Preliminary Results from Driveability Investigations of Vehicles with Continuously Variable Transmissions

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The aim of the work described in this paper was to appraise and compare the driveability of three test cars, each of which included a continuously variable transmission. The approach was to acquire objective data during test drives and compare the results with the subjective assessment of the drivers. The objective data used were those considered to be the most influential on driveability issues: delay times, acceleration and jerk values. The results were also used to provide guidelines for future work.

Keywords / Continuously Variable Transmission, Driveability, Acceleration, Jerk, Delay Time

1. INTRODUCTION

The only CVT to achieve successful market penetration to date is the Van Doorne push belt fitted in small and medium sized cars. One of the reasons that greater acceptance of CVTs in the world market has not yet taken place is because their major benefits of reducing fuel consumption and emissions have not been realised with adequate driveability. Therefore some fundamental research into the characteristics of CVTs is required to define driveability requirements and to establish appropriate control strategies. Such investigations have already been made for conventional automatic gearboxes with the main focus on the effects of gear shifting and tip-ins on the driveability [1, 2, 3 and 4]. In these studies, acceleration and jerk values were identified to be the main influential variables. CVTs allow more freedom of control strategy than conventional automatic gearboxes and so more variables may have an influence on driveability. The requirements for good driveability have therefore to be redefined for CVTs.

This paper contributes to this research by presenting and analysing results from the experimental part of a larger research project in which a combined transmission and engine controller was developed [5]. The emphasis in this project was minimisation of emissions and driveability was not given a high priority. The first part of the paper gives background on the research project including the methods and equipment used for the experimental work. The second part of the paper presents the results of the work, which were also used to define the requirements of a follow-up project.

2. EXPERIMENTAL METHOD

The main objective of the controller to be developed was to investigate the potential for exhaust emissions reduction. This was achieved by having an IOL (ideal operating line) for steady state operation. Driveability aspects were to be considered by allowing deviation from this IOL during transients. However, guidelines that lead to good driveability with CVTs are not well established. Therefore investigations were made into the driveability of three CVT vehicles, the results of which are presented in the following.

2.1 Equipment

Table 1 compares the three test cars (referred to as car A to C in the following) which were assessed by twelve test drivers. Car A turned out to be the car with the best overall appraised results and was therefore chosen as the reference vehicle.

Table 1: Test Vehicles

	Car A	**Car B**	**Car C**
Fuel	Petrol	Petrol	Diesel
Engine Size/L	1.3	1.6	1.8
Mass / kg	850	1100	1100
Power/Weight Ratio/ (W/kg)	70.6 (100 %)	60 (86 %)	45.5 (71 %)
Transmission	VDT	VDT	VDT
Control	Electronic	Hydraulic	Hydraulic

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2.2 Description of the Experimental Tests

The driver's perception of the driveability is a complex process and depends amongst others on the driver's expectation of the vehicle and the particular driving situation. It is possible that two tests with fundamentally the same set of objective data can lead to completely contrary driveability perception in two different driving situations. Therefore different driveability categories were defined that relate to real and distinctive driving situations, which aims at achieving more comparable results. The driveability categories were defined as follows:

1. *Launch Feel*: The tests in this category involved starting from rest with mainly big pedal movements.
2. *Overall Performance Feel*: In this category, the drivers expected the cars to provide quickly maximum performance, e.g. when joining a motorway or overtaking another vehicle. The pedal position is in this category always depressed to its maximum position.
3. *Traffic Crawl*: The tests in this category involve small starting velocities and small pedal movements.

2.3 Driveability Assessment Approach

The approach to the driveability investigations was to acquire objective data during the test drives and to compare the results with subjective data, thus establishing which characteristics are liked by the drivers. The objective data were acquired during test drives using data acquisition and the subjective data were gained by having the test drivers fill in questionnaires about their perception of the car.

Objective Data: The main variables acquired were: *engine and vehicle speed*, *vehicle acceleration* and *pedal position*. This allowed comparison between different characteristics in both qualitative and quantitative terms.

Subjective Data: The questionnaires included questions about driveability and performance attributes assessing a total of 14 different aspects. A rating was assigned in the range from 1 and 10, with the latter being the best possible assessment. The questions were chosen, so that they could be related to the driveability categories.

