Project Report

ICCT Fuel Economy Data Collection Pilot Study

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Author	**TÜV NORD Mobilität GmbH & Co. KG** Institut für Fahrzeugtechnik und Mobilität Adlerstraße 7 45307 Essen Heiko Ehrich
Prepared for	**International Council on Clean Transportation** Neue Promenade 6 10178 Berlin Peter Mock, Francisco Posada, John German

Contents

1 Executive Summary

ICCT has identified the need to determine the characteristics of instantaneous fuel economy tendencies of vehicles in today's European fleet of light-duty vehicles. ICCT recognized that before a major nationwide instrumentation study of fuel economy characteristics could be undertaken, a pilot study addressing logistic and technical issues was required. ICCT contracted TÜV NORD Mobilität GmbH & CO. KG to conduct each a pilot study to identify areas of concern and possible alternative solutions in four areas: vehicle sample structure and size, vehicle recruitment methodology, data logger evaluations, and estimated project cost. This report summarizes the results of both the US and EU pilot studies.

1.1 Vehicle Sampling

The investigation of sampling methods showed that stratified sampling can be a proper approach for determining the vehicle sample size. The general stratification criteria have to be defined with regard to the objectives of the full-scale study. Related stratification parameters could be, for example, model year, vehicle model, engine type, fuel type, engine power, vehicle age, private or commercial vehicle use.

The stratification criteria and the sample size have to be determined in consideration of the representativeness of the sample. It has to be considered that the group of vehicles that is available for drawing the sample not necessarily represents the current fleet of registered vehicles appropriately. Not every vehicle provides the required OBD data for determining the fuel efficiency with the desired accuracy and, furthermore, the field study requires volunteer drivers. Thus, the sample has to be compiled by selecting suitable vehicles (with the required OBD data) from the pool of volunteers. This will assure the representativeness of the composed sample.

An exemplary sample size calculation has been performed based on certain assumptions. Depending on the main goals of the investigation, the resulting sample size can vary significantly. A smaller sample size in the range of 200 vehicles allows e.g. to analyze certain influences of the real vehicle fuel consumption for the vehicle fleet in general. A size in the range of 500 vehicles allows a more detailed analysis of the deviation of real fuel consumption from the type approval values. A large sample size in the range of 1,000 vehicles or above might be suitable if a detailed investigation with analyzing the fuel economy for multiple specific vehicle models is intended.

1.2 Vehicle Driver Recruiting

A survey with customers of different TÜV NORD stations showed that more than 50 % of the questioned people have the impression that the fuel consumption of their vehicle is higher than specified in the manufacturer's data sheet. Around 25 % of the people who filled out the questionnaire showed interest in participating in the fuel economy data collection study. Every third volunteer desires some level of monetary incentive. Incentives help a large scale data collection study in two ways: by increasing the probability of finding willing participants and by engaging participant in accomplishing some small tasks. The survey also showed the opportunity to recruit participants and support vehicle drivers with the installation of data loggers, if needed, via TÜV NORD stations.

The pilot explored different opportunities to recruit volunteers for the data collection project. Several commercial companies and organizations that have a large base of vehicle drivers were contacted. Vehicle clubs showed big interest in the results of the fuel economy field study. The most promising option for driver/vehicle recruiting are vehicle clubs. We found that the Fédération Internationale de l'Automobile (FIA) could be a potential field study partner, acting as the global contact for different vehicle clubs.

As the share of commercial vehicles is increasing in the new vehicle business, it seems meaningful to consider them in the sample, too. Vehicle leasing suppliers that were contacted showed no interest in participating in the study because of market policy reasons. Discussions with companies from other sectors showed that it is generally possible to include commercial vehicles from companies that operate large vehicle fleets or use vehicle fleets that are already equipped with data loggers. If this option were considered, cost and legal aspects would have to be clarified before launching a large-scale study.

1.3 Determining the vehicle fuel consumption via OBD data

The OBD standard specifies a large set of parameter identifiers to request sensor data and further information from the vehicle ECUs that are connected to the diagnosis system. We found that common vehicles support only a small set of the functionality specified in the OBD standard.

Fuel consumption data from OBD loggers was compared against dynamometer testing. Three Otto engine vehicles and three Diesel vehicles were equipped with OBD data loggers and tested with defined driving cycles on a chassis dynamometer. With the logged data, determining vehicle fuel consumption based on the stoichiometric air-to-fuel ratio was investigated. As vehicle OBD systems support the MAF and/or MAP sensor data, this data could be taken as a basis for calculating the vehicle fuel consumption. It turned out that, depending on the supported PIDs and also the engine and fuel type, the achievable accuracy varies strongly.

