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Literature Review and OEM/Test House Interviews on Alternatives for Determining Demerits of Vehicle Performance

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A. Executive Summary

The goal of the Coordinating Research Council (CRC) Project No. CM-138-16-1, "Literature Review and OEM/Test House Interviews on Alternatives for Determining Demerits of Vehicle Performance" was to develop an understanding of current technology available to determine vehicle driveability performance demerits using alternatives to human trained evaluators.

The motivation for the study is that CRC has used trained raters for many years to assess vehicle driveability for test programs. An established program to develop trained raters does not exist and most of the currently trained raters are past normal retirement age. The CRC Board of Directors thus instructed the Performance Committee to seek out possible alternatives to human trained raters to measure vehicle performance and driveability.

In a first step, FEV conducted detailed literature research on this topic, utilizing public-domain information. The literature study reveals that extensive work has been conducted in the area of developing objective methods for driveability evaluations of different powertrain systems. Often, a specific driveability phenomenon such as shift shock, vehicle shuffle, etc., is described (in a given publication) and possible metrics for these attributes developed in the literature. With the increasing complexity of modern propulsion systems and stringent customer requirements for refined vehicles the need for using objective driveability metrics remains high.

Further, FEV developed a targeted questionnaire which was tailored towards understanding how driveability evaluations are currently being conducted in the industry. The questionnaire was reviewed with CRC prior to using it in discussions with industry experts. The questions were related to the general use of driveability tools, the importance of certain application areas, and the satisfaction of the end-user with the objective methods utilized.

The results show that the evaluation of driveability includes multiple aspects, with the transmission-related driveability as one of main focus areas amongst the interviewees. Most of the participants in this study (92.6 %) use a mix of objective and subjective evaluations and none of them rely solely on objective methods to meet the requirements for a production program.

Objective evaluation tools benefit from the large quantity of data around standard driveability maneuvers that can be analyzed and easily compared. Further, driveability results are generally more repeatable and not biased by subjective opinions. However,

objective tools are expensive and according to the interviewees objective evaluations take on average approximately four times longer than subjective evaluations (74 hours versus 18 hours). Further, it was stated that objective tools often only rate specific aspects and driving maneuvers, but currently do not give a full picture of overall vehicle performance. Correlation between subjective impressions and objective tools is very important for acceptance of the tools. In the end, subjective evaluations trump objective measurements, when the two ratings disagree.

During the questionnaire it was stated that not all possible driveability issues are currently covered by the existing tools. Therefore, further customization and improvement of the tools regarding items such as data management, detection of outliers, tool robustness, and tool consistency, will be required.

In summary, objective driveability tools are well-established in the industry and these tools support driveability evaluations with respect to improved repeatability and documentation of results. Further, they can be used in combination with optimization algorithms for achieving a satisfactory baseline vehicle calibration in reasonable time. Since all experts (interviewed as part of the survey) indicated that they do not rely solely on objective driveability tools, a combination of subjective evaluations and objective tools will continue to be utilized in the vehicle development process.

B. Introduction and Program Objectives

FEV was contracted by CRC (Coordinating Research Council) to develop a thorough literature review and understanding of current technology available for capabilities to determine vehicle driveability performance demerits using alternatives to human trained raters.

The motivation for the study is that CRC has used trained raters for many years to assess vehicle driveability for test programs. These test programs have often either tested the driveability of hot-start maneuvers or cold-start and warm-up maneuvers associated with fuel test programs. An established program to develop trained raters does currently not exist, and some off the currently trained raters are coming close to or beyond retirement age. The CRC Board of Directors has thus instructed the Performance Committee to seek out possible alternatives to human trained raters to measure vehicle performance. As part of this effort, the technology status of these methods needs to be understood and assessed in order to potentially develop an effective replacement for trained raters.

In this study, tools and methods for objective driveability ratings are evaluated via a literature search and survey of a cross-section of industry experts in the field of vehicle driveability evaluations.

A summary of the key project tasks and highlights of the key results are outlined in the following sections.

C. Technical Approach

The scope of this work was split in three phases. The first phase was a domestic and international literature search of published and publically presented information on current vehicle performance testing techniques. Focus of the literature research was on identifying current metrics and methods for determining and quantifying vehicle driveability and performance based on objective values and ratings as an alternative to subjective vehicle ratings. The following definitions have been applied to describe the difference between subjective and objective evaluations:

- Objective rating:
  - Not influenced by emotions, opinions or personal feelings
  - Based in fact, in quantifiable and measurable terms
- Subjective rating:
  - Based on personal feeling, emotion, aesthetics, and impressions
  - Open to interpretation

In the second phase of this study, a questionnaire was tailored towards understanding how driveability evaluations are currently being conducted in the industry. In addition, the survey was designed to obtain feedback from industry experts (who provided feedback on the condition of anonymity) on their experience (positive or negative) with objective rating methods for driveability.

The third and final phase of the study was a detailed analysis of the findings and development of this report to capture the literature study and interview results in order to give CRC an accurate assessment of the state-of-the-art in-vehicle driveability evaluation methods and options.

D. Literature Research

Early investigations into vehicle driveability began with a study of phenomena that characterize it, along with their causes and associated influences. As driveability began to obtain increasing importance as a factor that influences marketability of vehicles [1], test programs were conducted to evaluate it subjectively on the road, under specific driving maneuvers, with regard to its characterizing phenomena. With the inherent flaws of a subjective approach towards driveability evaluation becoming evident over the years, efforts were made to develop objective metrics and methods that reflect and correlate with its subjective perception. Consequently, research progressed to the quantification and automated optimization of such objective metrics, aided by the application of software tools and control methodologies to perform the same. In later years, analyses of the driveability performance of various classes of vehicles, such as electric and hybrid vehicles, commercial vehicles, motorcycles and Sports Utility Vehicles were made with the help of the objective metrics, methods and software tools developed for that purpose. In this text, a review of existing literature on driveability and its evaluation is made, focusing on the above-mentioned aspects.

One of the first definitions of driveability was provided by Everett [2]. Everett provided an objective measure to objectively quantify the surge phenomena with the help of an instrument developed specifically for that purpose – a "surgemeter". A correlation to subjective measurements of surge was also made and the effect of EGR (Exhaust Gas Recirculation) on surge was studied. It was also checked whether the surgemeter could be used towards quantification of idle roughness. In addition, Everett also provided a definition of terminology that are nowadays commonly used to describe driveability problems and descriptions of driveability test procedures including cold start and driveaway under warmed-up vehicle and hot weather operation.

These driveability problems or phenomena have been the subject of investigations in later years into driveability. Krenz [3] studied the clunk and shuffle phenomena at throttle tip-in and tip-out with the aid of experimental procedures. Factors that affect clunk (engine torque rise rate, driveline lash, driveline compliance) were identified. Design practices and actions to reduce clunk were also mentioned. Biermann et al. [4] studied clonk and shuffle phenomena in vehicles with the aid of drivetrain measurements, and developed physical models of the drivetrain to study clonk and shuffle. They also identified the conflict faced by vehicle manufacturers regarding the trade-off between agility of the vehicle and reduction of clonk and shuffle during throttle tip-in. Choi et al. [5] investigated shuffle at tip-in experimentally under specific tests (2nd and 3rd gear) in a vehicle. They also developed a simulation tool with a simplified model of the engine and drivetrain to investigate the effect of physical parameters such as friction, driving torque and inertia of drivetrain components on shuffle. Crowther et al. [6] developed a reduced dynamic simulation model of a vehicle powertrain including lash, stiffness, damping and inertia of powertrain components for an automatic transmission powertrain to explain the clunk phenomenon. With the help of this model, they identified factors that cause clunk such as the rigid body motion of the powertrain, low mean torque, axle modal response when braking, etc. Crowther et al. [7] investigated clunk in an automatic transmission powertrain with multiple clearances. A detailed model of an automatic transmission powertrain system was simulated under a typical driving situation. It was observed that only transient loads affect clunk and not pulsating torque from the engine. This was also verified with experiments on a driveline test rig. Gurm et al. [8] developed a lumped parameter torsional model, used it to study the effect of lash on clunk at different load conditions, and validated it using load tests on a driveline test rig. They investigated clunk further using tip-out tests performed on the rig. Yonekawa et al. [9] developed a model of a Diesel engine powertrain including an engine control system to analyze the undamped fore-aft vibration of a vehicle. This model was used to perform a study on powertrain and engine control parameters that influence the fore-aft vibration. It was identified that the influence of injection system characteristics was particularly significant.

With ever-increasing investigations into vehicle behavior, particularly handling, arose the need to standardize test procedures to evaluate the same. This was noted by Rönitz [10], who, while identifying the challenges facing standardization of test procedures, provided a collective overview of work directed towards standardization over the previous 15 years.

Driveability test programs on the road, conducted by the CRC since the 1980s at various ambient temperature conditions, detailed in [11], [12], [13] and [14], performed a subjective study on the influence of fuel parameters such as fuel type, volatility, oxygen content and co-solvent (Ethanol or gasoline grade tert-butyl alcohol) percentage on the driveability of vehicles of different engine and powertrain types. Driveability was subjectively rated for malfunctions such as start time, stall, idle roughness, hesitation, stumble, surge and backfire during idle and during different driving maneuvers and these ratings were used to arrive at a TWD (Total Weighted Demerits) score. Thornton et al. [15] described the analysis and results of CRC driveability tests on four HEVs (Hybrid Electric Vehicle) for different fuels and fuel properties. The tests showed that HEVs responded to variation in fuel properties in a manner similar to that of conventional vehicles. The authors also identified the need to develop new driveability test procedures for HEVs noting that the existing CRC cold-start and warm-up test procedures do not account for their “unique driving characteristics”.

From the mid-1990s till the late 2000s the identification of objective metrics and development of objective methods used to characterize driveability in different powertrain systems were extensively carried out. Dorey et al. [16] provided an overview of methods used to characterize vehicle driveability objectively. They identified test conditions such as start, idle, pedal response, full load performance, etc. and considerations to be objectively characterized such as delay, stumble, oscillations, overshoot, prolonging of responses, hunting, and roughness. The analysis and characterization of tip-in/back-out driveability characteristics was provided as an example, and a vehicle model was developed to analyze driveability. Dorey et al. [17] described the functionality of tools that assist in the calibration of vehicle driveability through instrumentation, data acquisition, processing, and analysis. Examples were shown for evaluation of objective metrics, noted in [16], of start, engine idle response and tip-in/back-out responses in the tools and their corresponding correlation with the subjective ratings of the above-mentioned operating conditions.

Wicke et al. [18] investigated the driveability of three CVT (Continuously Variable Transmission) vehicles under the categories: Launch Feel, Overall Performance Feel and Traffic Crawl. The engine speed, vehicle speed, acceleration, and pedal position were obtained during an acceleration maneuver and the categories listed above were rated based on objective data such as acceleration, jerk, delay times, and smoothness. These objective data were then compared with subjective evaluations of the acceleration maneuver for the three vehicles to identify the important objective data that had the most influence in each category. The influential objective data in each category were then used in [19] to obtain requirements for a simulation program using vehicle, powertrain and driver models that predicts driveability with respect to Launch Feel and Performance Feel. Wei et al. [20] provided some objective metrics such as Sound Intensity to quantify interior noise level, RMS (Root Mean Square) and VDV (Vibration Dose Value) of acceleration, MTVV (Maximum Transient Vibration Value) and tip-in/tip-out acceleration profile for evaluating driveability problems such as hesitation, sluggishness, hard start, surge, idle roughness/instability, noise, and oscillations. The relationship between subjective evaluations of driving maneuvers and corresponding objective metrics was also observed. Giacomin et al. [21] investigated experimentally the subjective perception of vibration by seated subjects for test signals that mimic typical road inputs. This was correlated with objective data relating to the test signals which were the frequency weighted RMS level and the VDV. The need of a frequency weighting filter to obtain a good correlation was also noted.

Shift quality is an important aspect of driveability and objective metrics to evaluate the same have also been researched extensively. Anderson et al. [22] examined the applicability of jerk as an objective metric to evaluate shift quality. A device named the “Jerkmeter” was constructed to measure jerk and the data obtained from it was used to characterize a shift. Experiments were conducted on the road with test subjects to evaluate shift and the maximum jerk measured during a shift was compared with the subjective evaluation of the shift. A significant correlation between the two was obtained. In addition, Jerkmeter data was also used to investigate the effect of automatic transmission fluid properties on jerk. Schwab [23] developed a shift quality metric for an automatic transmission using the vehicle’s fore-aft acceleration using four of its components: peak-to-peak amplitude, peak-to-peak jerk, maximum average power and 10 to 14 Hz frequency content. Subjective testing on vehicles was performed with various drivers for different shift maneuvers. The four components were then mapped to the subjective ratings using linear regression and nonlinear neural network modelling to design a predictive tool for shift quality rating. Horste [24] examined the applicability of

VDV on fore-aft acceleration as a shift quality metric and validated the same with respect to subjective evaluations of driving maneuvers in different vehicles using the metrics "correlation" and "F-Ratio". It was observed that, barring a few exceptions, the subjective-to-objective correlation was above 95%. Sorniotti et al. [25] proposed the following qualitative parameters to evaluate shift comfort: AD (Acceleration Discontinuity), AH (Acceleration Hole) and UP (Upshift Sportivity) based on physical parameters of the vehicle obtained during a driving maneuver such as vehicle acceleration, engine speed/torque, pitch angle, etc. Subjective evaluations were carried out on an AMT (Automated Manual Transmission) gearbox and correlated with the objective parameters. A vehicle and driveline model was implemented to simulate gearshift and validated using experimental results.

With major objective metrics that characterize driveability having been identified in previous work, the focus subsequently shifted towards their quantization and automated optimization. In [1], [26], Schöggl et al. provided an approach for the objective and real time evaluation of vehicle driveability. Typical driveability criteria such as shuffle, jerk, kick, hesitation, oscillations and overshoots were identified under global operating modes of a vehicle such as idle, engine start, throttle response, warm up behavior, gear change, etc. Engine and vehicle data corresponding to these criteria were obtained and used for driveability calculation within a neural network system, with subjective assessments used for assigning weights to train the network with generic algorithms. An overall driveability rating was subsequently arrived at and was correlated to the subjective assessment. This approach was used for application in a dynamic test bed – a combination of hardware and simulation models of the vehicle powertrain system – to obtain real time driveability ratings. This enabled automated calibration of ECUs (Electronic Control Units) on a test bench for defined driveability related target parameters, reducing duration of calibration for driveability. In [27], as an example, functions for anti-jerk and transient torque were optimized by varying function parameters such as damping and filter constant with respect to a tip-in, with kick, jerk and response delay being the target parameters, to obtain a new transient torque control map. In a subsequent development, the virtual pre-optimization of vehicle and powertrain parameters before their application in vehicle hardware was treated in [28] with the aid of a co-simulation methodology using vehicle and drivetrain models, an evaluation tool and an optimization tool in a calculation loop, to achieve pre-defined target parameters.

Walters et al. [29] describe an "analysis-based co-simulation methodology" for prediction of driveability using simulation of powertrain models and objective driveability evaluation tools. The simulation and corresponding driveability evaluation of a particular vehicle were then compared to measured signals and subjective driveability ratings from an experimentally tested vehicle for negative torque tip-in and constant speed tip-out conditions. Parameter studies of the driveline and the engine were performed on the models, and the simulation results were compared with the test data. It was observed that further improvements were needed to be made to the model to obtain a better correlation between simulation results and test scores. Liu et al. [30] proposed the Fuzzy Hierarchy quantization method based on Analysis Hierarchy Process and Fuzzy comprehensive method in a closed loop control system of the vehicle for the evaluation of objective indices of driveability such as duration, maximum acceleration, VDV, response delay, etc. under different operating conditions such as driveaway, acceleration response, transient performance, steady-state performance, ride comfort, etc.

Accurate and repeatable measurements are necessary to obtain reliable driveability relevant metrics. Brol et al. [31] analyzed the applicability of an acceleration measurement made using a two-axis accelerometer mounted on a car body with respect to influences of sensor accuracy, accelerometer and working engine related noises, coordinate system reorientation during instantaneous acceleration or braking and road disturbances. They suggested the measurement of engine speed, suspension reaction characteristics, and pitch angle as well as filtering of the acceleration signal to compensate for these influences.

In later work, investigations into the suitability of a roller test bench to perform driveability assessments were also made. Nehlsen et al. [32] addressed the potential of and the challenges facing objective driveability evaluation on a roller test bench, taking into account the possibility of accurate reproduction of road inputs with control concepts for the same. A model-based approach to evaluate driveability objectively with the aid of DoE (Design of Experiment) on a roller test bench was also detailed by Vögl et al. [33]. Albers et al. [34] used the roller test bench as a platform to study the influence of low frequency vibrations of the powertrain on driveability assessments of a vehicle with the aid of a laser scanning vibrometer.

Consequential to work being carried out on the development and evaluation of objective metrics for driveability was their optimization with the aid of control algorithms. Mo et al. [35] propose an active driveability control algorithm to reduce shuffle, based on a linearized powertrain model of a vehicle. The algorithm was simulated under tip-in/tip-out and improvements in the shuffle were recognized. Balfour et al. [36] presented a “model-based” controls approach using neo-classical control design techniques to address the problem of shunt in a vehicle using a reduced order model of the vehicle driveline. The controller was implemented in a vehicle and tested, and was found to be effective in suppressing “undesirable driveline oscillations following step fuel changes”. Baumann et al. [37] presented a robust $H\infty$ controller for anti-jerk control in a Diesel engine. Vehicle tests were made and it was observed that drivetrain oscillations were significantly reduced. Schacht et al. [38] detailed an ECMS (Equivalent Consumption Minimization Strategy) algorithm used in a vehicle control strategy in an extended range electric vehicle, and explained how driveability concerns were addressed in the algorithm, with the aid of a reward function for driveability to hold the system at a stable operating point until a significantly more efficient operating point is reached. Serrarens et al. [39] analyzed the improvement potential that could be obtained in terms of driveability by the usage of a "k (Zero-Inertia) Powertrain" in a vehicle equipped with a CVT. A powertrain controller was designed for a defined driveability response and fuel economy of the vehicle and was tested with powertrain models of a CVT, ZI and an Automatic Transmission vehicle. For two types of experiments "pedal-jogging" and "kickdown", the response of the control system was observed. It was shown that the response of the ZI powertrain was superior to that of the CVT powertrain.

