. The other is an internal Volvo project called *Customer Fuel Follow-up* (CuFF). In both projects, data from multiple trucks have been collected, covering a wide area in Europe and also spanning over a long period of time, offering a variety of both geographic and ambient conditions.

The subset of data that we base our results on consists of over 1200 trips, performed by five Volvo trucks. Each truck has an automatic gearbox with 12 gears and Cruise Control system. Each trip contains over one hundred signals that are logged from the vehicles' internal Controller Area Network(CAN) as well as additional sensors, at 10 Hz sampling frequency.

The complete database amounts to approximately 100 TB of data. Even with this large amount of information, we do not have complete knowledge of all the relevant circumstances. Among the most important factors that we are missing are traffic and weather conditions.

III. METHODOLOGY

The first step in quantifying a driver's behaviour is finding a good representation of it, one that is simple enough to reason about, but at the same captures all the important aspects. In this work we have decided to focus on *Accelerator Pedal Position - Engine Speed* (APPES) maps. It is a way to describe truck usage information that is commonly employed both by automotive engineers and in driver training, as those maps are easy to understand and have very intuitive interpretations.An example of APPES map for a single trip is presented in Figure 1.

In this work we focus on analysis of driver performance. Therefore, we are only considering the time where the cruise control has been disabled. The surface represents how much time has been spent in various combinations of accelerator pedal position and engine speed during a trip. The first of those signals can be thought of as the request from the driver, while the second as an overall response of the vehicle. Most important aspects of truck operation are directly reflected in this map. For example circumstances such as road gradient, engine power or vehicle weight all affect how fast the speed will be changing when the accelerator pedal is pressed to a given level.

Another benefit of APPES maps is that they can be easily obtained from commercial vehicles, for example using telematics technology. Computing them on-board is a smalll effort, and they can be efficiently stored in existing control units to be periodically transmitted, either via wireless networks or during garage visits.

In the past, APPES maps have been used to evaluate drivers, but mostly in controlled experiments, under well-known conditions. Their potential and usefulness in a realistic setting have not been fully explored yet. For example, in [6] the authors focus on identifying regions of the APPES map that can be correlated to fuel consumption. They show increased vehicle efficiency through better driving, but their results are based on a single truck being driven on a pre-specified route.

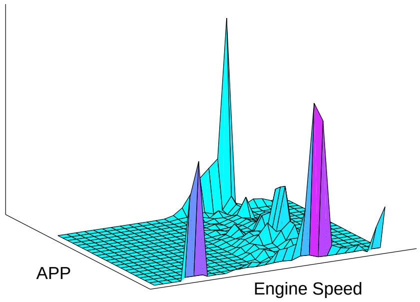

Fig. 1. APPES map for a single trip of heavy vehicle.

The contribution of our work is to demonstrate the usefulness of APPES maps in realistic scenarios, when the external conditions of driving vary in unpredictable ways. Actual situations on the road will put many constraints on what is possible for the driver to do, but we are interested in finding similarities and differences between different driving styles. We can use this to communicate to drivers information regarding their driving behaviour, for example give them advice on how to achieve better fuel efficiency.

One important aspect of vehicle operation that is not explicit in the APPES map is the gearbox. Different gears should be used at different speeds in order to maximise fuel efficiency. Modern truck engines always generate power by burning fuel, but some of this power is lost, as heat. The lost amount, however, varies depending on parameters such as torque and engine speed — each engine manufacturer designs their products with a specific *efficiency map* in mind. By changing gears, driver can optimise power output for any desired vehicle speed, by controlling the ratio between the engine and wheel speeds. This power is then used to overcome resisting forces, gravity and to maintain or increase velocity.

Figure 2 shows the APPES map for all the trips we are considering in this paper. We have identified four important regions in this distribution. We refer to them as *Neutral*, *Free Roll*, *Driving* and *Full Throttle*. Those names indicate the intuitive interpretation of the physical behaviour of the truck that corresponds to each of those regions in the APPES map.

The region we call *Neutral* corresponds to low engine speed, with the exact value depending on engine specification, and acceleration pedal being fully released. It can be seen in Figure 2 as the peak in the lower left corner. Those conditions can be achieved when the truck is in neutral gear, but it can be either stationary or moving.