MAF based FC estimation with Gasoline Vehicles

The experiments showed that estimating the fuel consumption for the tested Otto engine vehicle that supports the MAF sensor data via the OBD system leads to a result that is very close to the calculated fuel consumption based on the dynamometer emission measurement. For the tested vehicle and driving cycle, the total deviation is less than 2 %, but it should be noted that the deviation is not constant during runtime.

MAF based FC estimation with Diesel Vehicles

The vehicle test showed that the value of the determined fuel consumption for the tested Diesel vehicles using only the MAF sensor data is much higher than the real fuel consumption. This is because diesel vehicles always operate lean and the air-to-fuel ratio is never held constant.

Further experiments showed that the accuracy of the FC estimation can be improved significantly when additional OBD parameters are considered that are related to the current air-to-fuel ratio, commanded by the fuel management system. Thus, if the vehicle OBD system supports such parameters as the calculated load value and the equivalence ratio, then the accuracy of the FC estimation can be improved significantly. Without available OBD air-to-fuel ratio correcting parameters, the observed accuracy is not sufficient for the intended purpose of the full-scale study. The best solution would be accessing manufacturer specific PIDs that report on fuel rate. However, this option requires tailoring each data logger to capture the desired data on a model-by-model basis.

MAP based FC estimation

The estimation based on the MAP sensor does not lead to sufficient results for both vehicle types, Diesel and Otto engine vehicles. Estimating the air flow based on the MAP sensor data requires consideration of further OBD parameters such as the engine speed and the intake air temperature and also knowledge on the engine's volumetric efficiency. The volumetric efficiency is usually unknown for a specific vehicle engine and varies for one engine in different operation conditions. Specific vehicle tests could be designed to determine the volumetric efficiency of a vehicle, but the high costs probably makes it unfeasible for all vehicles of the sample.

Based on the experienced acquired from these vehicles experiments, it is recommended to use the following vehicles in the sample: Gasoline vehicles (GDI or PFI) that support MAF sensor data; and Diesels that besides MAF data also support calculated load value and the equivalence ratio or oxygen sensor data. A mapping of PID availability for the fleet has to be performed. It is expected that non-standard vehicle PIDs would be required, especially for Diesel vehicles.

Access to non-standard PIDs (manufacturer specific PIDs) are not offered for purchase in the European public domain. Several data logger manufacturers perform intensive reverse engineering activities with existing vehicles for improving their product functionality by providing access to manufacturer specific PIDs. Incorporating vehicle specific information that may be available via non-standard PIDs can improve the accuracy of the FC estimation. It can be assumed that reading the engine fuel rate as defined in SAE J1979 via PID $5E leads to an accurate result. The accuracy of the PID $5E should be studied against laboratory grade instruments within the next steps preparing the field study.

Investigating factors that affect vehicle fuel economy such as air conditioning, tire air pressure variation or additional vehicle loading, an analysis of non-standard PID data availability is necessary. AC systems are one of the most significant factors of variability in fuel economy.

Evaluation of OBD Data Loggers

A large amount of different OBD data loggers is available on the market. Depending on the intended purpose, these devices differ in functionality, quality and costs. The pilot study evaluated different selected devices and showed that common loggers as used for fleet management applications are generally suitable to fulfill some of the requirements of the data collection project. Nevertheless, the evaluation pointed out some limitations of the devices, e.g., in runtime behavior, configurability and device handling.

The communication between a vehicle OBD system and an external scan tool might be implemented using different bus systems. Theoretical analysis of the OBD standard and experiments with different data loggers and different vehicles showed that the available bandwidth of K-Line based vehicle OBD systems is not sufficient to collect the intended number of parameters with a frequency of 2 Hz. As a consequence, for stable and reliable data collection with the required number of parameters and the desired data collection frequency, it is recommended to use only vehicles that support CAN-based OBD systems.

Experiments showed variations of the communication behavior, reaction times and supported PIDs of different vehicle OBD systems and also of different data loggers. Due to this fact and the ambiguity of determining accurate fuel consumption for different vehicles, it is highly recommended to select a data logger that allows implementation of project specific data collection mechanisms. In other words, the data logger should allow model-specific configurations, and preferably, an over-the-air update. If manufacturer dependent PIDs are available for particular vehicles, the data collection procedure should also consider these parameters. Depending on the data logger functionality, a conceivable solution for handling manufacture dependent PIDs would be a vehicle specific pre-configuration or an over-the-air update of the device.