Since the late 2000's, multiple studies have been made to evaluate driveability of different vehicle types – from motorcycles to passenger cars and commercial vehicles based on objective metrics and methodologies obtained in previous work. Zhang et al. [40] studied jerk and identified factors affecting the same in Hybrid Electric Vehicles under different operating modes and during mode switching in the HEV powertrain. It was observed that the management of the HEV powertrain should be optimized to improve driveability. Galvagno et al. [41] analyzed the driveability of a parallel HEV, with an IC engine powering the front axle and an electric motor the rear axle, during tip-in under the condition of constant gear ratios on both axles. A linearized model of the hybrid powertrain was used for simulation, and low frequency response of the HEV was compared with that of a conventional FWD (Front Wheel Drive) vehicle. Shin et al. [42] proposed a quantitative method for driveability evaluation of heavy duty vehicles using driveability indices obtained from previous studies on driveability correlated with subjective assessments under various driving conditions. Falk et al. [43] identified the driveability requirements of motorcycles as well as phenomena unique to them – aliasing effects and high noise level – during measurement of signals necessary for driveability evaluation. They then proposed the evaluation of driveability of motorcycles on a driveability evaluation tool with respect to defined targets. Jayaraman et al. [44] described an objective methodology adopted for the closed-loop optimization of tip-in response of a SUV (Sports Utility Vehicle) using a reference filter that controls and modulates transient torque. Lakshmanan et al. [45] described a methodology for the subjective and objective evaluation of driveability in commercial vehicles under nine major criteria such as start-ability, idle quality, launch-ability, driven idle quality, manoeuvrability, gear shifts, acceleration, gradeability, and throttle pedal response. Stoica et al. [46] investigated driveability in an electric vehicle with the aid of electric vehicle powertrain models. The models were simulated for throttle tip-in response to identify the appropriate model for application in driveability studies.

E. Industry Expert Survey

As obvious from the literature research (Section C), the topic of driveability is very complex. Studies described in the literature are often limited to a specific driveability phenomenon, driving maneuver or vehicle type.

For evaluating how tools and methods for objective driveability evaluations are utilized in the industry, a targeted questionnaire was developed by FEV and reviewed with CRC. Specifically, the questionnaire was tailored towards answering questions such as the following:

- How common are objective driveability tools in the industry?
- What's the effort (time, measurement channels, etc.) involved in obtaining relevant objective data?
- What applications are driving the use of objective driveability tools?
- How well do the tools perform for given maneuvers and driveability aspects?

On the condition of respecting confidentiality and maintaining anonymity, FEV approached individual experts from various industries including: domestic and transplant automotive OEM, suppliers, engineering consultancies, companies in the off-highway and heavy-duty areas, and research organizations.

It was agreed that both the individual as well as his/her affiliation would remain anonymous, so that un-biased input could be obtained. Furthermore, the participation in the survey was sought on a voluntary basis. Several individuals approached for this questionnaire declined to participate on grounds of not wanting to divulge company-specific processes. In addition, participants who engaged in the survey were given the option of not answering any questions that they did not feel comfortable answering (e.g., due to concerns of confidentiality).

The questionnaire itself was developed as a web-based survey. FEV scheduled individual web meetings with the individuals for the survey. Occasionally, more than one person of a company participated in the initial web-based meeting. Within the web meeting, the background of the study was provided and the questionnaire reviewed with the participants. Specific questions regarding individual aspects of the survey were answered and clarifications provided, if needed. These interviews took about 30-60 minutes each, depending on the amount of clarification needed.

Following the review of the survey, each participant was asked to fill out the survey offline at a time of their convenience. The goal was to allow everyone sufficient time to fill out the survey and add comments, as applicable. In total, FEV identified 27 individuals that participated in this study. The initial goal of the study was to interview up to 20 candidates. With the additional voices in the study, FEV believes to have a statistically relevant sample and was able to cover interviews with a wide cross-section of driveability evaluation experts across multiple industries.

E.1 Questionnaire

The questionnaire used in the survey was developed by FEV and vetted/authorized by CRC members for use in this study.

The survey included single-choice, multiple-choice, and open-ended questions about subjective and objective methodologies to evaluate driveability. The questions were about the general use of the different tools, how important certain aspect and application areas were for the user, and how the user would rate them with respect to their satisfaction with the utilized objective method. All questions offered a text field to add any comments or further explanations, if this was needed or desired to provide additional clarification.

Details of the individual questions (in chronological order) are provided together with key results in the following subsections.

E.1.1 Utilization of Driveability Tools

This section provides an overview regarding relevant participant demographics with respect to industry, background, and their individual focus for driveability evaluations. Further, an overview about objective driveability methods, tools, as well as the amount of time/effort the participant/department spends on driveability evaluations is discussed. **Figure E.1.1-1** gives a high-level breakdown of the survey participants with respect to their occupation. In order to get a wide cross-section of driveability experts FEV sought out key individuals in different industries and industry-segments. In this plot, engineering consultancies and universities are combined in the University/Research category.

For the data analysis of the survey, each question of the questionnaire is listed in the upcoming figures. In addition, key results are included as comments in the tables on each figure (or on additional pages, as appropriate).

Figure E.1.1-2 highlights the main focus area of driveability for the individual participant. This chart is an example of how multiple choice questions were evaluated. Additional key comments/clarifications that were made for the question shown in Figure E.1.1-2 are illustrated in **Figure E.1.1-3**.

Figures E.1.1-4 through E.1.1-6 show results from responses to questions on the use of subjective vs. objective methodologies to rate driveability. Further, 'pros' and 'cons' for objective and subjective driveability evaluations are listed. Interestingly, none of the participants surveyed rely solely on objective evaluations. The large majority (~92%) utilize both subjective and objective methods.

More than half of the participants utilize commercially available driveability tools (instead of relying on in-house metrics), see **Figure E.1.1-7**. **Figure E.1.1-8** lists the commercially available tools, as well as software tools / packages that are utilized for programming and evaluating the in-house metrics. Some of the software packages used in combination with in-house metrics are designed for specific applications (e.g., LMS Test.Lab or Head Acoustics for NVH (Noise, Vibration and Harshness) related measurements and analysis), while other tools are very universal (such as Matlab, Simulink or Excel). **Figures E.1.1-9 and E.1.1-10** provide comments provided by the surveyed experts who used commercially available driveability tools and/or utilized additional in-house metrics.

The next question attempted to assess how long a given expert/organization was using the current toolset and the results are summarized in **Figure E.1.1-11**. In addition to the mean value (in this case years of utilization) the span of all answers is shown. Further, the width of the standard deviation (-0.5 σ to + 0.5 σ) is also indicated in order to give an impression of the spread in the response to this question. Participants that use the tools for relatively long times (in particular 10+ years) state that these methods have continuously been improved and modified over time, even if the basic tool name and purpose remained the same.

The effort in estimated engineering hours for an objective evaluation is shown in **Figure E.1.1-12**. Specifically, the effort is broken up into three parts: vehicle instrumentation, data acquisition, and data processing. Additional comments are given in **Figure E.1.1-13**. The estimated time shows high spread; there are two main reasons causing this. First, the level of instrumentation can differ significantly depending on the application and level of detail. Further, while OEM's utilize CAN-based (Controller Area Network) measurement systems and have knowledge of the corresponding CAN information, competitive vehicle benchmarking projects have a higher level of complexity of instrumentation. Secondly, as focus of the driveability studies can differ, the test matrix of driving maneuvers are correspondingly different. Accordingly, the time spent for data acquisition and post processing will vary. **Figure E.1.1-14** shows the effort in engineering hours for typical subjective evaluations. Depending on the level of evaluations and number of evaluators involved, there is a wide spread in the effort involved for subjective evaluations. On average, objective evaluation require approximately 74 hours for all three phases of the testing (Instrumentation, data acquisition, and data processing) compared to only 18 hours for subjective evaluation.

Figure E.1.1-15 summarizes how many vehicles the participant evaluates on average per year. The spread in the number of vehicles evaluated per year is high because some engineers in the survey exclusively work on driveability evaluations and therefore evaluate many vehicles while others evaluate driveability part time, so they only evaluate a few vehicles. Further, some participants gave the evaluation for their entire department as several engineers (within the department) were working on the same topics. Generally, the amount of variants and calibration levels in vehicle development shows the importance of driveability aspects for the manufacturers. **Figure E.1.1-16** provides the main additional comments in response to the question of engineering effort expended for driveability studies.

E.1.2 Driveability Tools Evaluations

This section discusses several individual criteria of driveability evaluation tools.

An overall level of satisfaction with respect to correlation between the objective metrics and the subjective ratings is shown in **Figure E.1.2-1**; additional comments are provided in **Figure E.1.2-2**. Details for individual criteria of the utilized driveability tools are given in **Figure E.1.2-3** in form of a spider chart. This chart includes lines for both the average on how important the evaluators rated the given criteria, and how they would rate the utilized driveability tools. Interestingly, both lines in the spider chart show a similar shape, criteria which are rated as being more important also show a higher rating by the interviewee. The spreads of standard deviation are given in **Figures E.1.2-4 and E.1.2-5**. Additional comments are provided in **Figures E.1.2-6 and E.1.2-7**.

Details about applications where the driveability evaluations are currently utilized are given in **Figure E.1.2.8** for the different powertrain (propulsion) options. Similarly, **Figure E.1.2-9** lists the transmission types which are evaluated and **Figure E.1.2-10** the vehicle types. Multiple answers were possible for these questions.

The questionnaire included a list of numerous possible driving maneuvers and situations that can be rated regarding driveability. The interviewees rated again how important these situations are to them, and how they would rate the utilized tool for evaluating them. **Figure E.1.2-11** gives the overview for these points, **Figures E.1.2-12 and E.1.2-13** show the average results for importance and rating, including the σ-spread. Additional comments that were made during the interviews are given in **Figure E.1.2-14**.

Figure E.1.2-15 gives an overview on the level and detail of instrumentation required for objective driveability studies. Obviously, this is very dependent on the application and focus of the evaluation. The question was formulated to exclude signals that were directly obtained from vehicle CAN bus to get an idea of the discrete instrumentation that the interviewees require for the evaluations. Interestingly, 26% of all participants did not answer this question. Sensors that are commonly recorded are listed in **Figure E.1.2-16**. It should be noted that this list is only an extraction of measurement signals that might be used for driveability evaluation. Also here, this is dependent on the focus of the study. Please also note that this list is only a snapshot showing some of the common signals; other measurement signals are often added depending on the application and level of detail of the study. **Figure E.1.2-17** provides insights into the test facilities used for conducting driveability evaluations. **Figure E.1.2-18** includes additional comments regarding the measurement channels and road conditions for objective driveability studies.

Some of the metrics utilized in objective evaluations are shown in **Figure E.1.2-19**. As this is a sensitive topic for companies due to confidentiality and IP concerns, feedback of the interviewees for this question was rather generic, if answered at all. In addition to this figure, the information of the literature survey (Section C) includes some more details on data analysis for specific driveability areas.

The importance and actual rating of the utilized driveability tools with respect to data management and handling are shown in **Figures E.1.2-20 through E.1.2-22**. For all discussed criteria there is about a one point gap between importance (of a given aspect) and actual rating of the utilized tool, suggesting room for improvement.

For adding further background information of the test conditions, **Figures E.1.2-23 and E.1.2-24** reveal what environmental boundary conditions such as weather are normally taken into account when conducting objective driveability evaluations.

As driveability rating evaluations are a continuous process during calibration of vehicles and powertrains, it is desirable to have an automated optimization tool for driveability in vehicle development. For completeness of this study, **Figure E.1.2-25 and E.1.2-26** show how the interviewees stated if they have such an optimization tool available, and if they use it. About 75% of the interviewees state that they do not have such an optimization algorithm, do not have the corresponding license, or are not aware that they could have access to this. 50% of the experts that have access to an optimization tool are using it; hence the overall usage of this feature lies at around 12.5% of the participants surveyed.

E.1.3 Improvement Potential for Driveability Tools

As part of the industry survey the participants were asked what improvement of the current objective driveability tool/method they would like to see, and what additional features would be desirable. The results are shown in **Figures E.1.3.-1 and E.1.3.-2**. Main areas for improvement can be summarized as:

- Increased level of consistency
- Improvement in finding "outliers" and rejection of corresponding test-runs
- Enhancement with respect to "user-friendliness", documentation, and tutorials

The overall satisfaction level of the optimization tool was the final question in this survey, see **Figure E.1.3-3**. As this question could be a little misleading at the end of the survey, **Figure E.1.3-4** compares the result of this question with Question #6, which was related to the overall satisfaction of the correlation between objective and subjective ratings. As Figure E.1.3-4 shows, answers are very similar/consistent, so this can be rated as the overall satisfaction of the driveability tool.

F. Summary and Recommendations

As the literature survey reveals, investigation and development of objective driveability phenomena began in the 1970's. Often, specific driveability phenomena such as shift shock, vehicle shuffle, etc., are described and metrics for these were developed. From the mid-1990's till the late 2000's the identification of objective metrics and development of objective methods used to characterize driveability in different powertrain systems were extensively carried out. With the increasing complexity of modern propulsion systems and customer requirements for refined vehicles the need for an objective evaluation remains high.

The results of the questionnaire show that the evaluation of driveability includes many different aspects, with transmission-related driveability as a main focus amongst the interviewees. Most of the participants in this study (92.6 %) use a mix of objective and subjective evaluations and no one used only objective methods. Each methodology revealed its own advantages and disadvantages. Subjective evaluation is faster and the total vehicle performance is rated. Objective evaluation tools benefit from the large quantity of data around standard driveability maneuvers that can be analyzed and easily compared. Nevertheless, subjective trumps objective, when the two ratings disagree. Further, it was stated that objective tools often only rate specific aspects and driving maneuvers, but currently do not provide a full picture of overall vehicle performance.

During the interview, concerns with respect to driveability were raised regarding the objective tools. The main areas of concern were:

- Non-standard driving maneuvers can get missed or eventually not evaluated properly with the objective tools
- Objective driveability evaluation on average takes four times longer than subjective evaluation (74 vs. 18 hours)
- Cost of tools
- Some items can only be effectively evaluated subjectively / total vehicle subjective impression is not rated
- Correlation between subjective impression and objective tools is very important for acceptance of the tools

Due to these concerns with objective driveability tools, none of the participants rely solely on objective tools as their measure of vehicle evaluation. However, the large majority of the interviewees stating that they utilize both objective and subjective measures for driveability evaluation shows that objective tools and metrics are commonly utilized for driveability ratings. The key benefits of objective tools were listed as:

- Allows for analysis of large quantities of data around standard driveability maneuvers and hence, improved comparisons between vehicles
- Automation of driveability evaluations
- Repeatability and consistency, especially for cases where a long period of time elapses between vehicle tests
- Documentation and validation
- Removal of “varying personal opinions” (subjectivity)

In particular during vehicle development and calibration, objective tools have become vital as the level of calibration and complexity has become too large for subjective evaluations alone. For any calibration change repeatable feedback on how the change affects driveability can be rated and documented with an objective tool. Further, objective tools can allow for development of a baseline calibration early in the development phase of new powertrains. Optimization tools can be enabled as an efficient way to support powertrain calibration, although based on the results of this study, only a small group of users currently utilize these features.

Based on this study, a variety of different driving maneuvers and operating modes are being rated with objective tools. The focus of the evaluations can differ depending on the goals of specific activities. Shift quality and transmission development seem to be the most common area for use of objective driveability evaluation tools. The effort of the objective evaluation (in engineering hours) can vary over a wide range. This is very dependent on the focus and interest of the executed evaluation, level of instrumentation, number of driving maneuvers, etc. A small "fingerprint" as an evaluation will require less effort than a full study or calibration development and sign-off for production.

This study revealed that objective driveability evaluation is utilized in a broad variety of industries, as well as propulsion systems, such as different engines, transmission types or (hybrid) electric vehicles. While all these technologies can be evaluated objectively, there might be a need for further customization of the driveability tools towards these technologies. It was also stated that not all possible driveability issues are currently covered with the existing tools. Based on suggestions of the interviewees of the questionnaire, further improvement of the driveability tools is desired in the following areas:

- "User-friendliness" and documentation
- Detection of outliers
- Data management
- Metrics for specific driving maneuvers, load cases, and powertrains
- Tool robustness and consistency

While objective driveability tools are well-established in the industry, at the current state these tools support driveability evaluations with respect to repeatability and documentation of results. It should be noted that none of the participants in the questionnaire utilized a combustion analyzer for routinely performed driveability evaluations. While some conditions such as idle roughness or idle stability can be objectively rated with such a system, e.g., via a stability index, the instrumentation effort of in-cylinder pressure measurements justifies the use of such systems in relatively few situations.

Further, they can be used in combination with optimization algorithms for achieving a satisfactory baseline calibration in a reasonable time. However, the last "fine-tuning" of driveability evaluation is still expected to remain on a subjective level, but supported with objective tools. None of the participants in the study are currently performing driveability evaluations solely using objective measurements. Based on the findings of this study, FEV's recommendation to CRC is to introduce objective metrics and test methods for driveability and define a process for combining objective tools and subjective evaluations to meet the needs of a given program.