The *Free Roll* region is characterised by the accelerator pedal being fully released, but engine is rotating above idle speed. This generally means that the vehicle is in gear other than neutral and that it is moving forward. In this mode

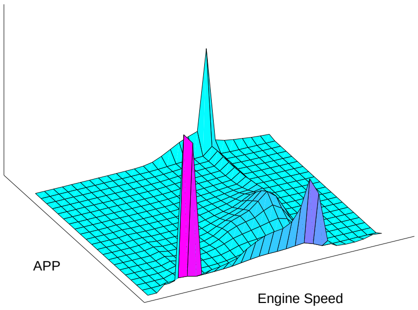

Fig. 2. Combined APPES map for all the trips.

the engine is not using any fuel. This situation most often happens when travelling downhill, where the driver can use gravity to maintain the desired speed, or when they anticipate that a speed reduction will be needed in the near future, and use kinetic energy to propel the vehicle forward for a short time. In Figure 2, this region corresponds to the ridge along the bottom.

Full Throttle corresponds to the accelerator pedal being fully pressed. It can either indicate that the driver is attempting to reach the desired speed in the minimum amount of time or trying to maintain the highest speed allowed by the electronic limiter, which is set to 90 km/h. This region can be seen as the peak near the top right corner of Figure 2.

Finally, the *Driving* region captures the full spectrum of driver behaviour in between the three aforementioned extremes. It covers engine speeds that correspond to driving using different gears and at different velocities, as well as how much the accelerator pedal is pushed, either for acceleration or for compensating for road conditions such as hills. This region is probably the most interesting one, since the exact distribution of data within it can tell us, for example, when this particular driver changes gears, possibly leading to creation of driver profiles that can later be used, with long term observation, to track driver performance. In Figure 2, this region can be seen as the triangle-like shape in the middle of the plot.

Based on this rough classification, we have decided to model the data using a Gaussian Mixture Model. Figure 3 shows the obtained result. Blue dots correspond to the data that was extracted from the APPES map using uniform random sampling within each map cell. The four red dots denote the location of means of the four Gaussians that were fitted to this data. As can be seen, they correspond quite well to the four regions we identified above. The coloured ellipses around each mean visualise the covariance matrix of each model.

In the following section we will present the results of comparing the parameters of those Gaussians across different trips.

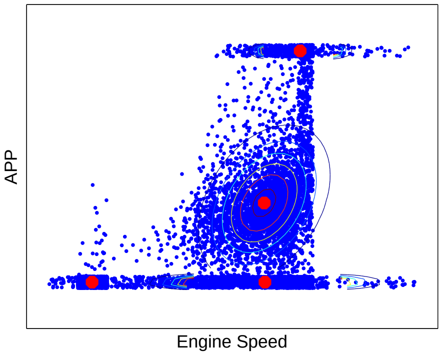

Fig. 3. Gaussian Mixture Model, with blue points corresponding to the data and red points corresponding to locations of four Gaussian means representing different regions. The two lower are Neutral and Free Roll. The top is Full Throttle. The middle one is Driving.

IV. RESULTS

In this section we report the results of our experiments concerning the usefulness of APPES maps in a real setting, especially with respect to fuel consumption. We base our analysis on comparing parameters of the Gaussians Mixture Models corresponding to the four types of driving that we have introduced in the previous section. There are three important comments regarding our methodology that need to be explained before we present actual results.

First of all, the goal is to relate various factors of interest to the APPES regions that we have identified as the most important ones. In order to do that, it is useful to categorise those factors as either *cause* or *effect*, in particular from the driver's point of view. For example, traffic density requires drivers to change their desired behaviour and affects their decisions. In this paper we analyse a factor from each category, choosing ones that are easy to understand and using available expert knowledge. As a *cause* type we have selected gross vehicle weight, while as an *effect* type, fuel consumption. We have decided upon those two because it is interesting to analyse how weight affects driving style, while at the same time we are very much aware that it also heavily influences vehicle fuel usage.

Second, since our data comes from real commercial trips, we do not have access to any form of ground truth concerning actual performance level of drivers. Therefore, we are interested in a finding as few parameters describing each APPES map as possible, preferably ones that are easy to visualise and whose correlation to variables of interest can be discussed in this text. To this end, we have chosen to only take into consideration the proportion that each Gaussian occupies in the complete model, ignoring both the exact location of the mean and the covariance matrix.