3. EXPERIMENTAL RESULTS

The experimental results are presented in three parts. Firstly, objective results are shown and discussed for all three cars during one typical acceleration manoeuvre. Secondly, the overall assessment of the three cars is given by consideration of the *Overall Driveability Feel*. In the third part, the objective data are broken down into the defined driveability categories and are compared to their corresponding subjective assess-ment.

3.1 Objective Results

The results presented for the 3 vehicles show an acceleration transient following a step increase in pedal position from 20% to 60% as in Figure 1. Figure 2 shows the corresponding vehicle response.

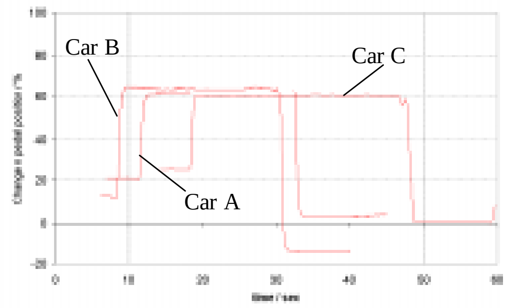

Figure 1: Change in Accelerator Position

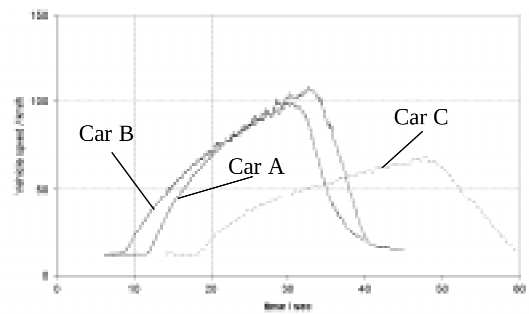

Figure 2: Vehicle Response of the Test Vehicles

The timing of the start of the event for the three cars is slightly different, which allows the time traces to be clearly separated. In Figure 2 it can be seen that the vehicles A and B have a similar response. Due to the lower power of car C and its control strategy, its velocity not only changes more slowly but also aims for a lower terminal speed.

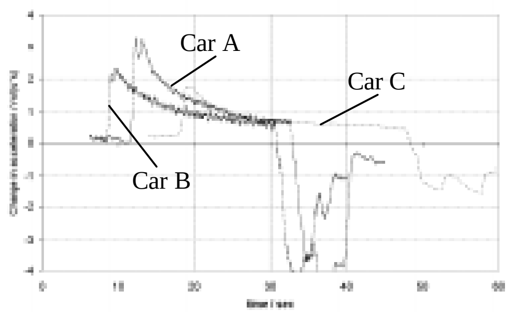

Figure 3: Comparison between the Acceleration Traces

Figure 3 shows the corresponding acceleration traces during the tests. The accelerations increase very quickly and fade away over the manoeuvre down to a constant level until the accelerator is released and the vehicles decelerate to lower speed levels.

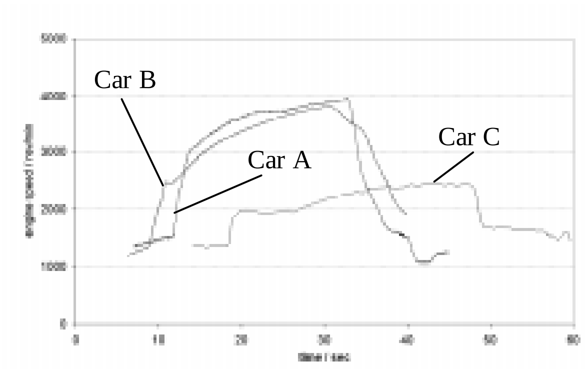

Figure 4: Comparison between the Engine Speed Traces

Figure 4 shows the time traces of the engine speeds and typical behaviour resulting from the use of the CVT can be observed. At the beginning, the ratio of the transmission is changed in a way that enables the engine speed to increase very quickly being decoupled from the rest of the drivetrain. This provides the engine with more power for the following acceleration but also increases the vehicle response delay times. Having accumulated enough power, the increase in engine speed slows down with the engine now having to overcome not only its own inertia, but also the inertia of the whole drivetrain. The progression of the engine speed during transients has a large influence on the performance and the economy of the vehicle and is therefore the most important part of the CVT control strategies [5,6 and 7].

3.2 Subjective Results

The most general rating describing the subjective feel of the cars - the *Overall Driveability Feel* - is shown in Figure 5.