G. List of Abbreviations and Definitions

AD	Acceleration Discontinuity
AH	Acceleration Hole
AMT	Automated Manual Transmission
CAN	Controller Area Network
CRC	Coordinating Research Council
CVT	Continuously Variable Transmission
DCT	Dual Clutch Transmission
DoE	Design of Experiment
ECMS	Equivalent Consumption Minimization Strategy
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
FWD	Front Wheel Drive
HEV	Hybrid Electric Vehicle
IC	Internal Combustion
LFP	Low Frequency Percentage
MTVV	Maximum Transient Vibration Value
NVH	Noise, Vibration, and Harshness
RMS	Root Mean Square
SUV	Sports Utility Vehicle
TWD	Total Weighted Demerits
US	Upshift Sportivity
VDV	Vibration Dose Value
ZI	Zero Inertia

Objective
- Not influenced by emotions, opinions or personal feelings
- Based in fact, in quantifiable and measurable terms

Subjective
- Based on personal feeling, emotion, aesthetics, and impressions
- Open to interpretation

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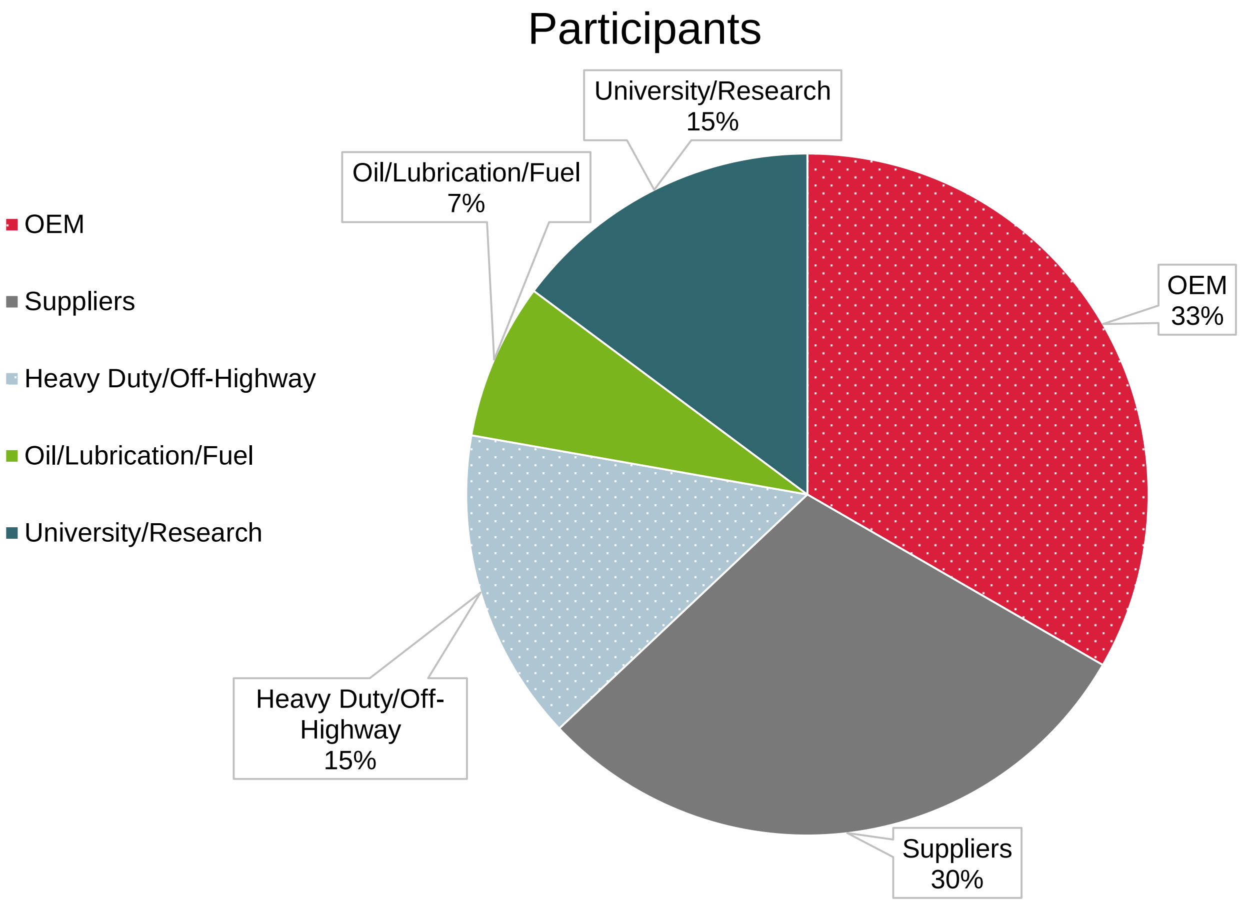
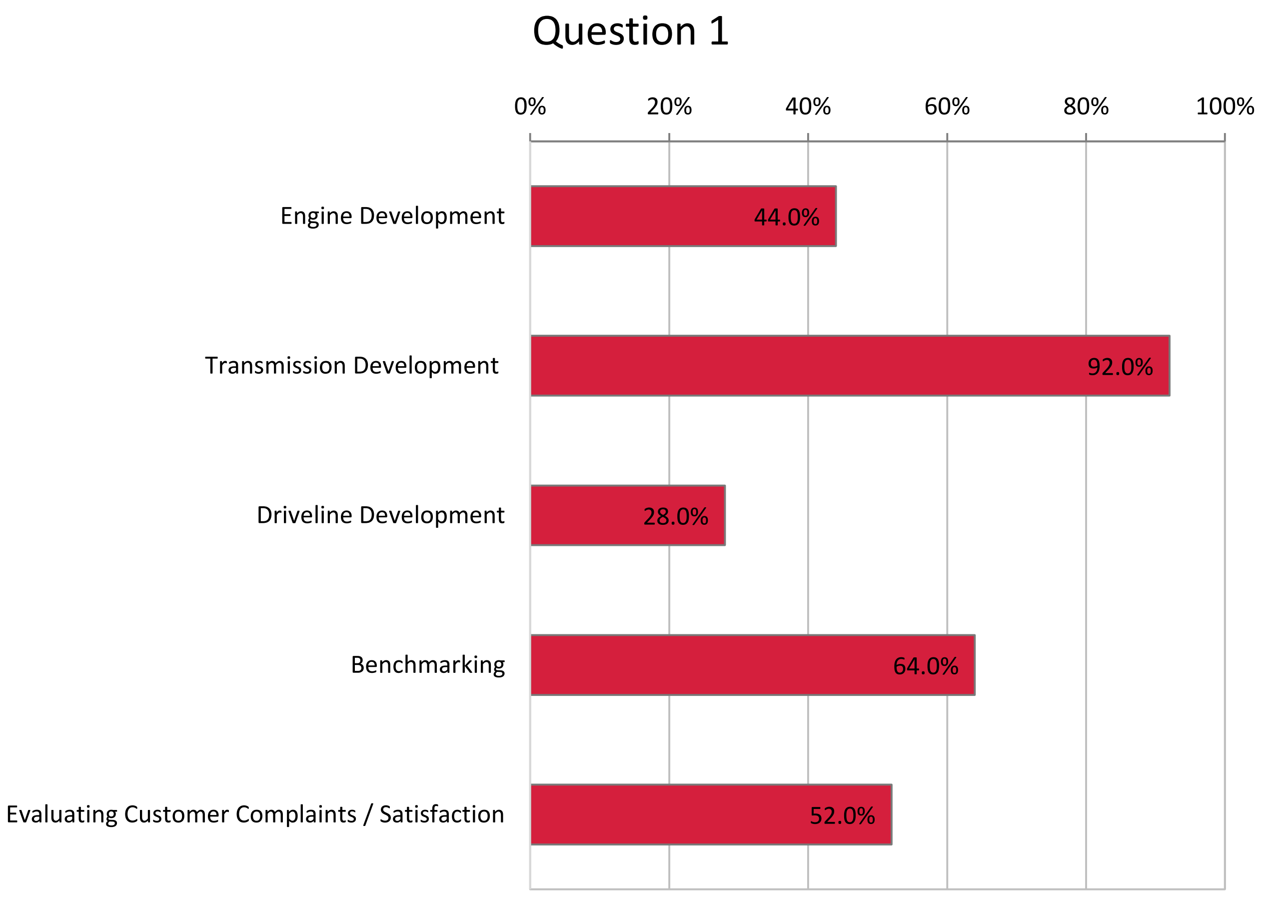
Result of Questionnaire



Participants
▪ Total amount of participants: 27

Figure E.1.1-1

Result of Questionnaire



Question 1

- What is your main focus for evaluating driveability?
- FEV-Comment:
  - Multiple answers were possible
  - Significant focus from many participants was on Transmission Development

Answered by 25 out of 27 participants

Figure E.1.1-2

Result of Questionnaire

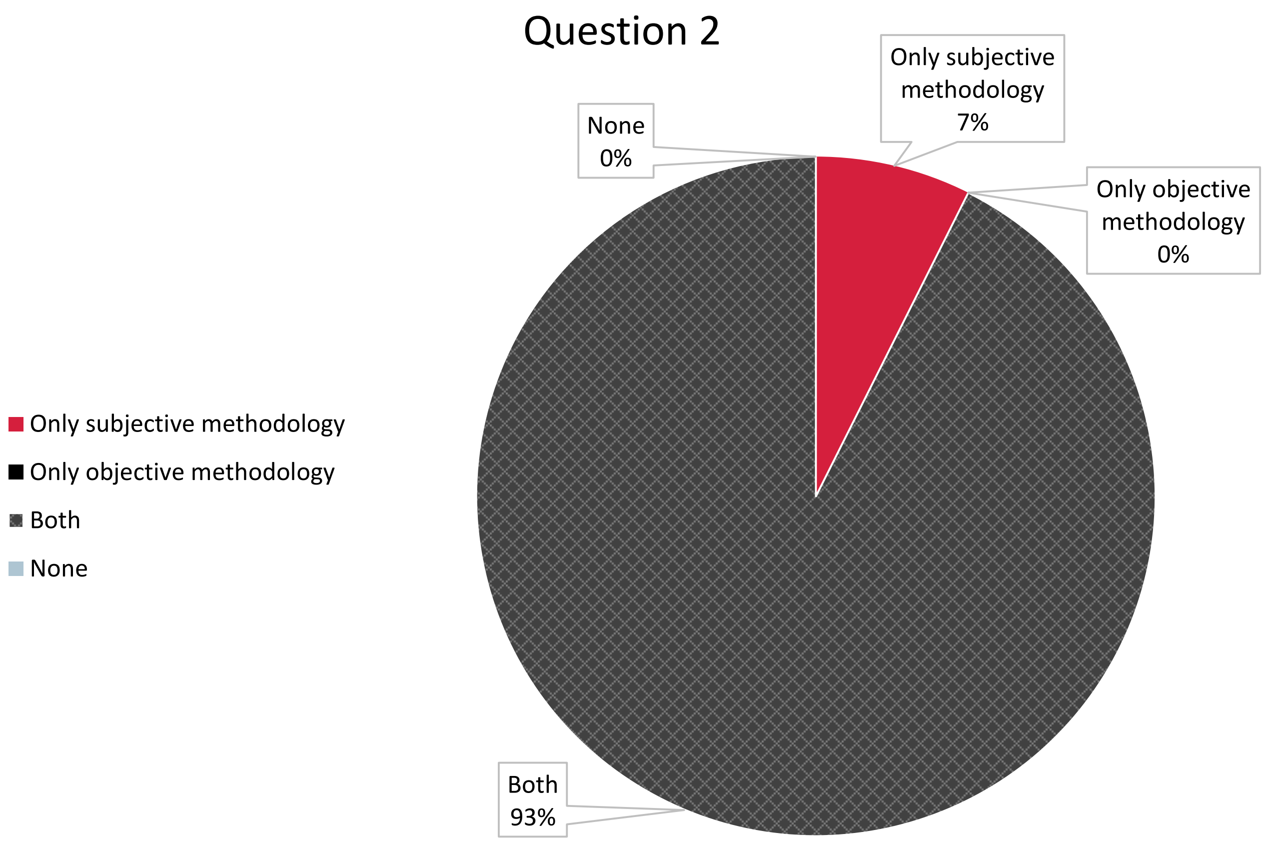
- Focus on:
  - Automatic transmissions: planetary and dual clutch
  - Clutch-to-clutch shift events / shift quality
  - Hybrid and electric drive units
  - Torque converter clutch transients
  - Driveline torsional vibration
  - Noise and vibration
  - Chassis and suspension
  - Fuel development

Question 1a

- Comments on the focus of driveability
- FEV-Comment:
  - The focus of driveability includes various technical areas, depending on company and engineering roles of the participants in this study

Figure E.1.1-3

Result of Questionnaire



Question 2

- Are you using a subjective or objective methodology (or both)?
- FEV-Comment:
  - Most participants use both objective and subjective methodologies
  - No one is utilizing only objective methods w/o subjective evaluations

Answered by 27 out of 27 participants

Figure E.1.1-4

Result of Questionnaire

FEV

- Subjective evaluations
  - Enables to capture non-standard driving maneuvers and areas that current objective tools can miss
  - Often required/requested by customer (OEM)
  - Some items/issues can only be effectively evaluated subjectively
  - Time (faster than objective evaluation)
  - Cost of tools to objectively measure driveability
  - Total vehicle performance can be rated
- Objective evaluations
  - Allows for analysis of large quantities of data around standard driveability maneuvers and better for comparisons
  - Automation of driveability evaluation
  - Repeatability and consistency
  - Documentation and validation
  - Avoid varying personal opinions

Description 2a

- What factors lead you to choose subjective, objective or both?

Figure E.1.1-5

Result of Questionnaire

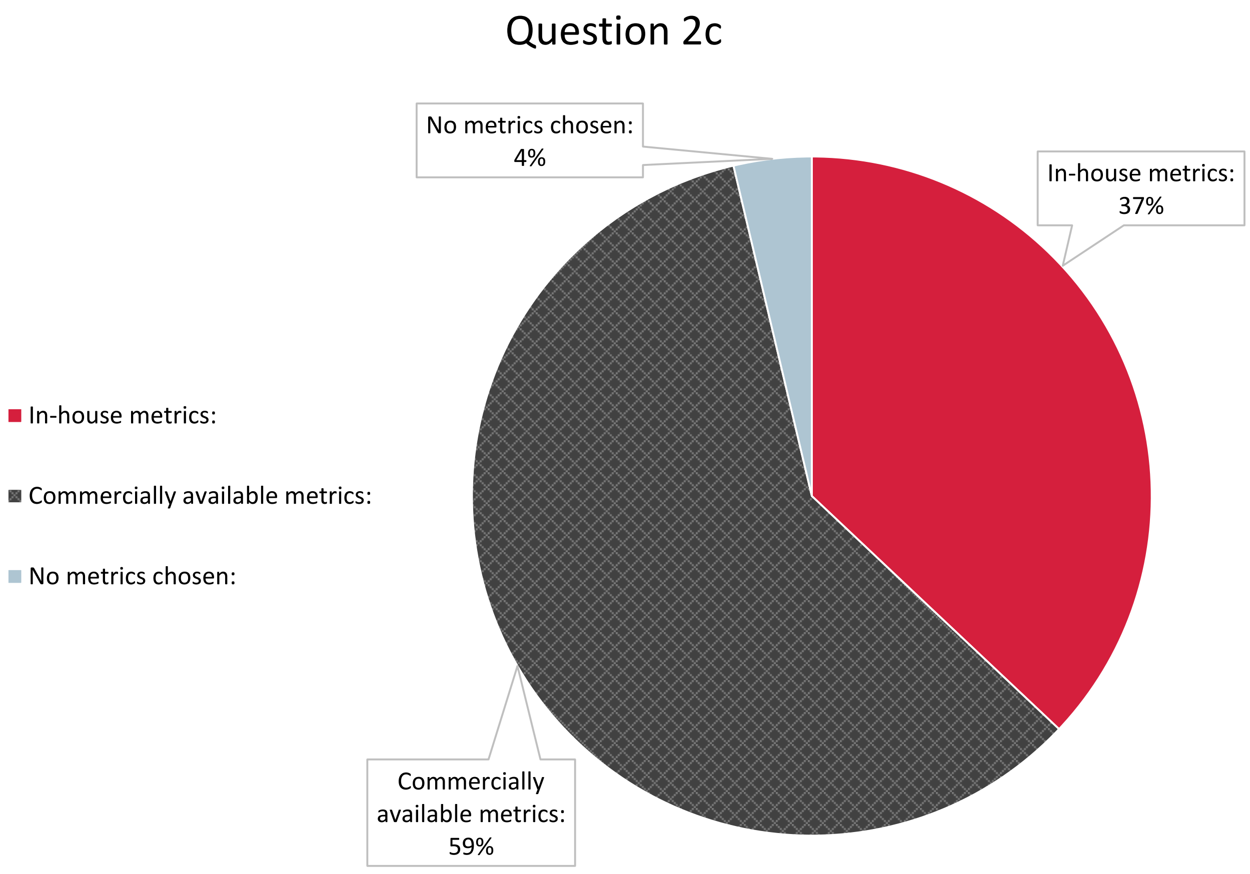
- Speed of evaluation
- Costs (tools and extra work)
- Total vehicle performance can be rated
- Provides true customer viewpoint
- Subjective trumps objective when the two ratings disagree
- Subjective evaluation has revealed gaps that were not found with objective evaluations

Question 2b

- If Subjective is selected, where do you see the advantages over an objective method (e.g. costs, reliability)

Figure E.1.1-6

Result of Questionnaire



Question 2c

- If objective is selected, are you using in-house metrics or commercially available tools?

Answered by 26 out of 27 participants

Figure E.1.1-7

Result of Questionnaire

Commercially available:

- AVL Drive or AVL Cruise
- FEV Top Expert Tool Suite

In combination with ‘in-house’ metrics:

- N-code
- Matlab / Simulink
- INCA
- LMS Test.Lab
- Head Acoustics
- Microsoft Excel

Question 2d
■ If objective is selected, which software package are you using?

Figure E.1.1-8

Result of Questionnaire

- Yes
  - Matlab scripts
  - Simulink models
  - In-house tools
  - Using an optional interface
- No
  - It is available but we don’t use this feature
  - Not yet done
  - Matlab scripts that needed “tweaking”
  - Data is reprocessed via internal tools by a different group

Question 2e

- If objective is selected, can you adjust and integrate custom metrics easily? Explain.
- FEV-Comment:
  - Customization seems possible, but often not utilized

Figure E.1.1-9

Result of Questionnaire

- The one drawback from AVL Drive (or the final score derived from it): it does not help us in quantifying the improvement needed to achieve the targets, all though the criteria are explained
- The internal report sheet does not bucket the issues rightly between engine and transmission
- There has always been an issue for Diesel applications as the tool does not consider items such as smoke limitation or turbo lag

Question 2f

- Comments/Suggestions
- FEV-Comment:
  - Tools seem to have limitations in root-causing driveability concerns
  - Not all potential driveability concerns can be evaluated with the driveability tools