Finally, many of the individual trips did not have enough data to build reliable Gaussian Mixture Models with all four regions of interest properly represented. Individual drivers rarely cover all of them in one trip, which is a direct effect of the length of those trips as well as high usage of cruise control. This often caused undesired effects of Gaussian

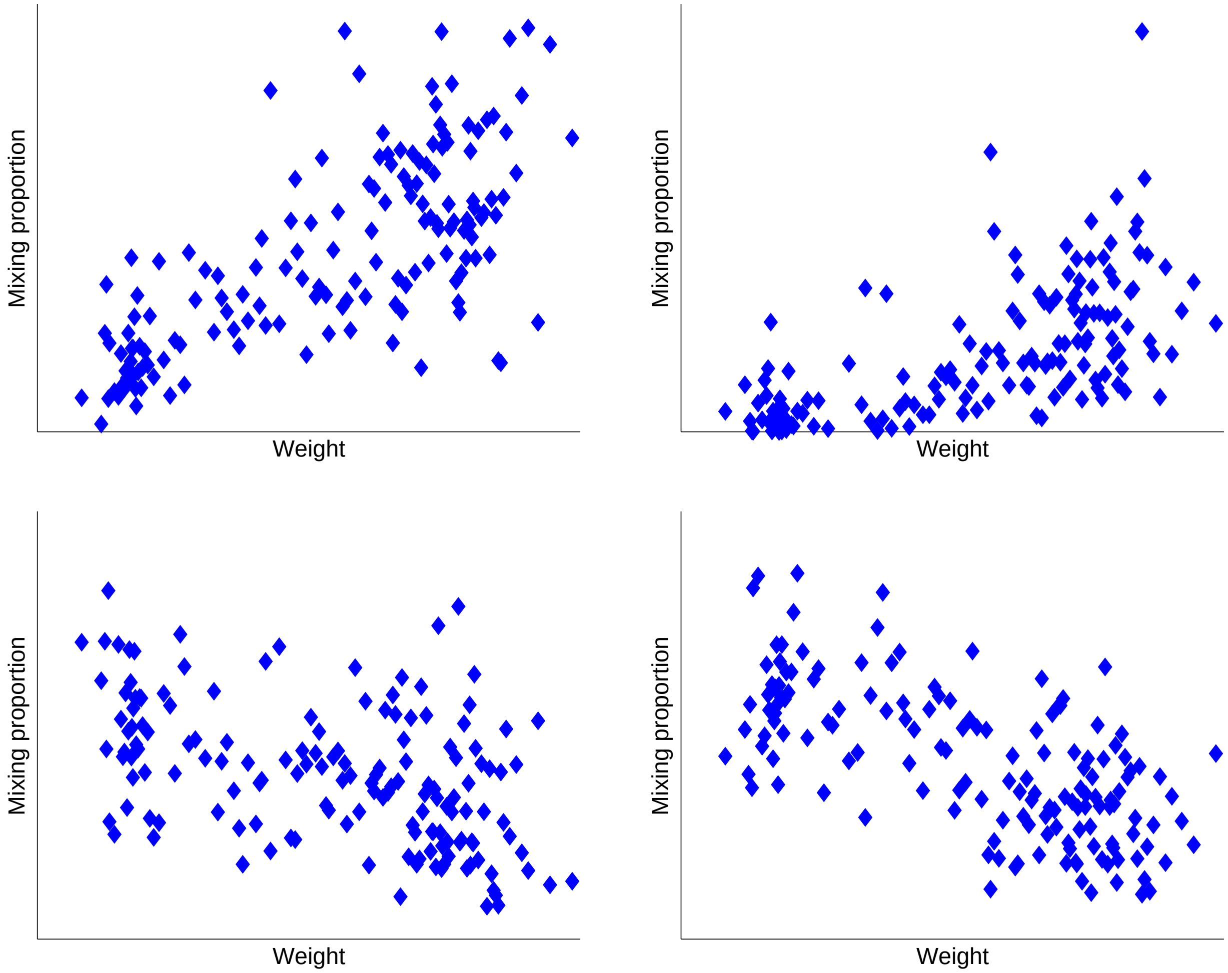

Fig. 4. Mixing proportions of *Free Roll* (top left), *Full Throttle* (top right), *Neutral* (lower left) and *Driving* Gaussians for groups of 8 trips based on weight.

means moving to different locations.