The study describes the necessity of implementing project specific functionality into the data logger software. Within the scope of the study, a list of data logger requirements was created that can be used for designing a suitable data logger application.

1.4 Cost Estimation

Table ES-1 shows an exemplary cost estimation for performing the data collection field study. As the desired sample size depends on the main goals of the field investigation, the knowledge about the vehicle population and the sampling method, the costs were estimated for different sample sizes of 200, 500 and 1,000 vehicles and assuming a one-year operation. It should be noted that cost reduction can be achieved by extending the operation along several years which allows reducing the number of required data loggers while keeping the same sample size. The cost estimation also draws a comparison between different data logger prices: a € 120 data logger, often used in common M2M fleet management applications; and a more expensive device of € 500 per unit, close to pilot study objectives.

Project Step	Subject	Data Logger Unit Price	€ 120			€ 500		
		Vehicle Sample Size	200	500	1000	200	500	1000
Vehicle Sampling	Sample design		€ 30,000					
	Driver Incentives		€ 20,000	€ 50,000	€ 100,000	€ 20,000	€ 50,000	€ 100,000
Driver Maintenance	Data logger installation logistic		€ 15,000	€ 20,000	€ 25,000	€ 15,000	€ 20,000	€ 25,000
Data Logging Solution	Data logger hardware,		€ 36,000	€ 90,000	€ 180,000	€ 112,000	€ 280,000	€ 560,000
	Data logger customization		€ 75,000					
	Non-standard PIDs		€ 50,000	€ 90,000	€ 130,000	€ 50,000	€ 90,000	€ 130,000
Data Evaluation	Data collection and pre-processing		€ 75,000					
	Analysis of data and documentation		€ 20,000	€ 25,000	€ 30,000	€ 20,000	€ 25,000	€ 30,000
Total Sum [€]			€ 321,000	€ 455,000	€ 645,000	€ 397,000	€ 645,000	€ 1,025,000

Table ES-1 – Nationwide OBD FE/CO2 data collection cost summary

2 Introduction

Fuel economy chassis tests executed by car manufacturers, for label or type-approval requirements, follow prescribed driving cycles that are executed under predefined laboratory conditions. These driving cycles do not represent the real operational conditions of a passenger vehicle during its lifetime, as there are multiple variations in driving, environmental and geographic conditions. Vehicle in-use fuel economy shows great variability, and assessing the magnitude and causes of this variability is an important step to better predict vehicle performance in real life.

The ICCT has identified the need for determining the characteristics of instantaneous fuel economy tendencies in passenger cars operating in the European Union. Covering a wide range of vehicles across more than one member state implies significant logistic and technical challenges. Therefore, before a European-wide in-use FE data collection study could be undertaken, a detailed evaluation of its main design features is required.

The subject of this pilot study is to analyze the feasibility of an investigation on determining the fuel economy, i.e. fuel consumption and CO_2 emission of passenger vehicles in the European Union. The results, of this pilot study intends to assess the requirements, in terms of technology and costs, and to develop a methodology for collecting and analyzing vehicle in-use fuel economy data from passenger vehicles according to variations in driving, vehicle, power train technology, and environmental and geographic conditions.

3 Vehicle Sampling

The planned fuel economy data collection shall point out the real vehicle fuel economy in road use. Therefore, a sample containing a number of vehicles registered in Europe shall be drawn for collecting data over a period of one year. To obtain a representative result, the vehicle sample must have a certain size and consider several aspects related to the investigation purposes.

3.1 Sampling Methods

The main objective of sampling theory is to draw conclusions about particular characteristics of a statistical population.

In order to reduce the effort required for the analysis, a selected subset of the population is analyzed, instead of all elements of the complete population. To acquire statistically valid data, the investigated sample has to be representative for the whole population with respect to the analyzed characteristics. A large sample size may lead to a more representative result but implies higher costs. More important than the sample size is its compliance with the statistical population.

In order to ensure both the statistical validity of the data and reasonable expenses, it is necessary to consider several preliminary deliberations concerning the goals of the investigation, the population, the sampling method, the required sample size and parameters that influence the results and their validity.

Beside scientific aspects of the theoretical method to determine the ideal sample size, in practice the definition of the sample size is also affected by economic, personal and time restrictions.

A common approach for preparing a significant sampling survey starts with the specification of the goal in form and content as well as the delimitation of the statistical population and the characteristics to be investigated. Based on these initial considerations, a reasonable sampling method can be selected and the sample size can be determined on the basis of the investigated characteristics and the probability and margin of errors.