Figure E.1.1-10

Result of Questionnaire

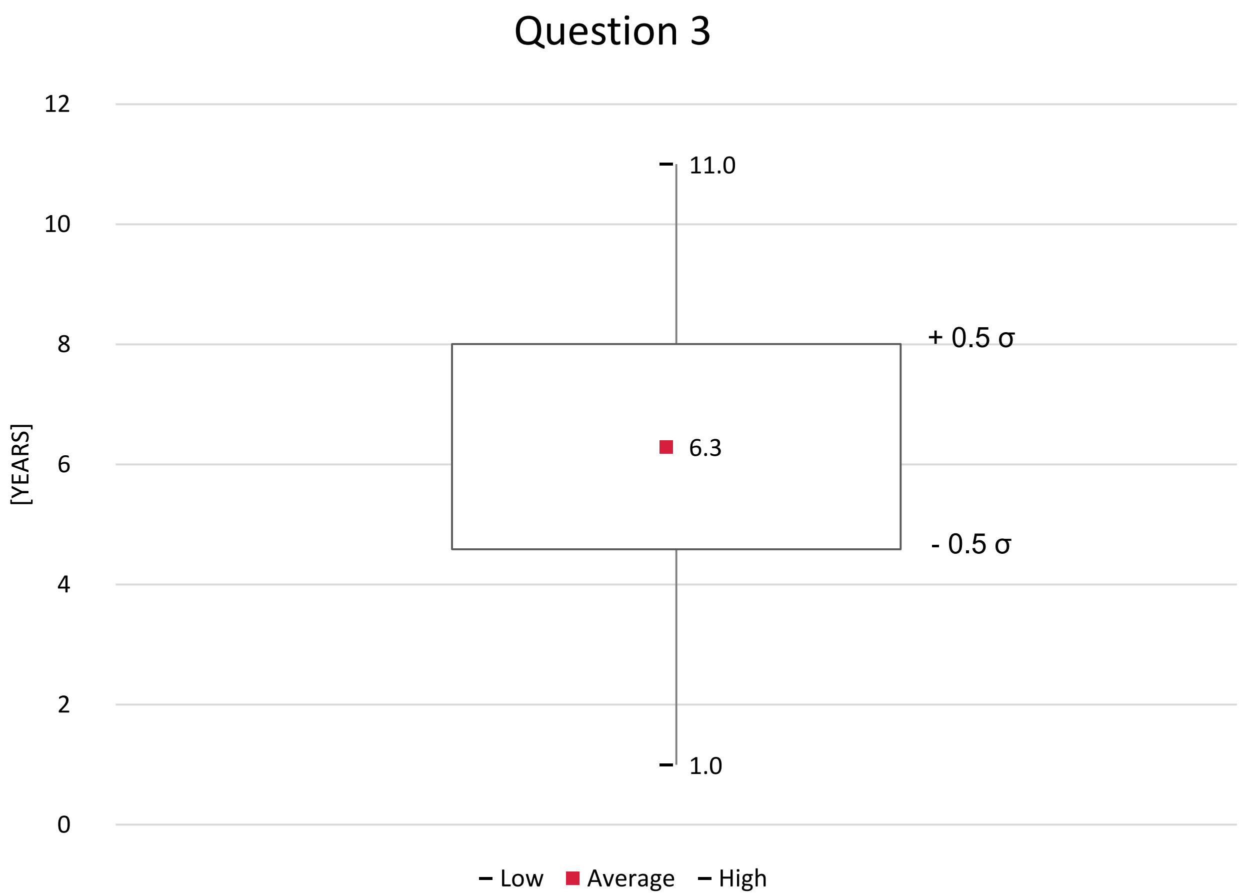


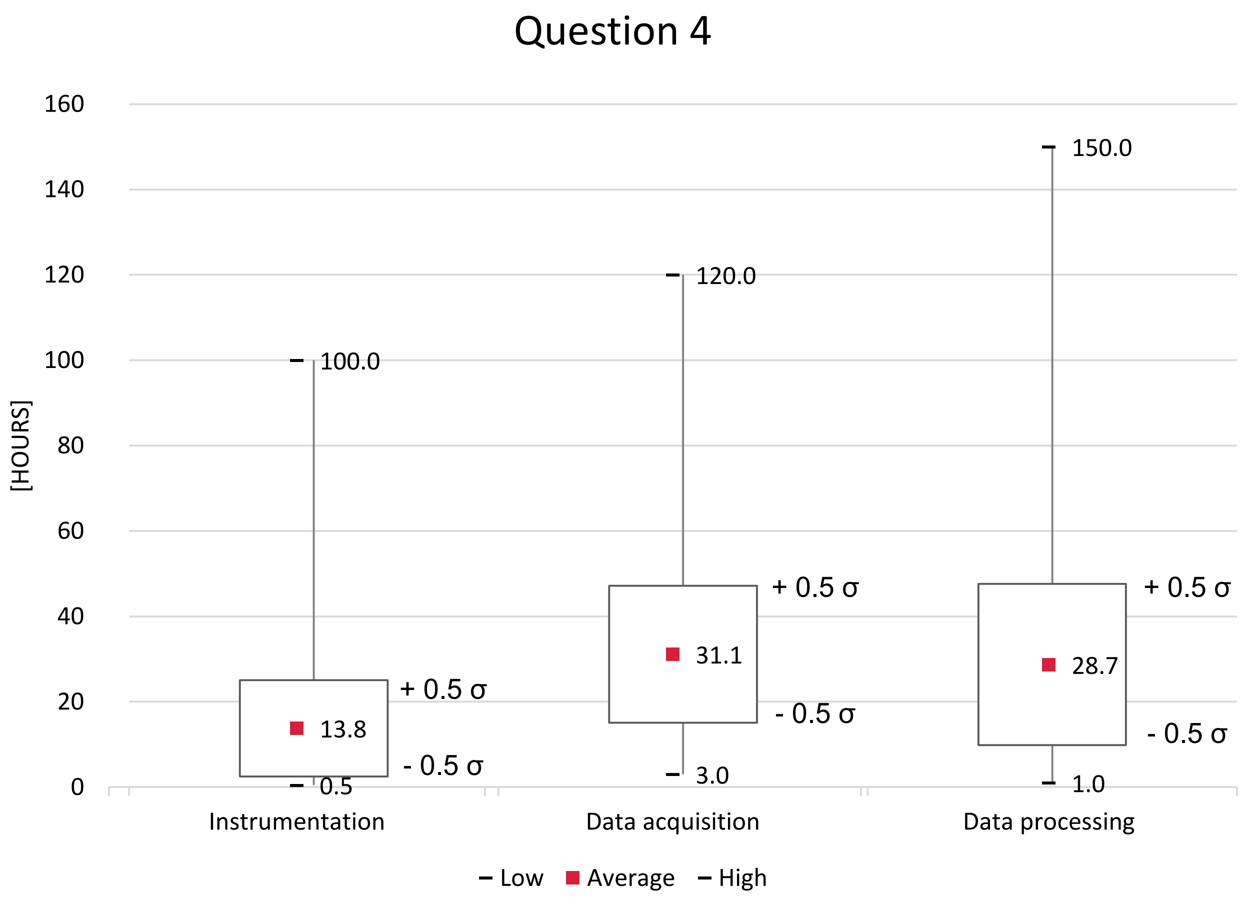
Figure E.1.1-11

Question 3

- For how long have you been using the current tool/methodology?
- FEV-Comment:
  - Long time users state that their toolset have evolved over time
  - Takes about ~6 months to become proficient user
  - Utilized tool is continually updated
- $\sigma = \sqrt{\frac{\sum_1^n (x_{avg} - x_n)^2}{n}}$
  - $\sigma: standard\ division$
  - $n: sample\ size$

Answered by 27 out of 27 participants

Result of Questionnaire



Question 4
■ Please estimate the engineering hours spent for objective evaluations: – Test preparation (instrumentation) – Data acquisition – Data processing ■ FEV-Comment: – High variation of answers depending on focus and level of detail on driveability evaluations

Answered by 23 out of 27 participants

Figure E.1.1-12

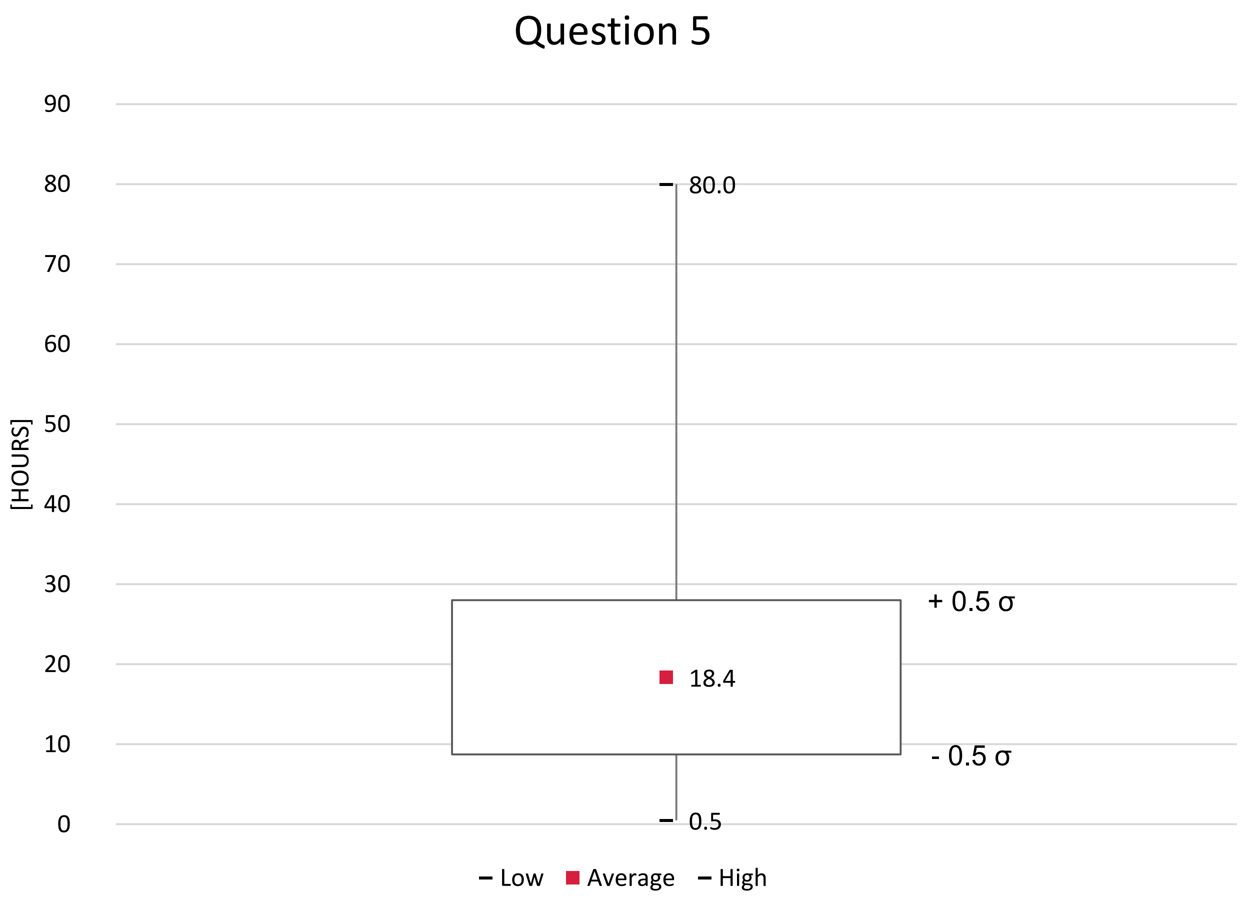
Result of Questionnaire

- Significant post processing time is required to filter out false positive detection of poor driveability (14 of 16 hours in post processing)
- Difficult to give an estimation for duration of driveability evaluation; depends on the complexity of the system, availability of input data, and customer requests
- Data processing depends on the number of issues that get flagged and mostly improves as calibration matures
- Timing provided is a rough estimation as it depends on investigation depth
- Post processing includes evaluating outliers and generating summary reports

Question 4a
■ Comments/Suggestions

Figure E.1.1-13

Result of Questionnaire



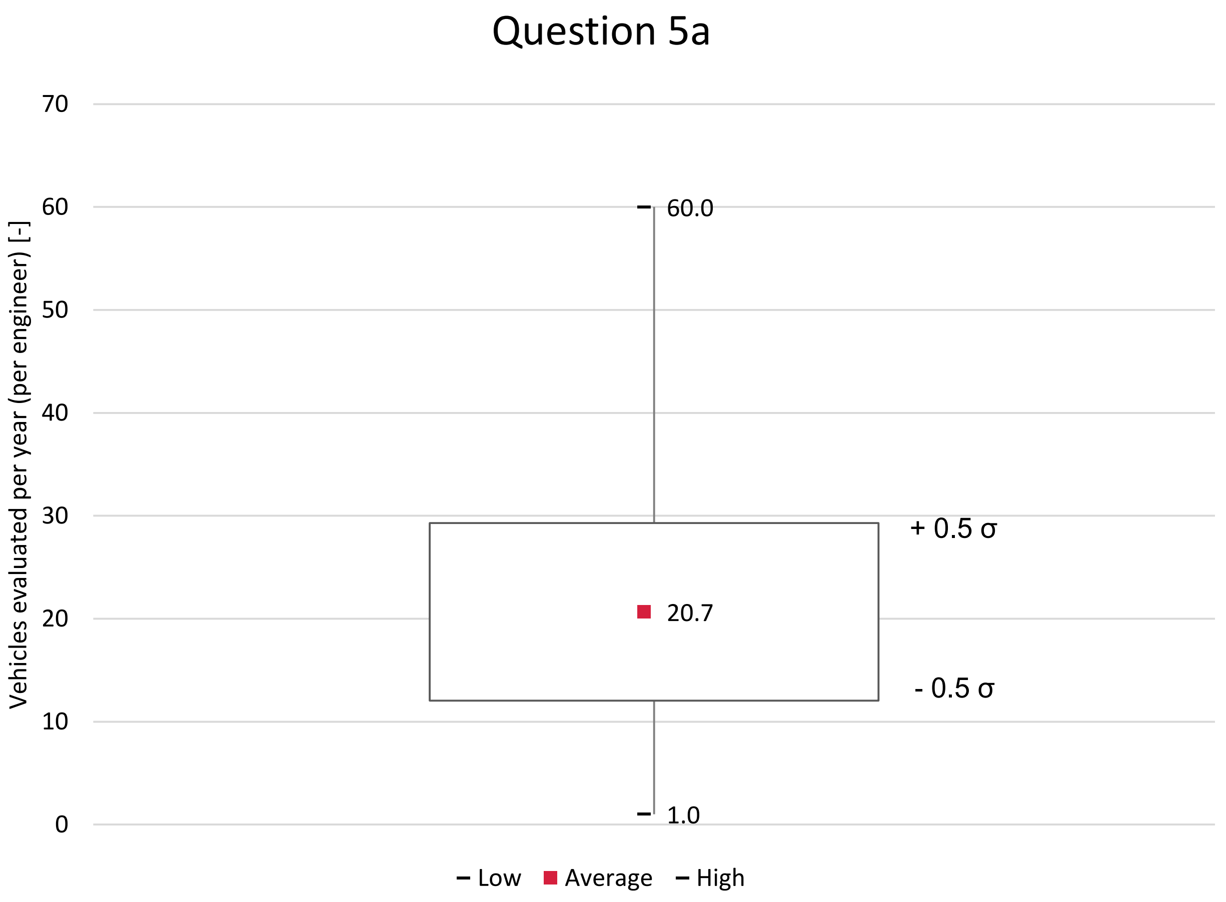
Question 5

- On average, how many hours do you spend for a standard subjective driveability evaluation per vehicle?
- FEV-Comment:
  - High variation of answers depending on focus and level of detail on driveability evaluations

Answered by 24 out of 27 participants

Figure E.1.1-14

Result of Questionnaire



Question 5a

- On average, how many vehicles do you evaluate per year?
- Notes:
  - In addition 3 participants answered 150 and 2 participants 100,
    - High count included entire department (hence not included in plot)
    - Large organizations have personnel exclusively working on driveability
    - Engineers of smaller companies evaluate ~2-3 vehicles/year

Answered by 19 out of 27 participants

Figure E.1.1-15

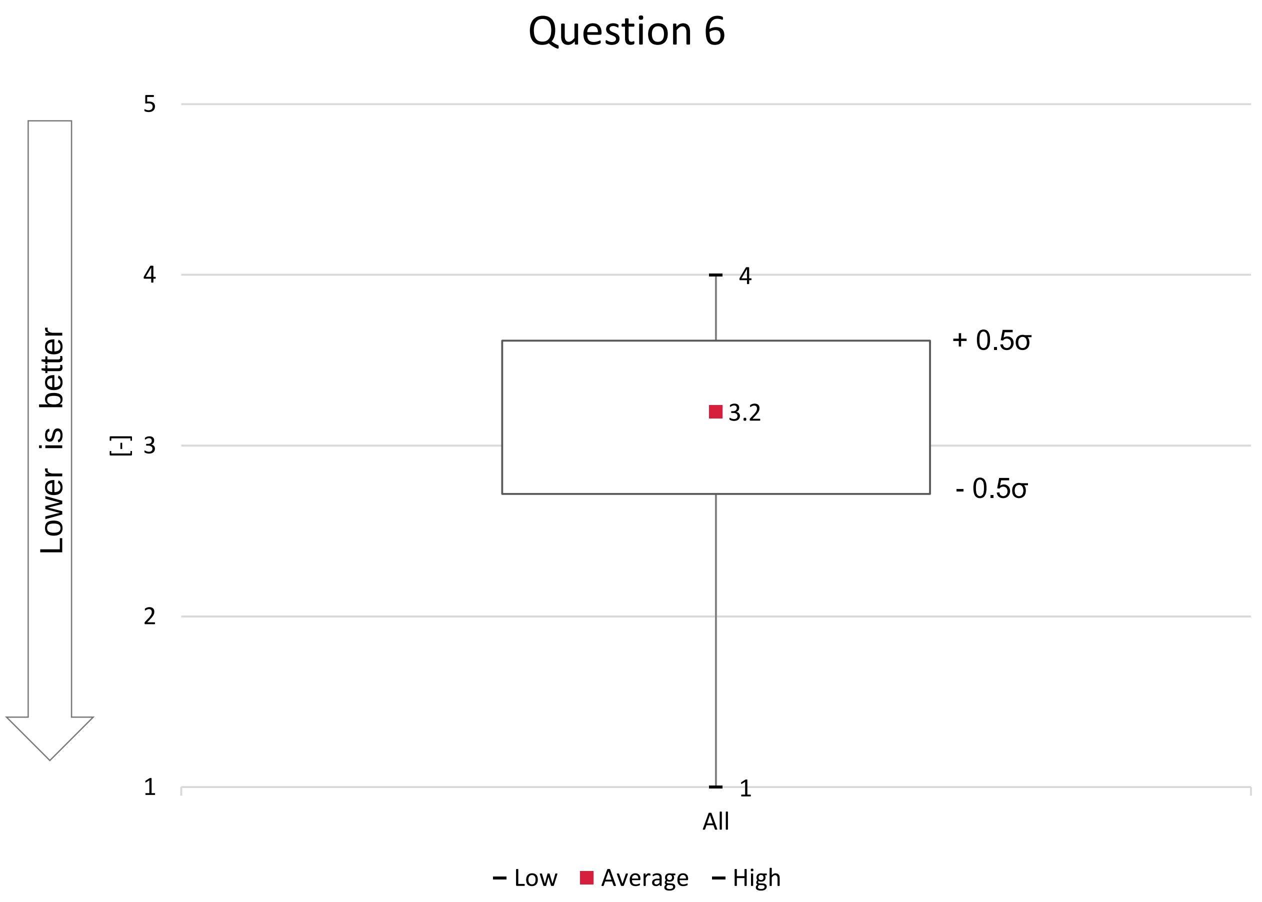
Result of Questionnaire

- Duration depends on request (shift quality, shift strategy, etc.)
- Duration depends on project (small benchmark, reference vehicle for calibration project)
- Subjective driveability evaluations can vary between 0.5 and 10 hours:
  - 0.5 by an executive to get a thumbs up or down on a calibration milestone
  - 10 if requested for an extended evaluation.
- During development the product was essentially continuously evaluated subjectively as the calibration was progressing from, e.g., 50% to 100%
- Most times a development ‘buy off’ is obtained by subjective evaluation for the issues that would have been flagged by an objective evaluation which are not achievable

Question 5b
■ Comments/Suggestions

Figure E.1.1-16

Result of Questionnaire



Question 6

- Please rate your overall satisfaction with the level of correlation between subjective ratings and objective metrics.
  - 1 = Completely satisfied
  - 2 = Very satisfied
  - 3 = Fairly well satisfied
  - 4 = Partly dissatisfied
  - 5 = Very dissatisfied

Answered by 24 out of 27 participants

Figure E.1.2-1

Result of Questionnaire

FEV

- The correlation between subjective and objective wasn't always the best and probably didn't provide as much value other than objectively documenting a product to compare against future products
- Some of the issues are sometimes not subjectively reported although it might have been flagged objectively
- The ratings of the objective evaluation are sometimes not reasonable or interpretable
- Objective tools could be better utilized in non-vehicle development, e.g., on a powertrain dyno where it is impossible to get an subjective drive quality score.
- It varies depending on event type (e.g., kickdown vs. coasting downshift)
- Especially during long evaluations subjective rating might differ a lot
- Correlation between objective tool and subjective ratings is pretty good