Those situations are not particularly interesting, since we believe they are usually caused by specifics of the individual mission. On the other hand, we do not want to ignore such data but rather evaluate the robustness of APPES maps. However, in order to evaluate it we need to perform experiments, e.g. test results with and without outliers. The immediate goal is to determine usefulness of APPES maps. In order to analyse how each factor correlates to selected regions of interest, we require all four of them to be present. Therefore, we did not fit Gaussian Mixture Models to individual trips, but to groups of several similar trips. Grouping of trips reduces the chance that any of the Gaussians is missing.

A. *Vehicle Weight*

Vehicle weight is a factor that is known to be very important for fuel consumption. However, there are no large scale, systematic studies of how a driver's behaviour is affected by vehicle weight. Therefore, in this section we present results that can be seen as a starting point towards this goal.

As explained before, APPES maps show a driver's behaviour for a given trip or a group of trips. We can describe each map by four numbers, the mixing proportions of the Gaussian models corresponding to each type of driving: *Free Roll*, *Neutral*, *Full Throttle* and *Driving*. Those proportions correspond to the amount of time that was spent in each of the regions. In order to analyse the relation between driver's performance and vehicle weight, we want to observe changes that happen when driving trucks with different loads. Therefore, we group similar trips and plot the mixing proportions of each APPES Gaussian, looking for interesting relations.

The clearest correlation, with value of 0.7, can be seen in Figure 4, top left. Each point on this plot corresponds to a group of 8 trips, with similar vehicle weights. The Y value represents the mixing proportion of the *Free Roll* Gaussian, while the X value represents the average weight within the group. As can be seen, the lightest vehicles very rarely use free roll, while the share of this driving type generally increases as the vehicle becomes heavier.