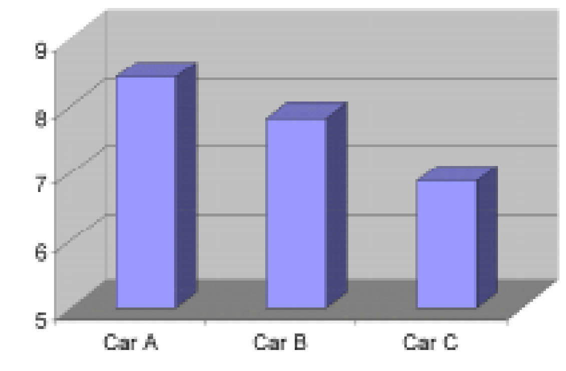

Figure 5: Assessment of Overall Driveability Feel

The data presented are averages of the values given by the twelve test drivers. The best assessment is taken as the reference value of 100%. This format is also used in the following sections, where the data are presented in a similar way. This allowed relative comparison between the cars for each category. According to Figure 5, car A was the best liked car with a rating of 8.42 (100%) followed by car B (93%) and C (82%).

3.3 Comparison of Subjective and Objective Data

In this section, the subjective driveability assessments by the test drivers are shown for the sub-categories introduced in section 2.2. Characteristic driveability values were defined and read from the time traces. These include the changes in acceleration and jerk as well as delay times. The latter was counted as the time between a first change in pedal position and a first change in the acceleration trace. The data presented are average values taken from several tests per vehicle.

Launch Feel: The first driveability category to be investigated is *Launch Feel*. Figure 8 shows the average assessment given by the 12 test drivers.

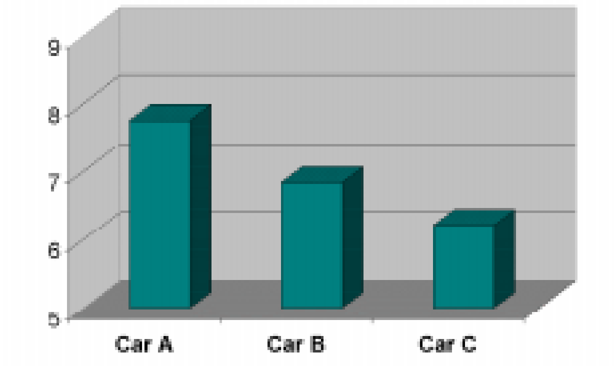

Figure 6: Overall Assessment of the Launch Feel by the Test Drivers

Car A achieved the best score with 7.75 (100%). Second and third come car B with 88% and car C with 80%. Comparing Figures 5 and 6 show that the gap in assessment between car A and B is bigger in this category than for *Overall Driveability Feel*. A possible reason for this is shown in Figure 6, where the characteristic acceleration and jerk values are shown for these tests. A significant lack of jerk can be observed for car B, when compared to the other two vehicles.

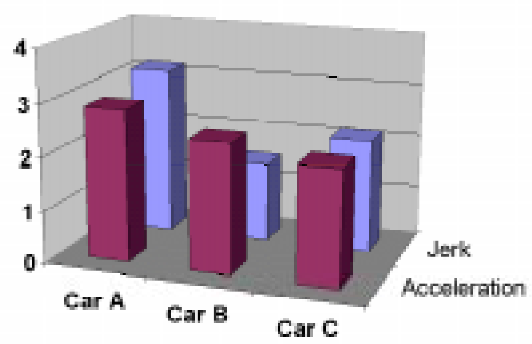

Figure 7: Average Acceleration and Jerk Values for Launch Feel

Even though the jerk data influenced the rating of car B relative to the other cars, the acceleration values still show a better correlation in absolute terms to the subjective *Launch Feel* data. This suggests acceleration data have a more significant influence on the driveability than jerk data when starting from rest.

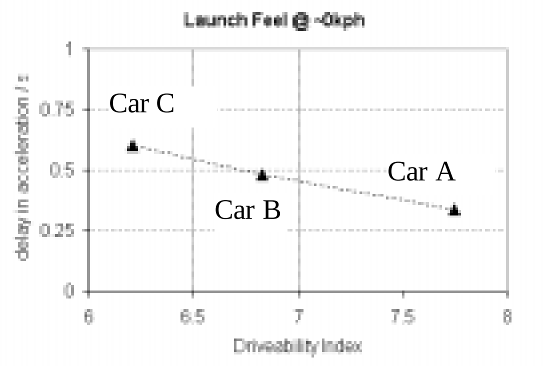

Figure 8: Average Delay Times in Acceleration versus the Driveability Index

In addition to the acceleration and jerk values, the delay times are also considered to be very important. The data acquired during the tests are shown in Figure 8. Car A also had the shortest delay time. The average delay times of car B are closer to the delay times of car C than to car A. Therefore, the delay times also correlate with the subjective assessment.