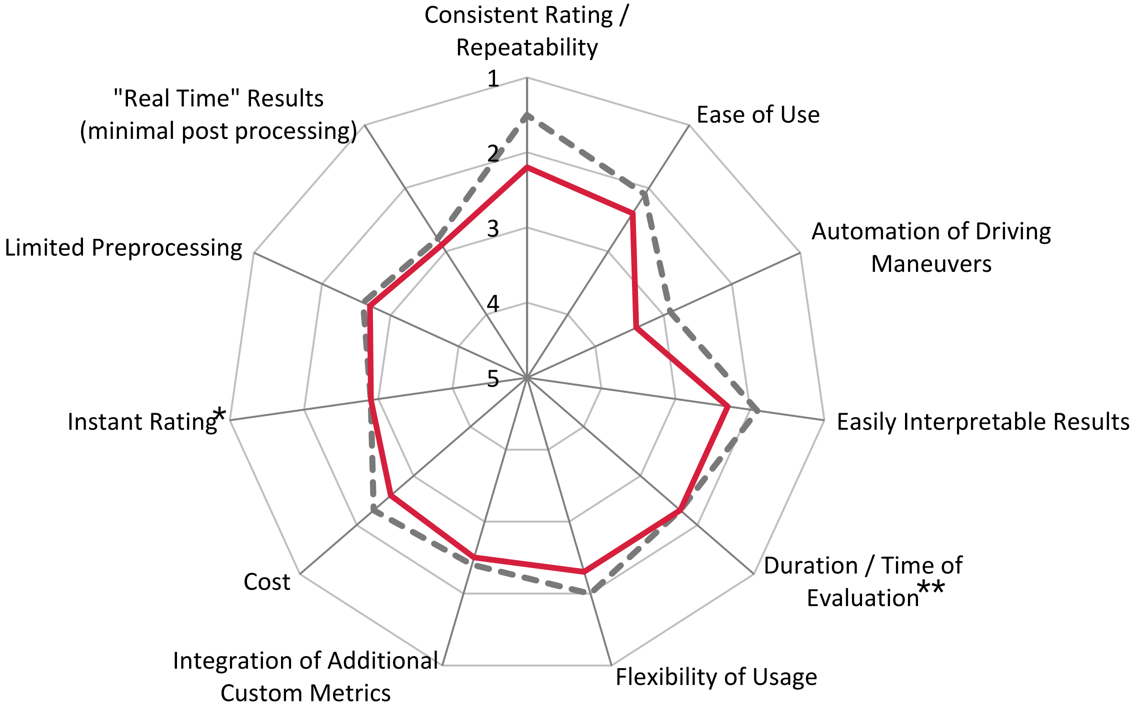
Question 6a

- Comments/Suggestions
- FEV-Comment:
  - Correlation between subjective and objective tool is often not entirely satisfactory
    - Heavily dependent on driving maneuver
    - Level of confidence can vary significantly for different participants. Experience using the tool could also be a factor

Figure E.1.2-2

Result of Questionnaire

Question 7 & 8



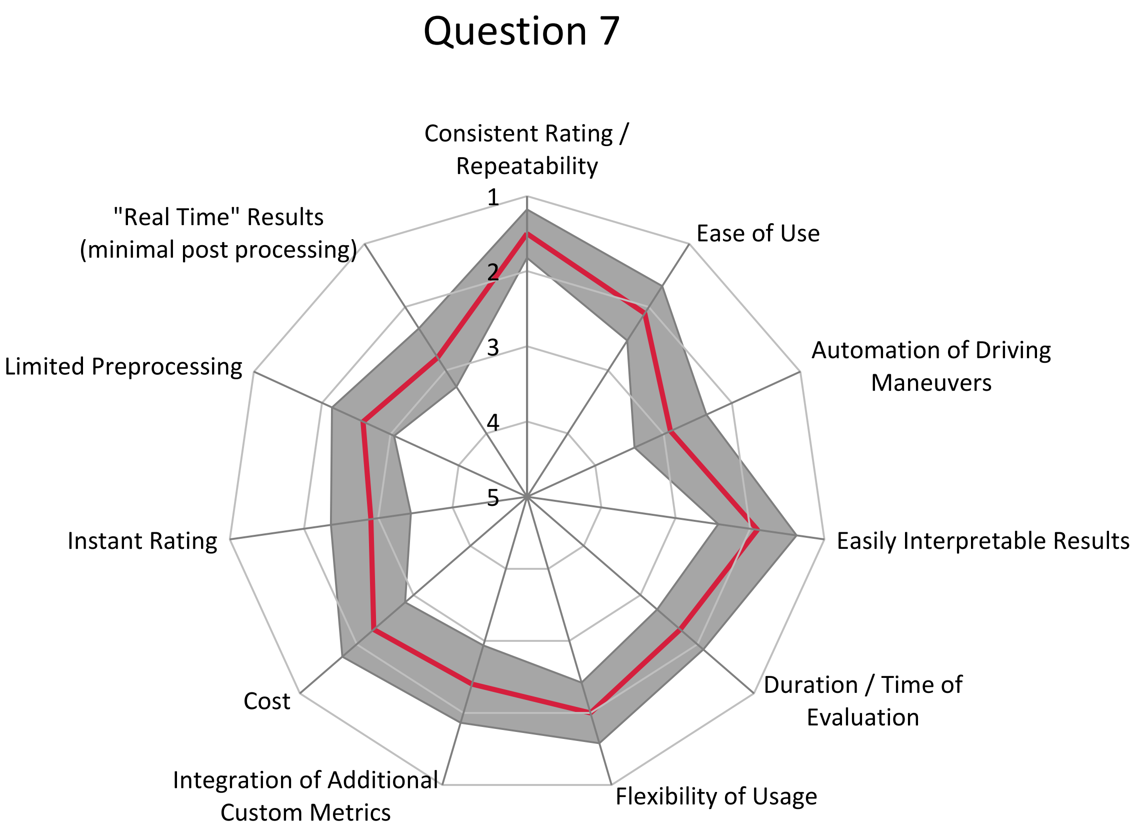
- Repeatability is the most important requirement

Question 7 and 8
- - - - Question 7: Importance – 1 = Very important – 2 = Important – 3 = Somewhat important – 4 = Relatively unimportant – 5 = Unimportant —— Question 8: Rate – 1 = Excellent – 2 = Good – 3 = Average – 4 = Poor – 5 = Very Poor

*Rating directly available after specific maneuver
** Duration of entire driveability evaluation

Figure E.1.2-3

Result of Questionnaire



Question 7

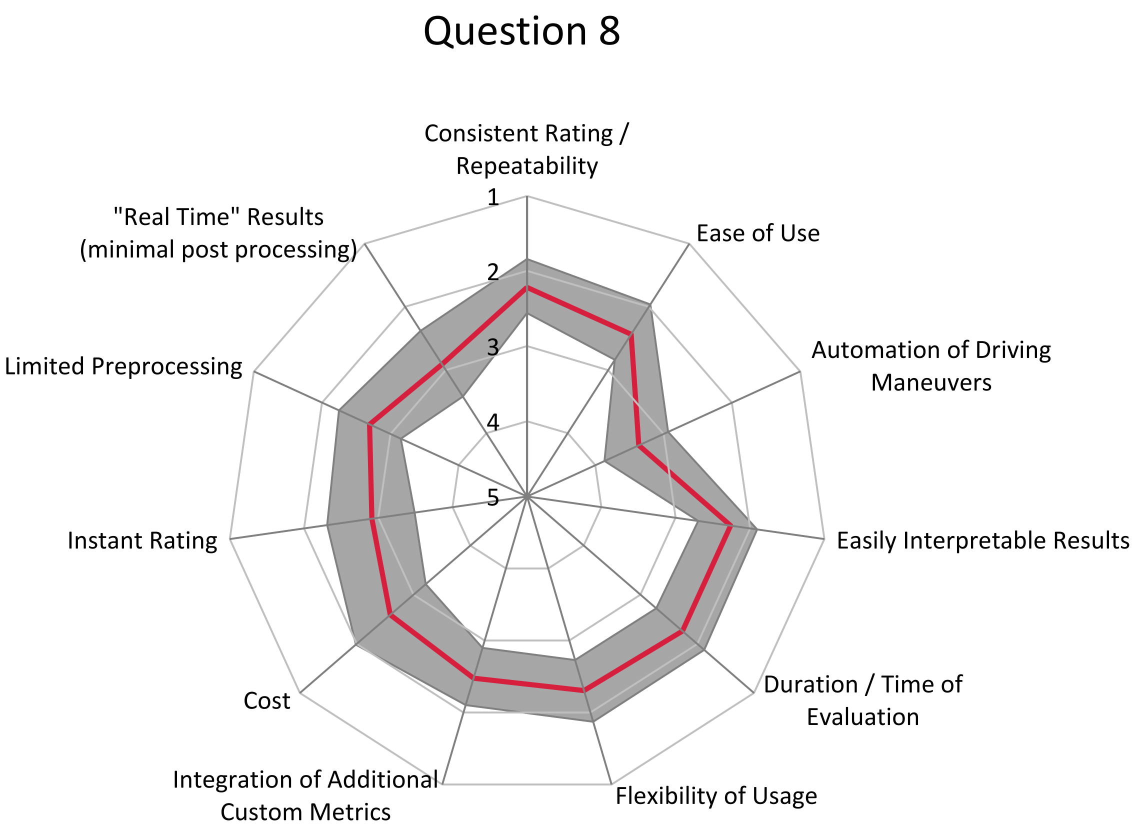
- Please rate the importance-level of the following requirements for an objective driveability evaluation tool.
  - 1 = Very important
  - 2 = Important
  - 3 = Somewhat important
  - 4 = Relatively unimportant
  - 5 = Unimportant

- Legend
  - Average
  - +/- 0.5σ area

Answered by 24 out of 27 participants

Figure E.1.2-4

Result of Questionnaire



Question 8

- How do you rate the capability of the tool you are currently using?
  - 1 = Excellent
  - 2 = Good
  - 3 = Average
  - 4 = Poor
  - 5 = Very poor
- Legend
  - Average
  - +/- 0.5σ area

Answered by 23 out of 27 participants

Figure E.1.2-5

Result of Questionnaire

- Tool provides consistent rating given consistent inputs
- User experience with software/navigation is good
- Ability to use software both connected & not connected to a network for multiple users globally is good
- As based on accelerometer, the results are very consistent
- The tool provides workflows to guide you through the maneuvers.
- Custom metrics over Simulink
- Instant rating also possible in tool as the Simulink model runs in real time
- Gives a metric that checks a box and all are happy
- Low cost and high flexibility
- It does throw out an instant rating
- Tools are user configurable

Question 8a
▪ For metrics listed above that are good, why?

Figure E.1.2-6

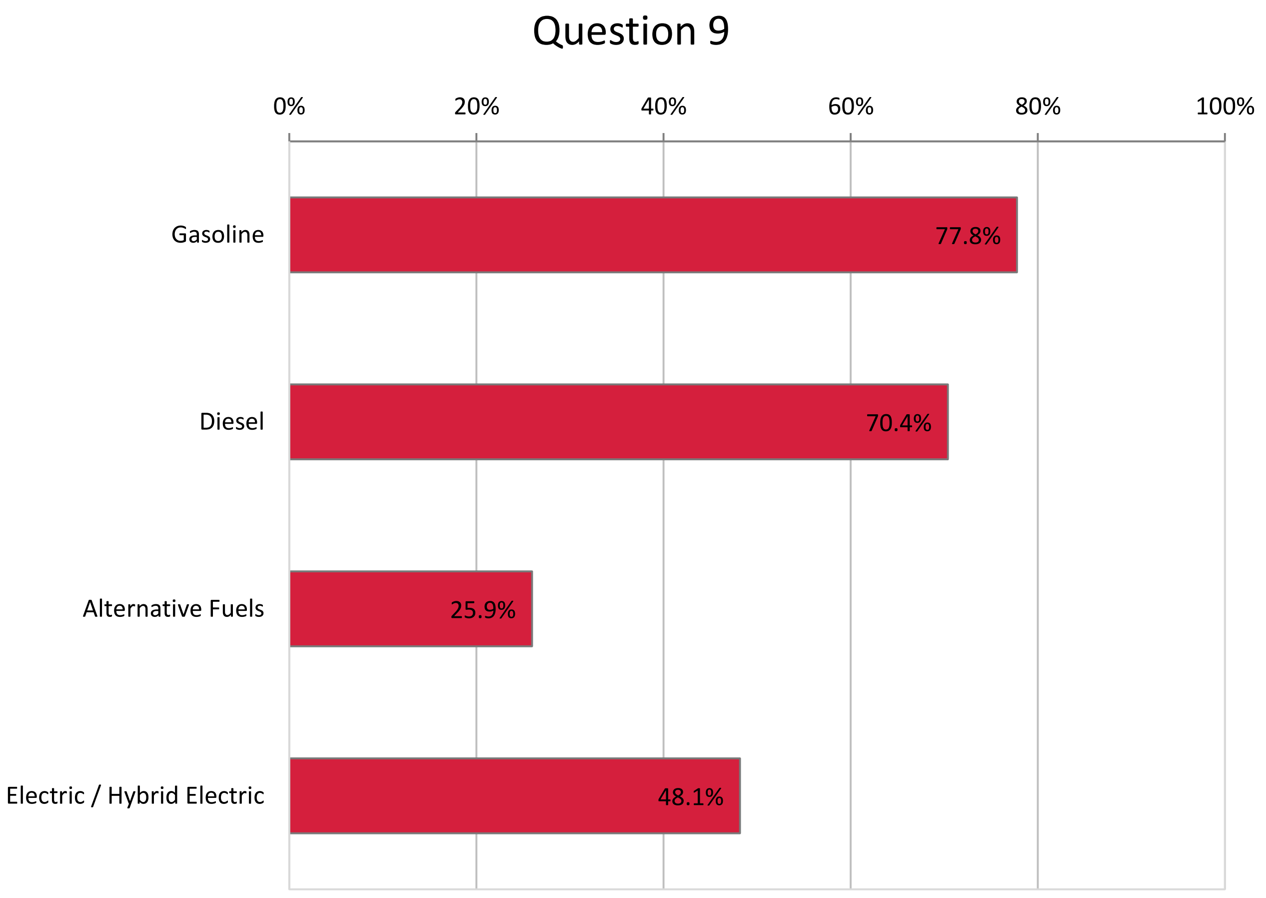
Result of Questionnaire

- Complicated inputs and difficult interface to set up
- Not clear descriptions of input data required
- Variability in driving maneuver input which can significantly influence the results
- Does not integrate well with other tools e.g., ATI/ETAS calibration tools
- Tool isn't always stable
- Not possible for the automation of test, and no real time rating or results
- Cost
- The tool requires post-processing to reach an evaluation 'score'
- No automation of driving maneuvers exist

Question 8b
■ For metrics listed above that are poor, why?

Figure E.1.2-7

Result of Questionnaire



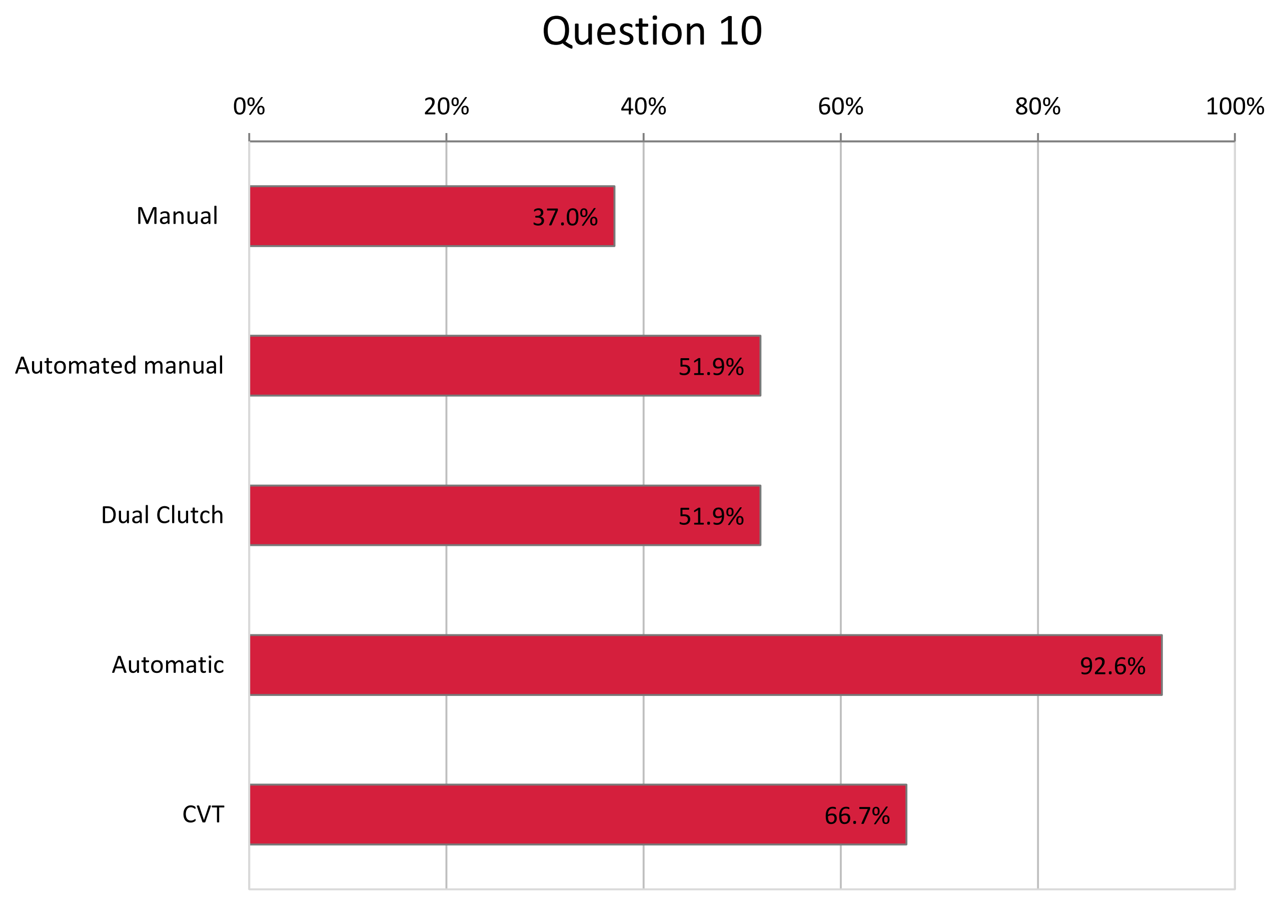
Question 9

- What type of powertrain do you test?