This is an anticipated result, since heavier vehicles have

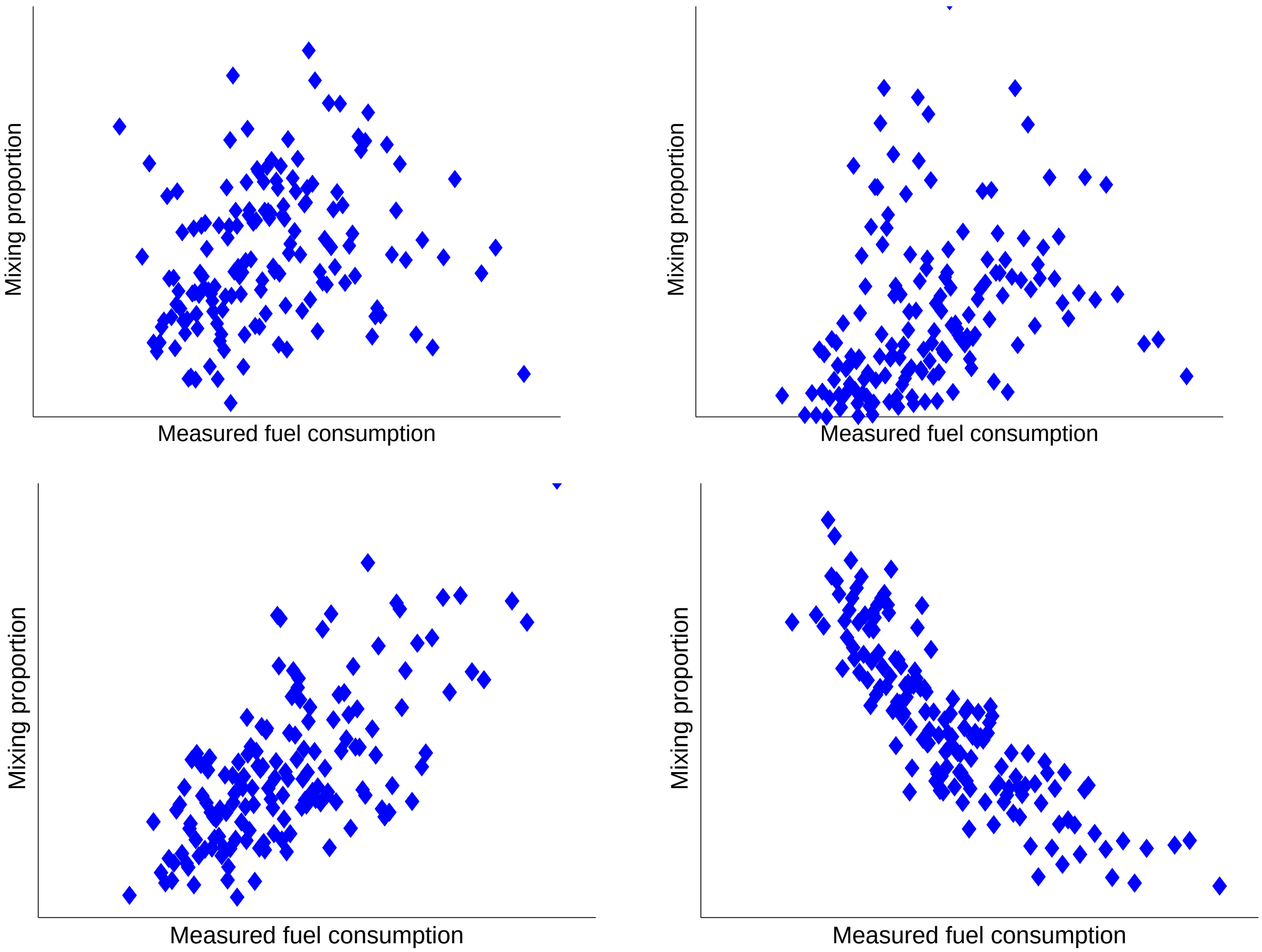

Fig. 5. Mixing proportions of *Free Roll* (top left), *Full Throttle* (top right), *Neutral* (lower left) and *Driving* Gaussians for groups of 8 trips, with respect to measured fuel consumption.

more inertia and therefore lose speed less rapidly. However, free rolling with a vehicle does not only depend on vehicle weight but also on a skill of the driver, mainly their ability to anticipate future situations and use ambient conditions to better use the vehicle. One circumstance that a good driver takes advantage of is coasting in gear. In such a case, if the road gradient is enough to keep the vehicle at desired speed, a *Free Roll* can reduce the fuel usage to zero.

However, the APPES map itself does not contain enough information to identify such situations, and finding them is a topic for future work. An anticipation situation is more often encountered in towns or in high traffic scenarios, where change of speed is more common. For example, driving towards a stop light and anticipating having red light upon arrival might prompt the driver to stop accelerating and let the vehicle roll. This situation could result, depending on the gear, in either *Free Roll* or *Neutral* behaviour.

Another aspect to consider is that heavier vehicles, having more inertia, also offer more opportunities to use free roll. For example, in anticipation of a steep downhill, the driver can choose to *Free Roll* for some time, on the flat road, and lose some speed which can then be regained during the downhill section.

Another aspect to consider for this Gaussian is what happens after the *Free Roll* ends. This, again, is not actually included in the APPES map, but *Free Roll* followed by, e.g., high acceleration is often an indication of insufficient anticipation. There are many possibilities and analysing them will reveal further information regarding drivers' behaviour in various scenarios.

Continuing to Figure 4, top right, the *Full Throttle* Gaussian, we can also notice a high correlation, at 0.62. This relation can be explained by the fact that engine power is a limiting factor for heavier trucks, and desired acceleration can often only be achieved by pressing the pedal fully. It could also be attributed to the fact that drivers are less inclined to try and optimise fuel usage for heavy loads, since in most cases their performance is measured in absolute terms, and therefore they know they cannot compete with lighter trucks.

If validated, this could be a strong argument towards introducing performance indicators that analyse fuel consumption and also consider vehicle and ambient conditions. As all trucks involved in this analysis are the same model, it is also possible that lighter trucks do not require full power fron the engine, especially if there is an acceleration level whicl generally satisfies the drivers. Heavier trucks may never reacl said acceleration, even with full throttle, leading to highe amount of time spent in that region.

Correlation for Figure 4, bottom left, the *Neutral* region has the value of -0.47. Weight seems to have a mino influence, if any at all, for time spent in neutral gear. On possible explanation for slightly higher average values fo lighter trucks is lower inertia. Instead of using *Free Roll* where engine braking occurs, lighter trucks choose to us *Neutral*. This way they the keep vehicle rolling longer.

Figure 4, bottom right, *Driving*, shows a stronger negativ correlation of -0.66. One explanation can be the opposit of *Full Throttle*: since drivers rarely need to use full throttl to maintain the desired vehicle speed profile, they end up i the *Driving* region more often. However, it is important t remember that the mixing proportions for all the Gaussian always sum up to 1. Looking at Figure 4, top left and top right respectively, we notice that the time spent in those regions is very small, which means that it has to be distributed among the remaining two regions.