Overall Performance Feel: In this category the overall performance of the test cars was again investigated by means of their maximum acceleration and jerk. The tests included acceleration manoeuvres with different starting velocities (12 and 40 km/h). Results for the higher starting velocities are not presented here. Figure 8 shows the assessment given by the test drivers for *Overall Performance Feel*.

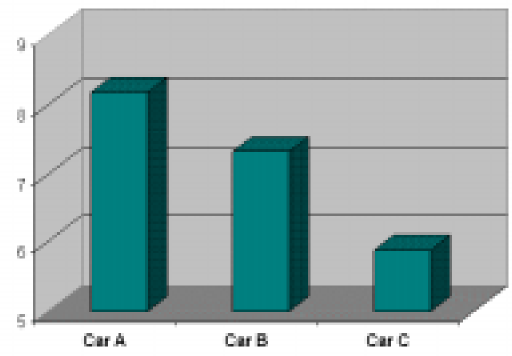

Figure 9: Overall Performance Feel Assessment by the Test Drivers

Car A is again taken as the reference car with a score of 8.17. Second and third are car B (90%) and car C (72%). An interesting point is the significant gap between car C and the two other cars.

The characteristic jerk values are shown for the same starting velocities in Figure 10. A considerable gap between car C and the other cars can be observed for both starting velocities, which correlates well with the *Overall Performance Assessment*. This suggests jerk having a stronger influence in this category than the acceleration, which is shown in Figure 11.

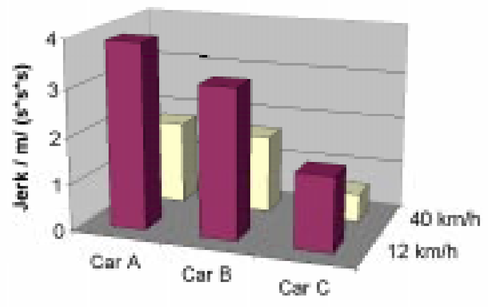

Figure 10: Maximum Jerk Values versus Vehicle Velocity for the three Test Vehicles

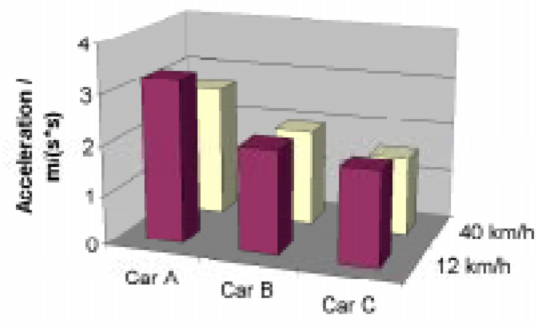

Figure 11: Maximum Acceleration Values versus Vehicle Velocity for the three Test Vehicles

Traffic Crawl: The third and last category presented is *Traffic Crawl*. The tests carried out for this category started at a velocity of around 12 km/h followed by slow accelerations with pedal position movements smaller than 30 per cent. The assessment by the drivers is given in Figure 12. Car A was assessed with 7.75. Car B achieved in this category its closest assessment to car A with a score that equals 98% compared to car A. Car C achieves a score of 91%.

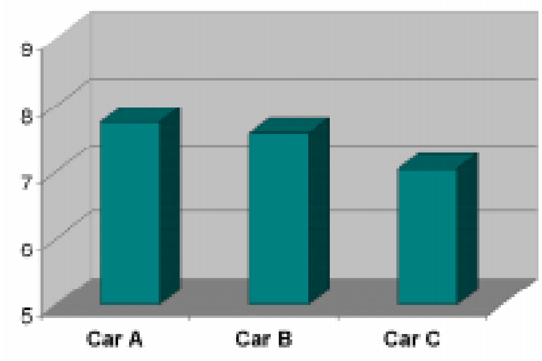

Figure 12: Overall Assessment of the Traffic Crawl by the Test Drivers

Two interesting details can be observed in Figure 12: Firstly, car C achieved - as the only car in any of the categories - a better assessment for *Traffic Crawl* than for *Overall Driveability Feel*. Secondly the gaps between the scores of the different cars are much smaller in this category than for all other categories.