Answered by 27 out of 27 participants

Figure E.1.2-8

Result of Questionnaire



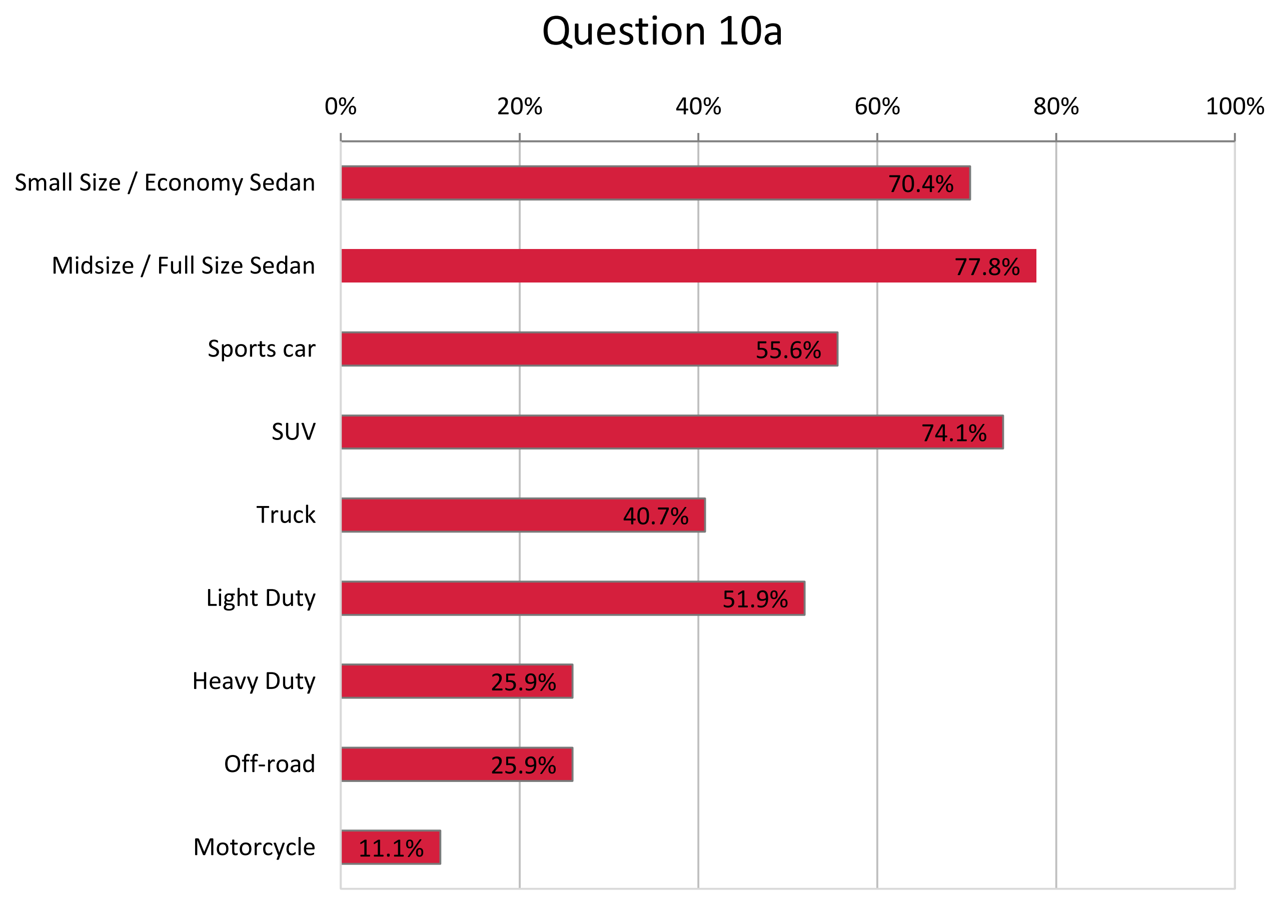
Question 10

- What transmission types do you test?

Answered by 27 out of 27 participants

Figure E.1.2-9

Result of Questionnaire



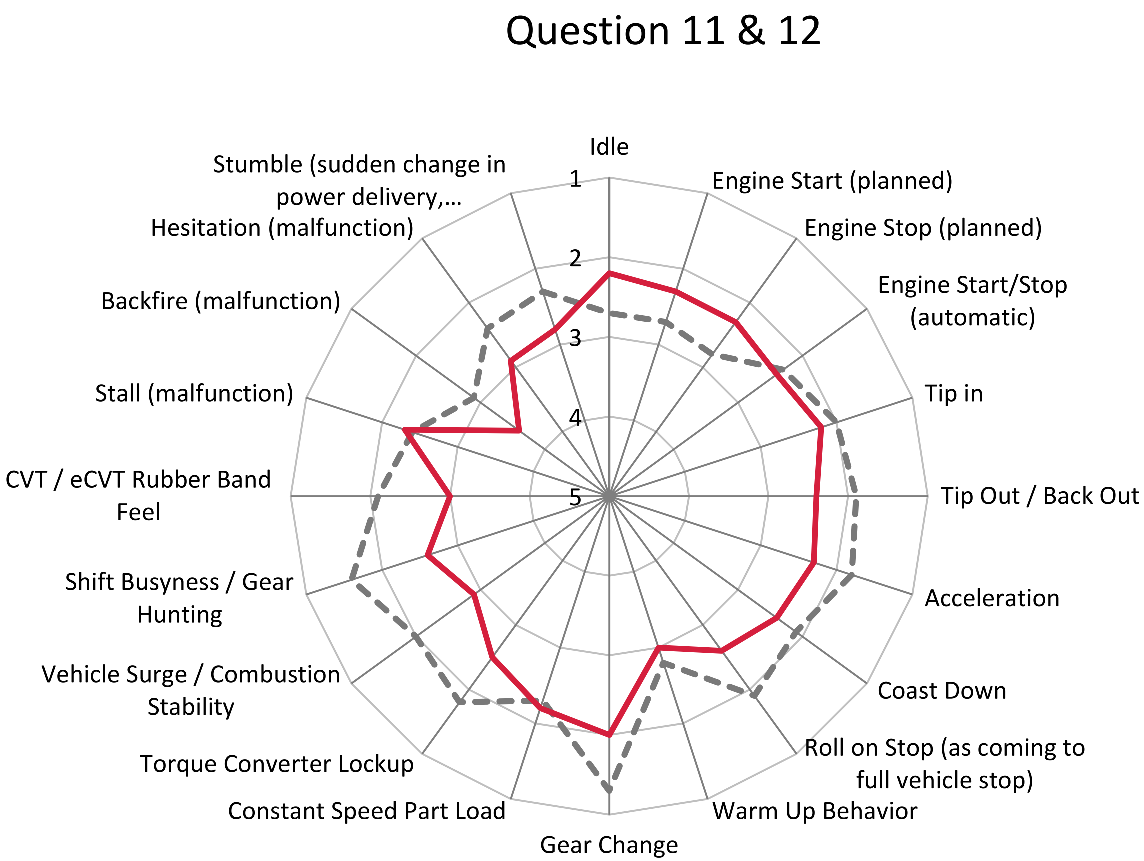
Question 10a

- What type of vehicles do you test?

Answered by 27 out of 27 participants

Figure E.1.2-10

Result of Questionnaire



- Shift Busyness is 2nd most important mode, but not well rated

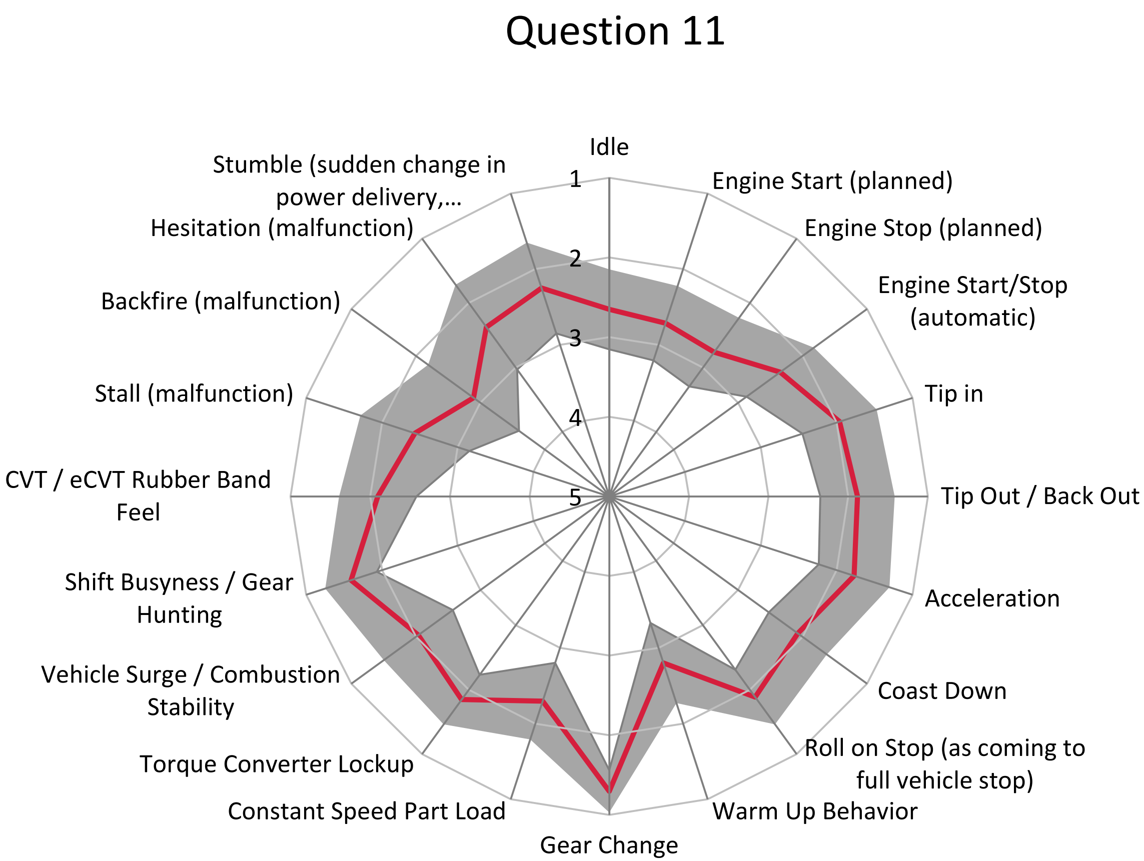
Figure E.1.2-11

Question 11 & 12

- - - - Question 11: Importance
  - 1 = Very important
  - 2 = Important
  - 3 = Somewhat important
  - 4 = Relatively unimportant
  - 5 = Unimportant
- —— Question 12: Rate
  - 1 = Excellent
  - 2 = Good
  - 3 = Average
  - 4 = Poor
  - 5 = Very Poor

Q11 Answered by 27 out of 27 participants
Q12 Answered by 23 out of 27 participants

Result of Questionnaire



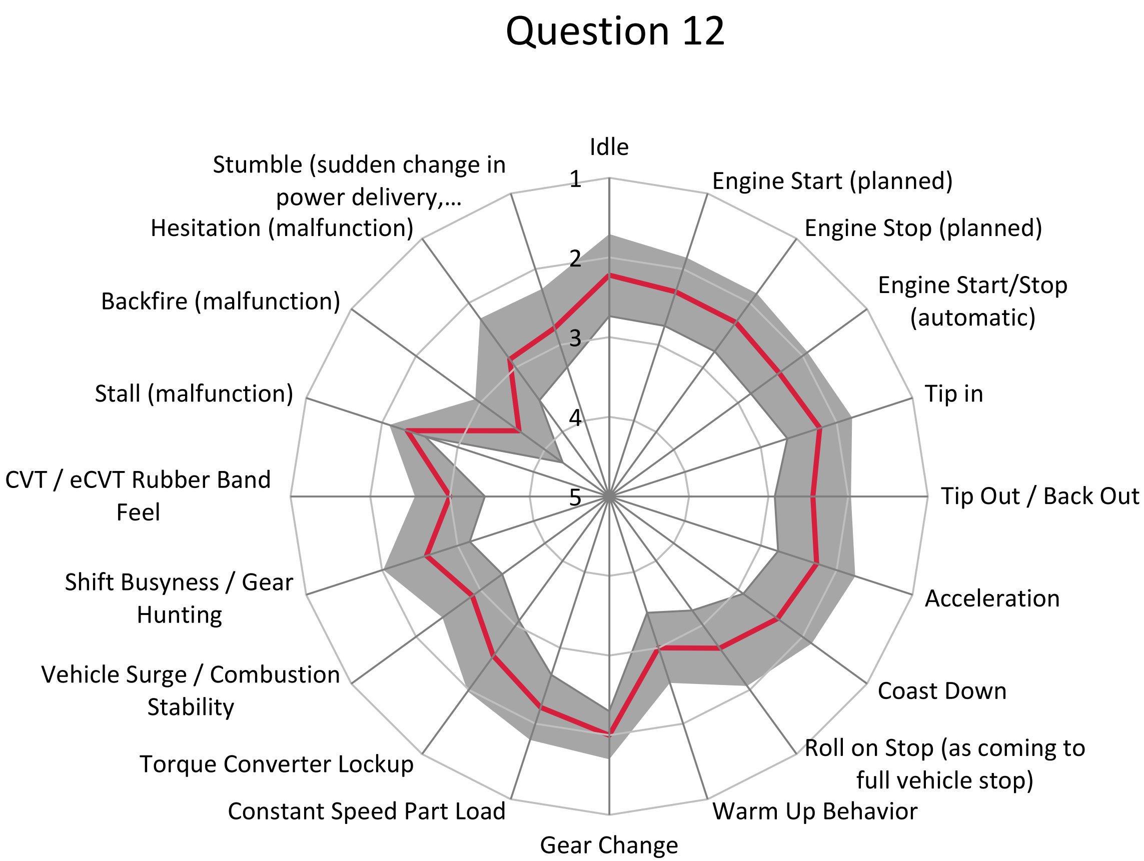
Question 11

- What level of importance does each operating mode have in regards to driveability
  - 1 = Very important
  - 2 = Important
  - 3 = Somewhat important
  - 4 = Relatively unimportant
  - 5 = Unimportant
- Legend
  - Average
  - +/- 0.5σ area

Answered by 27 out of 27 participants

Figure E.1.2-12

Result of Questionnaire



Question 12

- How well can your evaluation tool rate the following conditions/driving maneuvers?
  - 1 = Excellent
  - 2 = Good
  - 3 = Average
  - 4 = Poor
  - 5 = Very Poor
- Legend
  - Average
  - +/- 0.5σ area

Answered by 23 out of 27 participants

Figure E.1.2-13

Result of Questionnaire

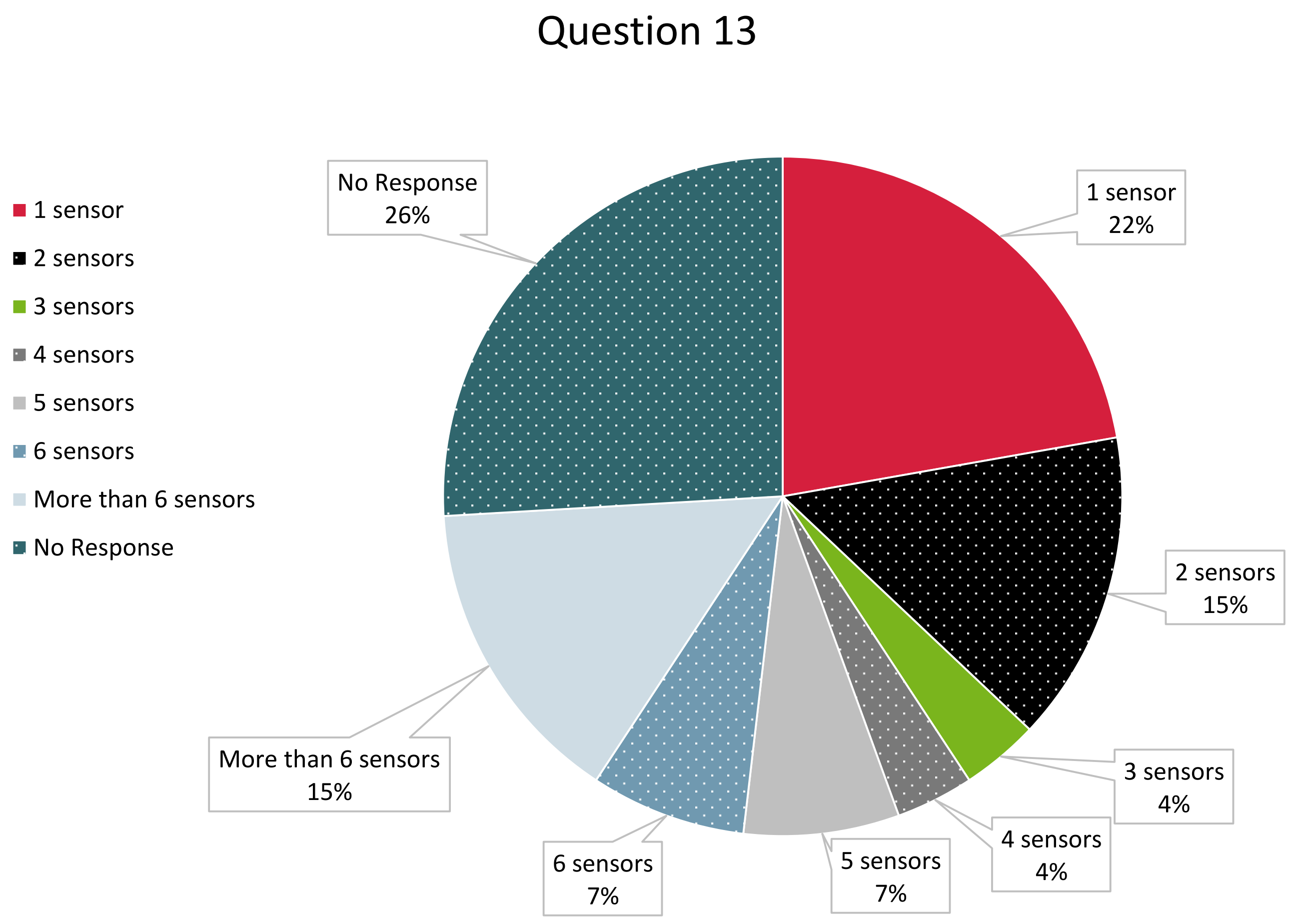
- Haven't seen any criteria on shift busyness (may be the configuration issue)
- Only drive away and not warm up behavior evaluated
- Most often cannot distinguish between road noise for any surge or coast down
- Our tools do not generate ratings