Finally, the four regions can be also seen as two groups of complementary driving styles. We can consider the first to be comprised of *Full Throttle* and *Driving* Gaussians, where light vehicles tend to spend more time in the *Driving* region while heavy vehicles end up in *Full Throttle* more often. The second group is formed by *Neutral* and *Free Roll*. Lower inertia and engine braking being relatively stronger make light vehicles use neutral gear more often, while heavier vehicles do not require it so much.

B. *Fuel Consumption*

As mentioned earlier, we consider fuel consumption to be an effect of driving style. Therefore, observing how different driving styles influence fuel consumption can be directly used to assess performance of drivers. We can estimate how beneficial it is to be in one region or another, ignoring other factors. However, the degree to which positioning oneself in the APPES map is up to a driver is unclear, as there are many conditions that constrain their decisions.

One of the surprising results is that there is no clear correlation, at a value of 0.22, between *Free Roll* and fuel consumption, as seen in Figure 5, top left. Expert knowledge tells us that if a vehicle is in gear and the acceleration pedal is released, the engine will not use any fuel. This has been verified directly with real world data and it strongly suggests that *Free Roll* is highly desirable behaviour.

One possible explanation could be that the beneficial effects are clouded by detrimental effects of other regions. Another would be that other factors, for example heavy traffic or hilly terrain, heavily influence when a driver can choose to *Free Roll*, and their own detrimental effect can outweigh the benefits. Further investigation is required before a more concrete conclusion can be reached, as this observation contradicts prior beliefs. However, it motivates our original thesis that APPES maps, due to their simplicity, can uncover interesting relations in the data.

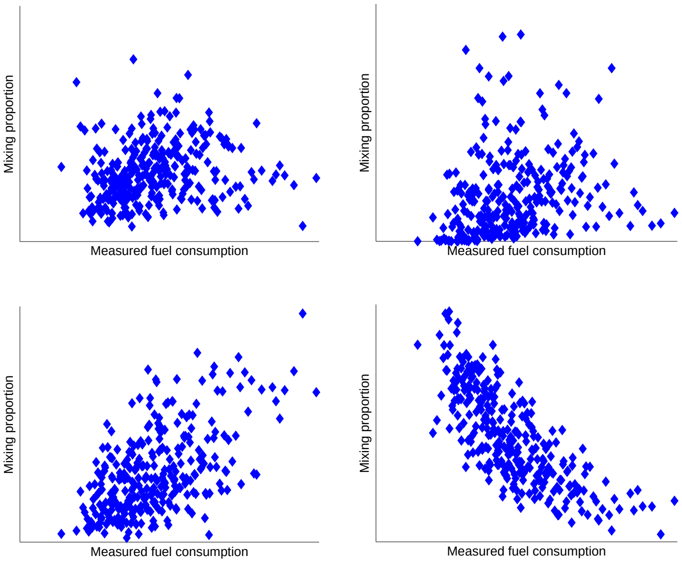

Fig. 6. Mixing proportions of *Free Roll* (top left), *Full Throttle* (top right), *Neutral* (lower left) and *Driving* Gaussians for groups of 4 trips.

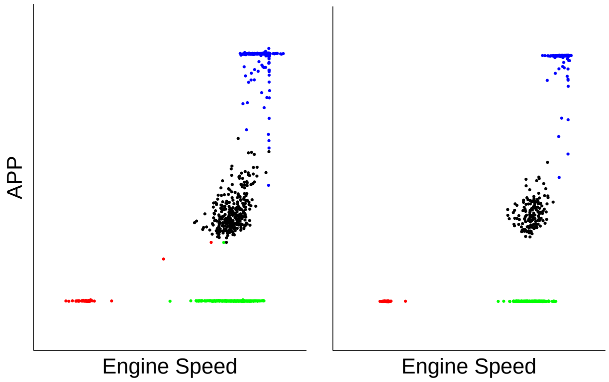

Fig. 7. Gaussian means for groups of 4 trips(left) and 8 trips(right)

It is also interesting to note that this region has higher correlation with weight, as depicted in previous subsection, Figure 4, top left. Consequently, further investigation should focus on how both weight and fuel consumption influence each Gaussian.