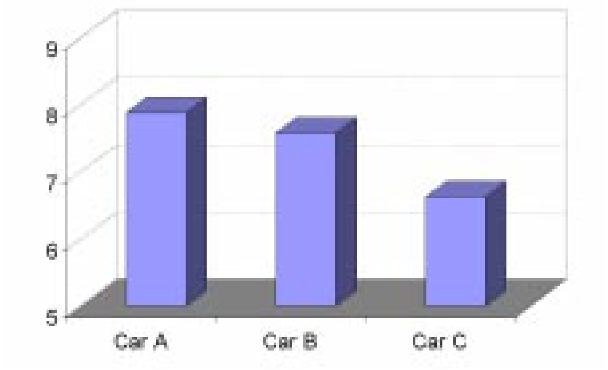

Figure 13: Assessment of the Smoothness of the three Vehicles

Figure 13 shows the assessment of the smoothness rather than the acceleration or jerk values. These show a much better correlation to the assessments during traffic crawl than the latter values.

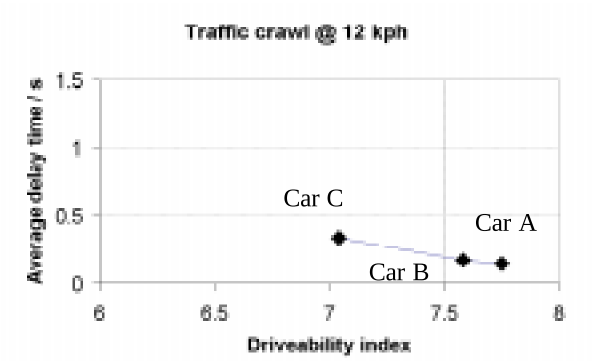

Figure 14: Average Delay Times versus the Driveability Index

The delay times for this category are shown in Figure 14. The delay times of the cars A and B are very similar whereas Car C has a much higher delay time. This indicates a good correlation to the subjective data shown in Figure 12. It seems in this particular driving situation - with small distances between vehicles – small delay times and smoothness are rather more important than the remaining driveability values. These lead to good controllability with the expectation that the car behaves smoothly and predictably.

3.3 Repeatability of the Results

The results presented above are all based on average values. However, the perception of individual persons varies and so does the behaviour of the vehicles even for similar operating conditions. This makes it necessary not only to assess average values but also to monitor the range and distribution of the data acquired. Figure 15a and 15b compares test results of the two cars B and C in the category *Launch Feel* by presenting the acceleration and jerk values of seven tests.

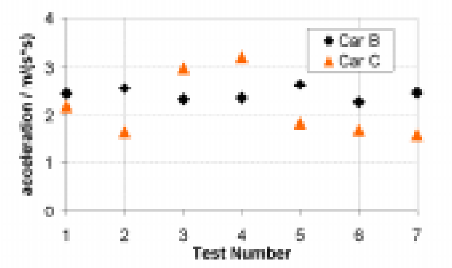

Figure 15a: Comparison of the Distribution of the Acceleration Values versus different Tests

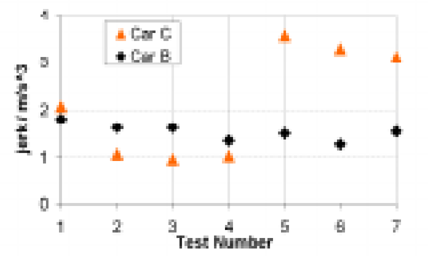

Figure 15b: Comparison of the Distribution of the Jerk Values versus different Tests

The acceleration values for car C vary between 1.62 and 3.25 m/s^2 whereas the acceleration values of car B vary only between 2.27 and 2.64 m/s^2. The jerk values, shown in Figure 15b, show a fairly good repeatability for car B with values between 1.26 and 1.79 m/s^3 compared to the results of car C, which vary between 0.96 and 3.56 m/s^3. This high distribution in the objective data leads to a high range in the driveability assessment and a low average assessment for car C.