Question 12a

- Other/Comments

Figure E.1.2-14

Result of Questionnaire



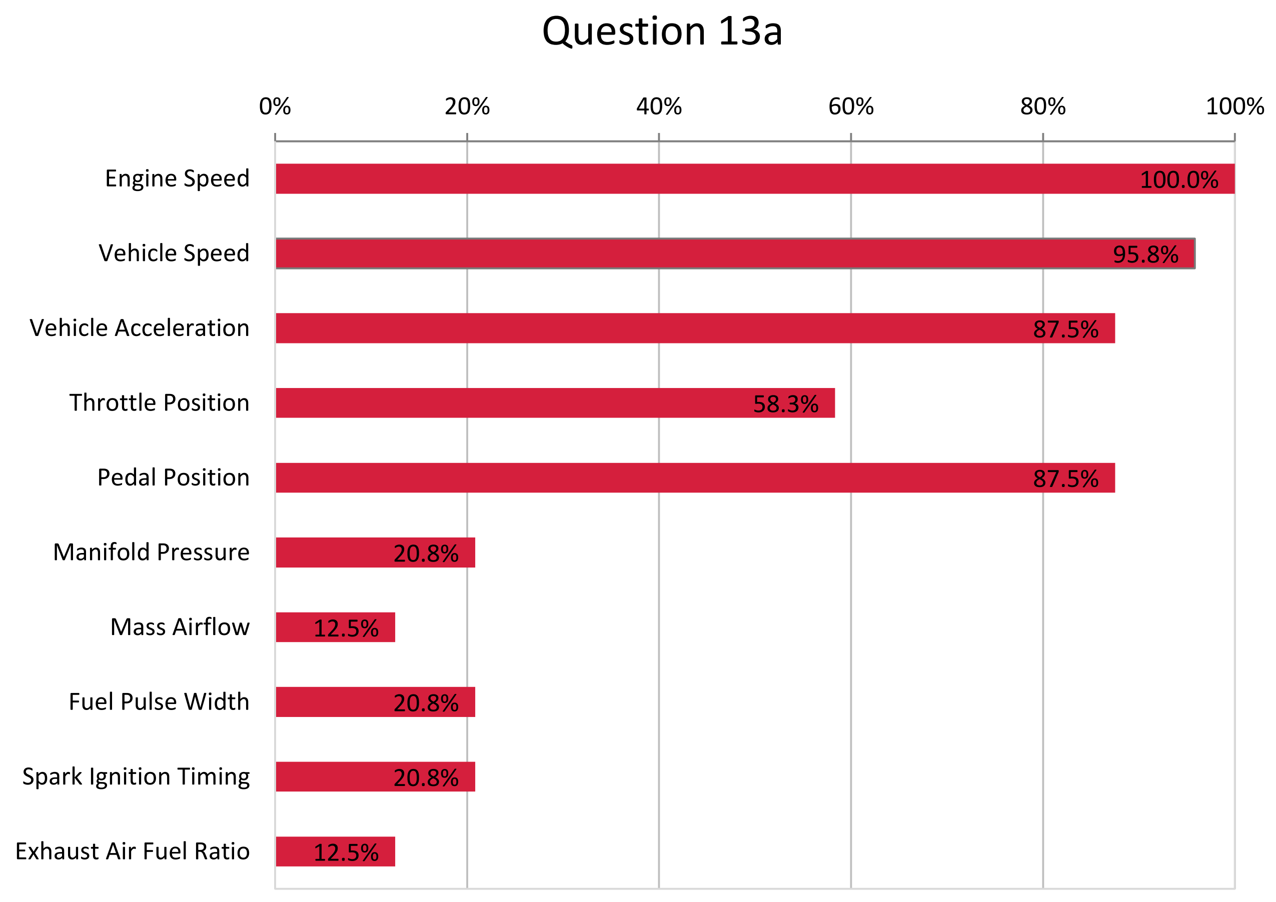
Question 13

- For objective ratings, how many measurement locations/sensors are required to rate driveability with your current software?
- Note:
  - Signals in addition to CAN bus data

Answered by 20 out of 27 participants

Figure E.1.2-15

Result of Questionnaire



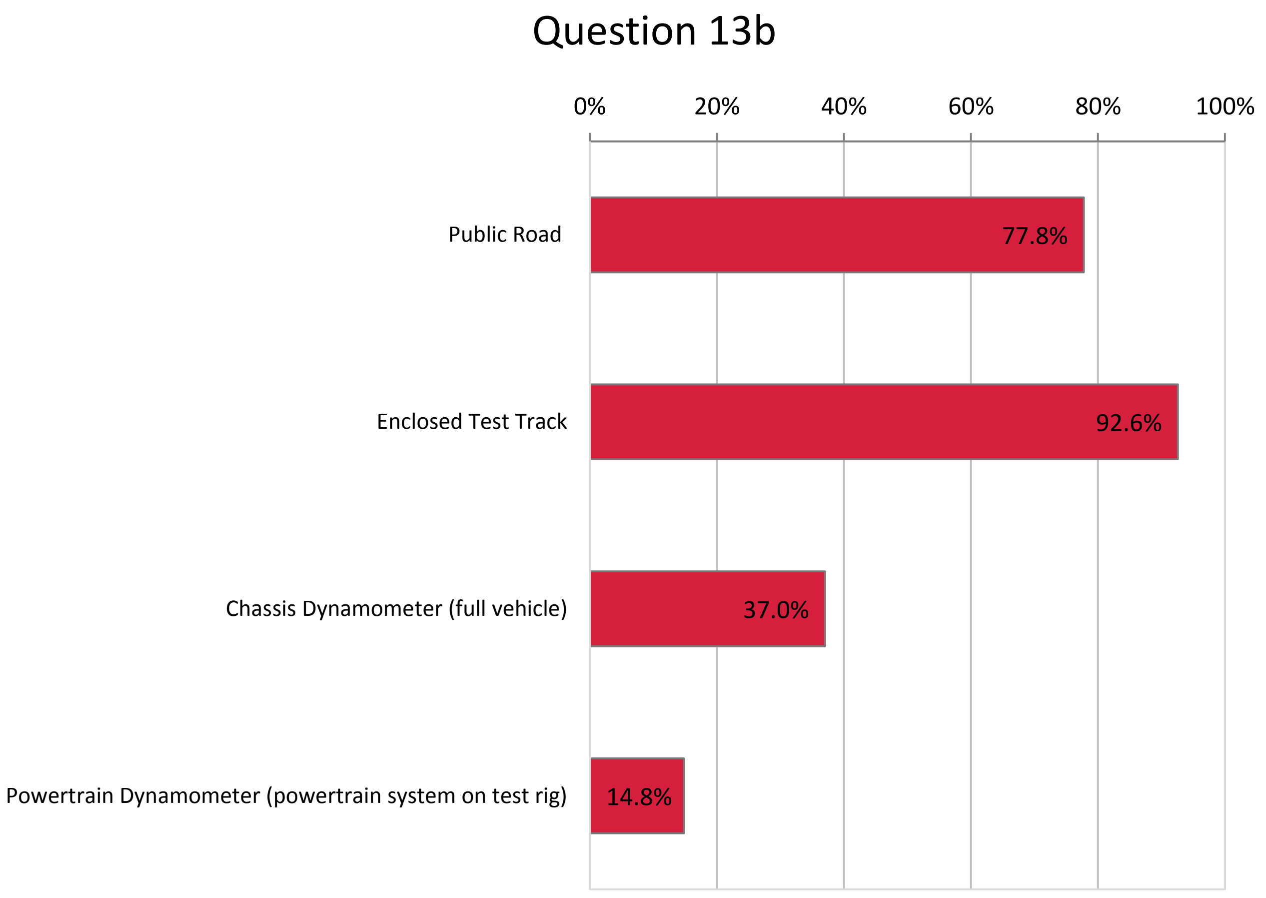
Question 13a

- What signals are typically taken for driveability analysis?

Answered by 24 out of 27 participants

Figure E.1.2-16

Result of Questionnaire



Question 13b

- Where do you evaluate vehicles for driveability?
- FEV-Comment: Enclosed test track is the most used place for evaluation

Answered by 27 out of 27 participants

Figure E.1.2-17

Result of Questionnaire

- Public roads occasionally, because the tool is not great at avoiding false positives due to poor road conditions
- Evaluations are also performed at customer sites
- Sensors - accelerometer on the control arm of the suspension and a second accelerometer on the seat track (driver)
- Engine turbine, output, acceleration, engine torque, gear command, throttle
- Generally the most min signals from the ECU that will be needed other than mentioned are
  - Wheel speed sensors 4 wheels, brake pedal, torque convertor state, turbine state, gear
- The answer for Question 13 is a minimum number:
  - Pedal Position, Vehicle Speed, Vehicle Acceleration, Transmission input- and output speed. We typically use many more signals than those minimum 5

Question 13c
Other/Comments

Figure E.1.2-18

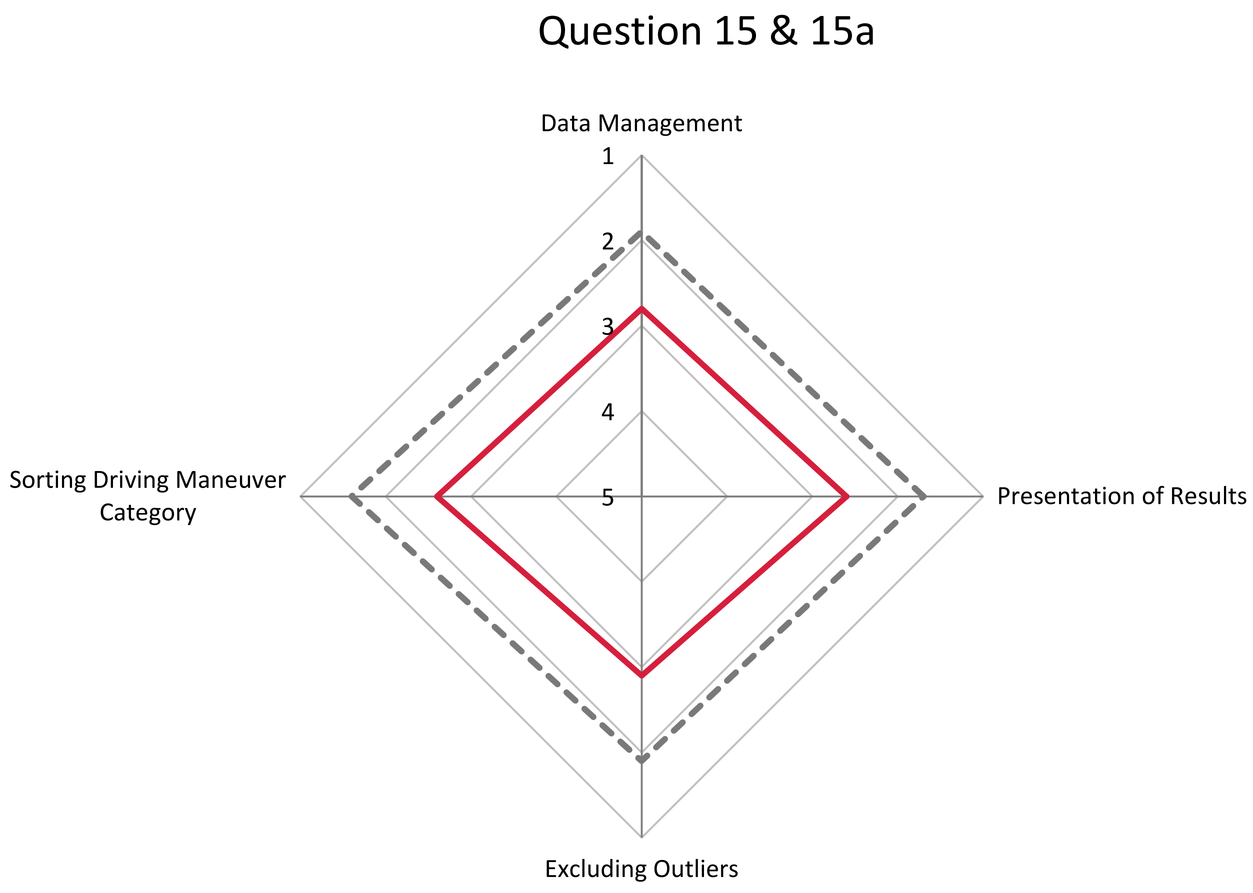
Result of Questionnaire

- VDV (Vibration Dose Value)
- LFP (Low Frequency Percentage)
- Seat track jerk
- Shift-times
- Other metrics for shift-quality
- Acceleration time
- Engine output torque and transmission output torque maximum values

Question 14
Could you describe the specific metrics/formulation utilized for objectification of specific driveability as listed in Question 13?

Figure E.1.2-19

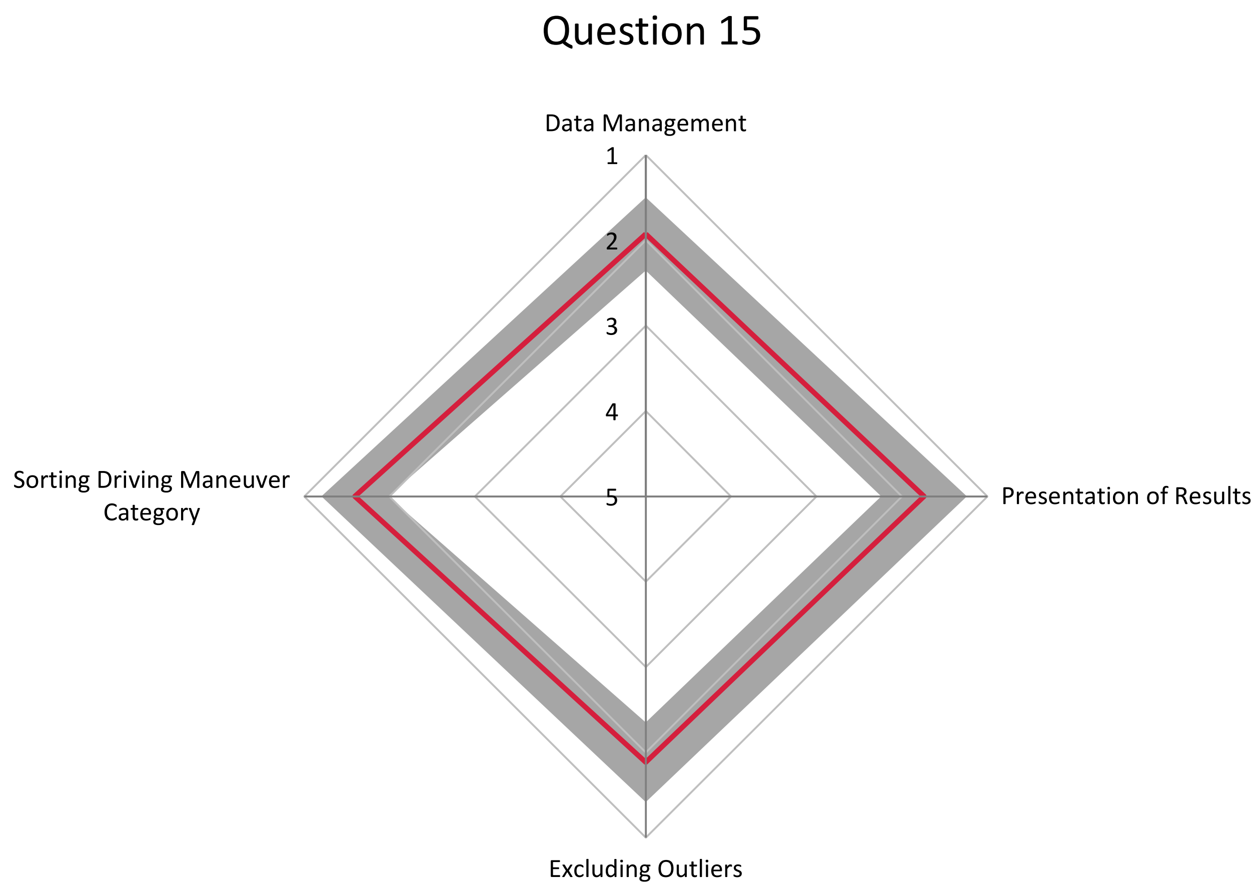
Result of Questionnaire



Question 15 and 15a
■ - - - - Question 15: Importance – 1 = Very important – 2 = Important – 3 = Somewhat important – 4 = Relatively unimportant – 5 = Unimportant ■ ——— Question 15a: Rate – 1 = Excellent – 2 = Good – 3 = Average – 4 = Poor – 5 = Very Poor

Figure E.1.2-20

Result of Questionnaire



Question 15

- How important are the following areas?
  - 1 = Very important
  - 2 = Important
  - 3 = Somewhat important
  - 4 = Relatively unimportant
  - 5 = Unimportant
- Legend
  - Average
  - +/- 0.5σ area