Figure 5, top right, corresponding to the *Full Throttle* region, shows 0.32 correlation. Even despite it being so low we can notice that there is a tendency for low fuel consumption to be associated with low *Full Throttle* proportion. One way of explaining this is by taking into account a cause, such as the previously discussed vehicle weight. We noticed a much higher usage of full throttle for heavier vehicles, which in turn can be associated with higher fuel consumption. This suggests that APPES maps can also be used to link relations between various factors.

On the other hand, a strong positive correlation of 0.68 can be seen in Figure 5, bottom left, for *Neutral* mixing proportion. This agrees with our expectations, since we measure fuel consumption in $L/100km$ and having a vehicle in neutral gear burns fuel but does not propel the truck forward. However, some drivers may choose to use *Neutral* instead of *Free Roll* under certain circumstances, as it means is no engine braking.

The final Gaussian, *Driving*, shown in Figure 5, bottom right, exhibits a very strong negative correlation of -0.88. We conclude that adapting the fuel demand as well as keeping an appropriate speed, both of whom can be done by active driving, uses the fuel most efficiently.

For comparison, Figure 6 presents the same relations as the previous four figures, except this time each point represents a group of 4 trips. We have chosen two different group sizes to show the amount of noise that is present when less data is available to fit each Gaussian Mixture Model. Overall, however, very similar relations can be found between fuel consumption and time spent in each region, but increasing the number of trips in each group makes them clearer.

Figure 8 shows the changes in correlation coefficients between fuel consumption and the Gaussians, for different group sizes. The largest decrease occurs for *Neutral* and *Driving* at 3 trips in each group. The other two regions display more stable relations.

We also present the positions of the four Gaussian means for all the groups, of both 4 and 8 trips, in Figure 7. It can be seen that there is significantly less variation in the data for the right plot. This observation agrees with Figure 8, where we see a decrease in correlation coefficient with lower number of trips per group.

It is important to stress once more that this data comes from real operation of commercial vehicles, and thus captures the actual situations that take place. In particular, there are individual trips with extremely unusual patterns — for example, over 50% of time spent in neutral. It is therefore important that any analysis method designed for real world use can handle such outliers and does not assume too much conformity to the “expected norm”.

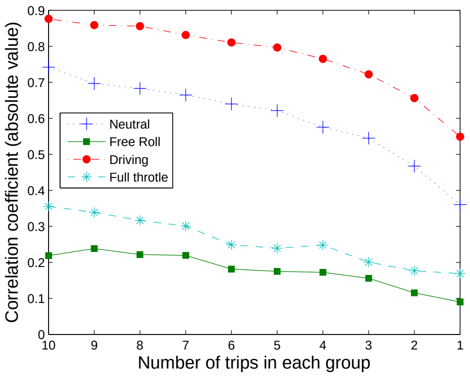

Fig. 8. Correlation of each gaussian vs number of trips in a group

V. CONCLUSIONS AND FUTURE WORK

In this paper we have analysed the usefulness of *Accelerator Pedal Position - Engine Speed* (APPES) maps for evaluating drivers’ behaviour from the point of view of fuel consumption. Such maps are an inciting tool, because they are very easy to calculate on-board and have very intuitive interpretations.

We have used data collected during commercial operation of a fleet consisting of five Volvo trucks used by multiple drivers, under the full range of operating conditions on over 1200 trips. This gives us confidence that the results are relevant for future products and services.

The goal of our work was to compare the performance of different driver, describe them using simple to understand features, and correlate those features to key performance indicators, such as fuel consumption. APPES maps can be easily used both for evaluating as well as for training drivers.

Our approach is based on fitting Gaussian Mixture Model to the data, and analysing the relative importance of the four regions we have identified as being of particular interest. We have shown that several of those are highly correlated with factors such as vehicle weight or fuel consumption.

The results presented in this paper are encouraging, but final conclusions have not yet been reached. We have identified both intuitive correlations, e.g., driving in neutral should be avoided, as well as counter-intuitive correlations, e.g., *Free Roll* leads to higher fuel consumption. We believe that that the next step is to find ways to identify external conditions that affect different trips in different ways: for example, it is plausible that *Free Roll* is more common in hilly areas, which would explain higher fuel consumption.

Future work ideas also include investigation of other ways to compare APPES maps. In the current approach, we only investigate the proportion between various Gaussians, but the position of individual means is likely to also contain interesting information. In addition, more complex Gaussian Mixture Models, as well as other formalisms, should be explored in the future.

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