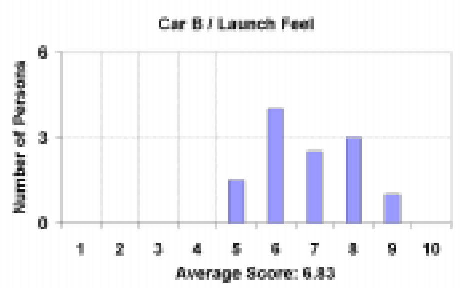

Figure 16a: Individual Assessment of car B by the Test Drivers

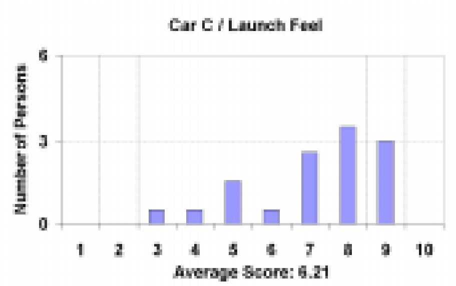

Figure 16b: Individual Assessment of the car C by the Test Drivers

The subjective ratings are illustrated in Figure 16a and 16b by means of bar charts. The assessment for car C has a very high distribution covering all scores between 3 and 9. Car B was rated more uniformly covering scores only between 5 and 9. Consequently, the average score of car C at 6.21 is significantly lower than the average score of car B (6.83) even though a number of drivers gave good ratings.

4. GENERAL DISCUSSION

The cars were rated very consistently with car A achieving the highest score in all categories. Car B and C came always second and third, with varying gaps between the scores. Possible reasons for car C coming last in all tests are the lowest power-to-weight ratio as well as the worst repeatability in the tests. However, it should be noted that the control strategy had not been optimised for operation with a Diesel powertrain. The relative difference in the assessment of car C compared to car A in *Overall Performance Feel* (72%) correlated well with their power-to-weight (71%) ratio. Car B was assessed better for the *Overall Performance Feel* (90%) than indicated by the power-to-weight distribution (86%). This shows that perception of the vehicle by the test drivers can differ from the actual power distribution of the car.

The importance of jerk: As already described in section 3.3 there is a lack in jerk of car B at launch from rest and this affects its subjective assessment negative. At higher velocities, the jerk values of car B improve relative to the other cars and so do the assessments for *Overall Driveability Feel* and *Overall Performance Feel*.

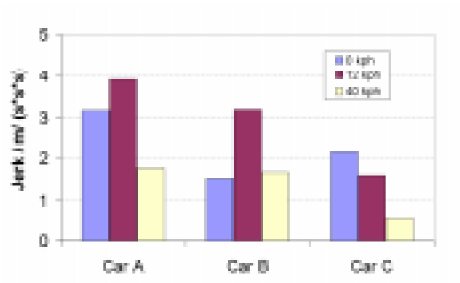

Figure 17: Jerk Values for maximum Pedal Position Movements at different Speeds

The significance of the jerk is supported by another argument: As can be seen in Figure 17, Car C is the only car with its highest jerk at zero speed and it is the only car with a better assessment for *Launch Feel* than for *Overall Performance Feel*.

Significance for further work: As part of a wider project, a novel control strategy was developed combining engine and transmission control. The results presented were biased towards emissions considerations lacking emphasis on driveability and two reasons were identified for this. Firstly, the controller was not tuneable. The influence of changing its strategy could therefore not be investigated. Secondly, the subjective data were average values given by the test drivers after having completed the full experimental program. Section 3.3 of this paper has shown the poor repeatability of the tests and this clearly shows the need to correlate subjective and objective data better by assessing each test individually. Both these aspects will be included in a follow-up project at the University of Bath.

5. CONCLUSIONS

Cars were assessed for *Overall Driveability Feel* and for three sub-groups: *Traffic Crawl*, *Overall Performance Feel* and *Launch Feel*. Comparing objective and subjective data allowed the following conclusions:

- Acceleration values and delay times showed better correlation than the jerk with the subjective assessment in *Launch Feel*.
- The most influential parameter during *Overall Performance Feel* was the jerk
- Delay times and smoothness showed the best correlation to the subjective assessment in *Traffic Crawl*
- It is important for the controller strategy to achieve good repeatability

This work was also used to plan future driveability studies. For this the following points are important:

- Subjective and objective data should be collected for the same events to eliminate scatter
- The application of a tuneable controller will make it possible to assess different control strategies

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