Answered by 27 out of 27 participants

Figure E.1.2-21

Result of Questionnaire

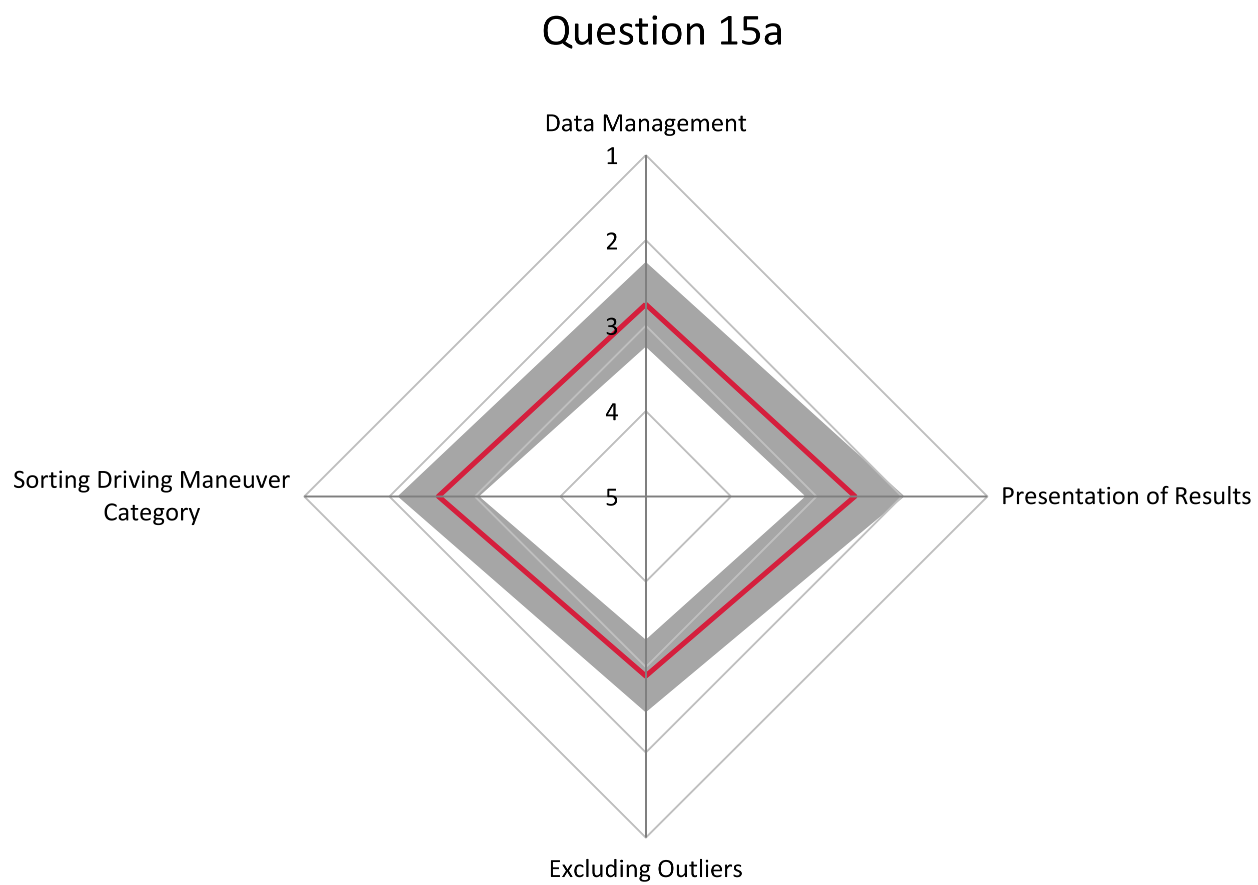


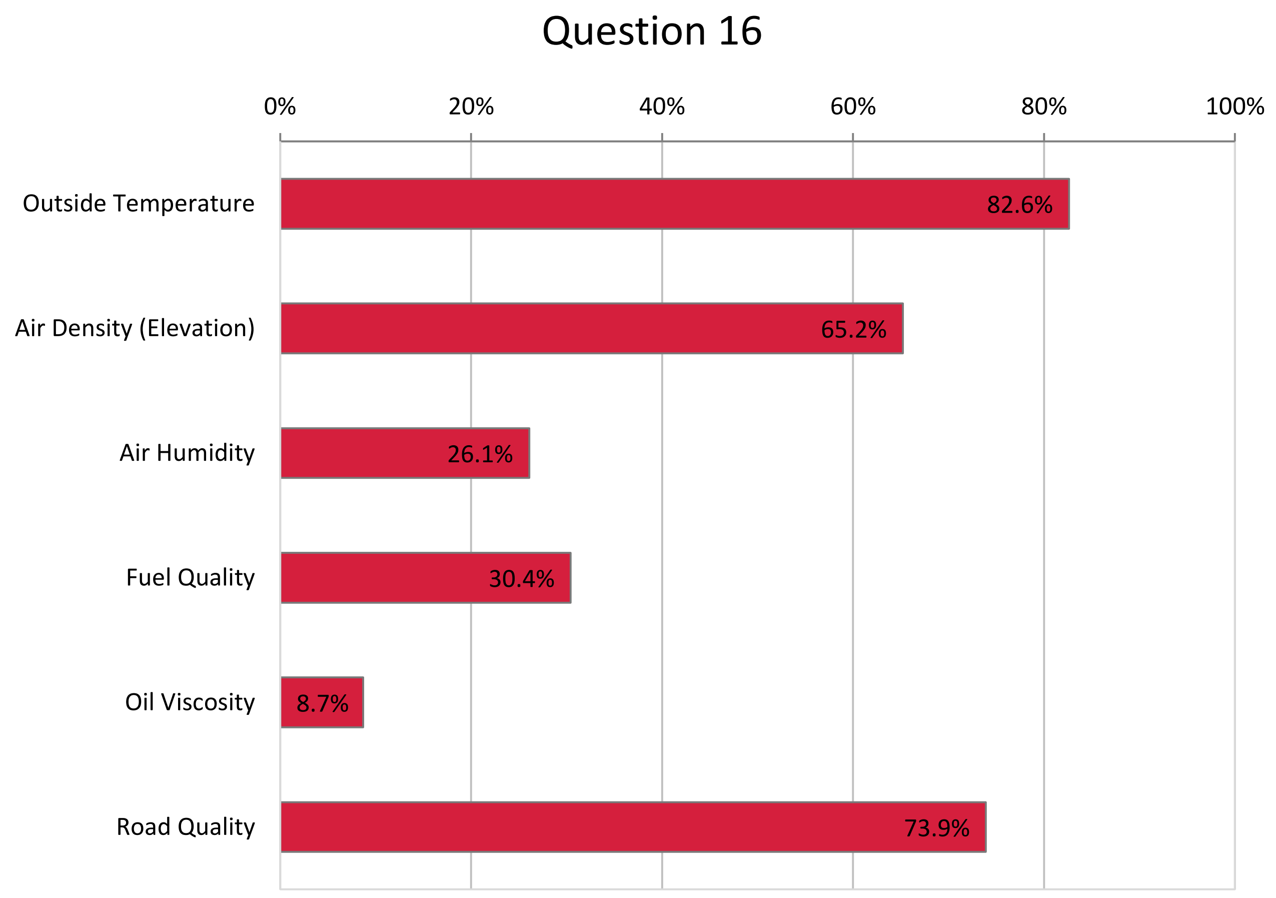
Figure E.1.2-22

Question 15a

- Does your tool service the following areas or are they done externally to the tool and how would you rate it?
  - 1 = Excellent
  - 2 = Good
  - 3 = Average
  - 4 = Poor
  - 5 = Very poor
- Legend
  - Average
  - +/- 0.5σ area

Answered by 24 out of 27 participants

Result of Questionnaire



Question 16

- Do you consider the following boundary conditions in your evaluation?
- FEV-Comment: Outside Temperature, Air Density and Road Quality are the most considered boundary conditions

Answered by 23 out of 27 participants

Figure E.1.2-23

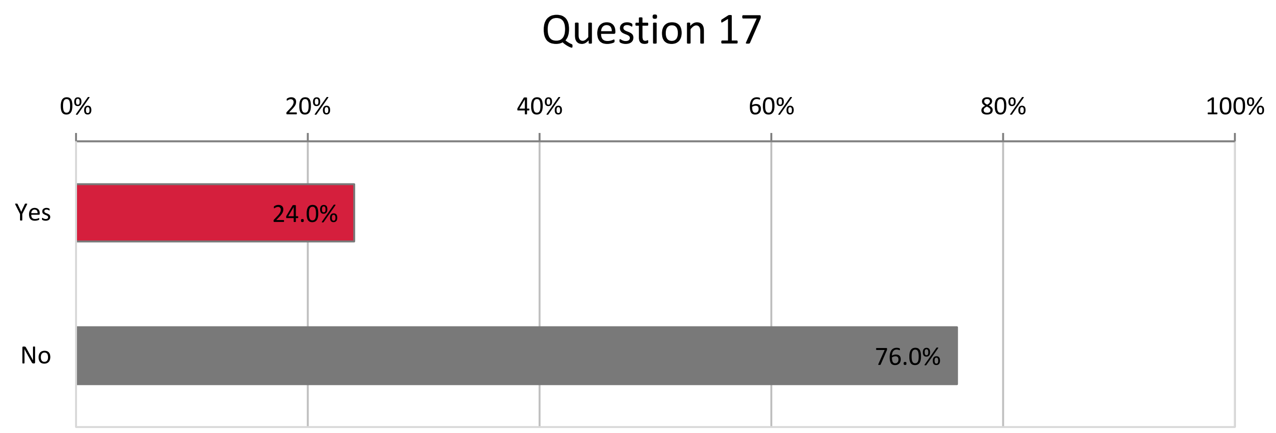
Result of Questionnaire

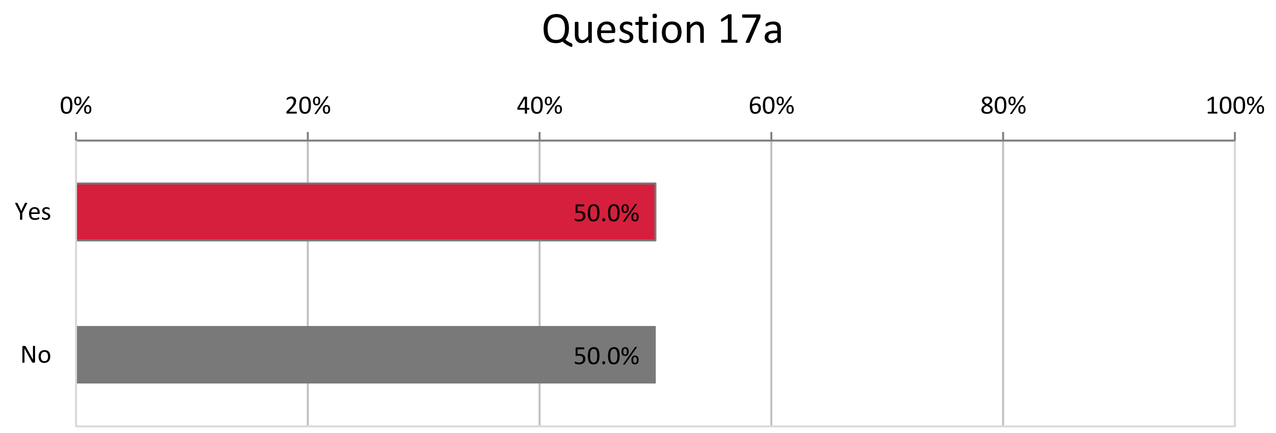
- The evaluation can be done at any ambient temperature, although would be ideal to consider a standard temperature
- Depends on test purpose
- We work within EPA regulatory standards in our lab

Question 16a
■ If a chassis dyno is used, are any other boundary conditions considered?

Figure E.1.2-24

Result of Questionnaire





Question 17 & 17a

- Question 17: Do your rating tools also support automated optimization?
- Question 17a: If yes, are you using the automated optimization tool?

Q17 Answered by 25 out of 27 participants
Q17a Answered by 15 out of 27 participants

Figure E.1.2-25

Result of Questionnaire

- I know some tools offer this service, but it doesn't appear to be widely available for in-vehicle work vs. automated powertrain dyno testing at the transmission level
- Automation requires buying additional tools
- Not on current application, except for active damping
- If this were available we would make use of it

Question 17b
Comments/Suggestions

Figure E.1.2-26

Result of Questionnaire

- Automation for use on powertrain dyno that has an easier user interface and be integrated with the control software of the transmission
- Searchable database to extract any data to test driveability hypothesis
- Real time data analysis, selectable conditions to find out the outliers
- Better rejection of false positives (road input, shift aborts)
- Improvement in detection of surge
- More user-friendly presentation of the results
- Move fully to objective tool
- Create an easy to follow tutorial
- I would like to see a more robust integration between subjective ratings and objective criteria for driveability
- More objective metrics, but a tool that can be cost-effective to implement would improve our ability to drive objective metrics and justify the business cost

Question 18

- What improvements would you like to see in the methods you are currently using?

Figure E.1.3-1

Result of Questionnaire

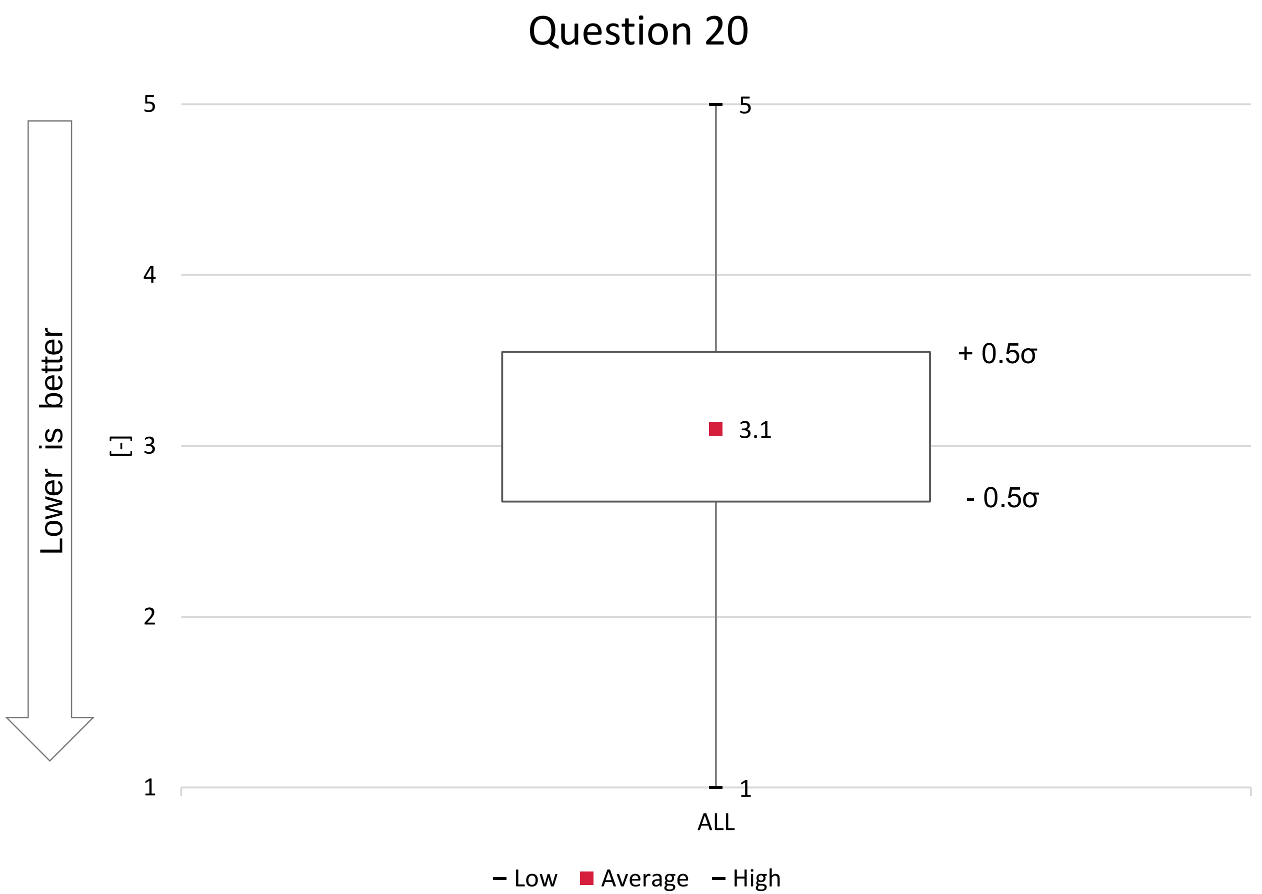
- Automation
- Ability to integrate with calibration tool environment
- Real time data analysis
- Selectable conditions to find out the outliers
- Tutorials (Troubleshooting)
- Easier coordination of test flash file and parameter map (A2L) files
- More integrated tool that allows engineers to manage the data flow from start to finish including data visualization utilizing standard templates
- More robust statistical tools for evaluating driveability comparisons between multiple vehicles

Question 19

- What additional features would you like to see in the tool you are currently using?

Figure E.1.3-2

Result of Questionnaire



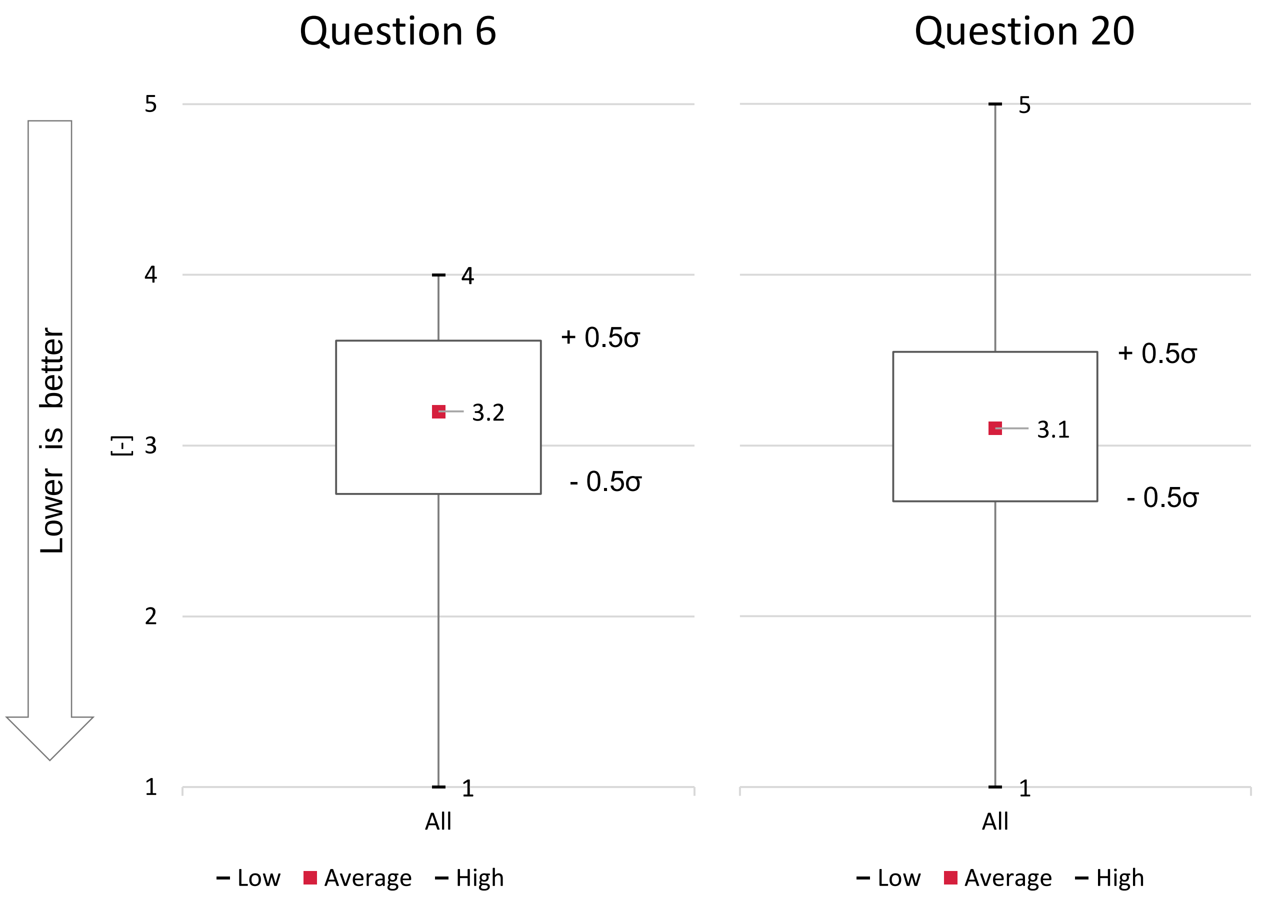
Question 20

- Please rate your satisfaction with the optimization tool.
  - 1 = Completely satisfied
  - 2 = Very satisfied
  - 3 = Fairly well satisfied
  - 4 = Partly dissatisfied
  - 5 = Very dissatisfied

Answered by 18 out of 27 participants

Figure E.1.3-3

Result of Questionnaire



Question 6 & 20
▪ Question 6: Please rate your overall satisfaction with the level of correlation between subjective ratings and objective metrics. ▪ Question 20: Please rate your satisfaction with the optimization tool. – 1 = Completely satisfied – 2 = Very satisfied – 3 = Fairly well satisfied – 4 = Partly dissatisfied – 5 = Very dissatisfied

Q6 Answered by 24 out of 27 participants
Q20 Answered by 18 out of 27 participants

Figure E.1.3-4