Statistics theory provides several methods for the definition of the sample size, which can be improved with scientific investigations and suitable assumptions. Within this study, the random and the stratified sampling methods are analyzed in view of applying to the planned fuel economy investigation. The following sections give a short overview of these methods and evaluate the applicability to the planned project. Finally an exemplary calculation of the sample size is done based on certain assumptions.

3.1.1 Statistical Population

The statistical population describes the number of elements available in the area of interest that shall be analyzed regarding the selected characteristics. As the main focus of the investigation lies on the fuel economy of passenger vehicles in European road use (i.e. the fuel consumption and the CO_2 emission), the set of registered passenger vehicles in Europe may be assumed as the population. Within this study it is planned to collect data by recording vehicle GPS information and vehicle OBD data. Thus, it has to be considered that not all passenger vehicles registered in the EU may have an OBD-II connection. Therefore, only OBD-II compliant vehicles that provide the required sensor data can be considered in the sample. As a consequence, the statistical population may be defined with the number of all vehicles registered in the EU that are equipped with an OBD-II system.

3.1.2 Random Sampling

An unrestricted random sampling applies if every element E_i of a population N has the same chance to get into the sample N'. Accordingly, the probability that an element E_i from N is selected for the sample is N' / N.

When a simple random sampling is used, the variance of the estimation increases with an increasing inhomogeneity of the population. Every element (vehicle) has the same chance to get selected. The representativeness of the sample for the statistical population improves with an increasing sample size.

For the purposes of the planned fuel economy investigation, it has to be considered that a completely unrestricted random selection from N is not given, because the participation of vehicle owners in the data collection phase is voluntary, so it cannot be assumed that every vehicle is available for the selection of samples. Furthermore, it cannot be assumed that every vehicle owner in Europe is asked for participation and also fuel consumption cannot be estimated with the desired accuracy for every vehicle.

It should be considered that the sample from the available population can be interpreted as a simple sample of the whole population, based on the assumption that the investigated characteristic has an equal share in both populations.

The availability of detailed information on the European vehicle population would allow selecting a representative sample from the set of available vehicles. It would be possible to limit the sample investigation to certain regions, if they are selected in view of the representativeness for the whole population with respect to the investigated characteristic.

3.1.3 Stratified Sampling

Stratified sampling methods can be used if the population can be divided into several layers. In comparison with the simple random sampling, these methods may lead to a smaller sample size with the same significance. The stratification of the population is performed with one or more layer characteristics that are related to the investigation characteristic. Thereby the elements of one layer shall be homogeneous but different layers shall be inhomogeneous by showing a high variance. This requires certain knowledge of the population to determine the layers that improve the efficiency of the stratified sampling method.

After the stratification of the population, a sub-sample can be taken from each different layer. Drawing elements from the population can be done with a proportional distribution, which means that the ratio of the distribution in the population and the sample is similar. Using a proportional distribution may cause small layers to be undersampled, thus reducing the possibility to draw reliable conclusions.

In the disproportional stratified sampling method, equal sample size can be selected for each layer. This approach ensures a sufficient number of elements for each layer but requires more effort for the evaluation of the investigation result regarding the whole population.

3.2 Stratification of vehicle population

There are several vehicle characteristics that correlate to the fuel economy and might be used for the stratification of the vehicle population. The challenge lies in determining the characteristics that allow picturing the vehicle population, considering vehicle types with different fuel economy and fulfilling the requirements of being homogeneous within the layer and inhomogeneous between different layers.

Criteria have to be determined which are required to draw statistically valid conclusions. If propositions to the vehicle fuel economy have to be taken into account on particular vehicle parameters, vehicle classes or on different vehicle models, these criteria have to be considered in the selection of vehicles and therefore in the stratification.

3.3 Examplary Sample Size Calculation

During the investigation of a sample, one or more characteristics that are available in the population are analyzed. Different types of characteristics can be investigated which influence the applicability of statistical methods and the determination of the parameters. The value of a quantitative characteristic (heterograde) can be scaled metrically and has a decimal number. A qualitative characteristic (homograde) is described with a category.

Depending on the conclusions that shall be drawn from the results of the investigation, there are several important criteria that could be considered in the definition of the sample size. It seems to be most reasonable to define a basis for further considerations. This might be:

- The average fuel efficiency of private vehicles in Europe
- The deviation of the real in-use fuel consumption from the manufacturers information for individual vehicle models

The main characteristic that has to be evaluated during the data collection is a heterograde characteristic, the fuel consumption in liters per 100 kilometers.

Thus, the minimum sample size n can be calculated with the following formula.

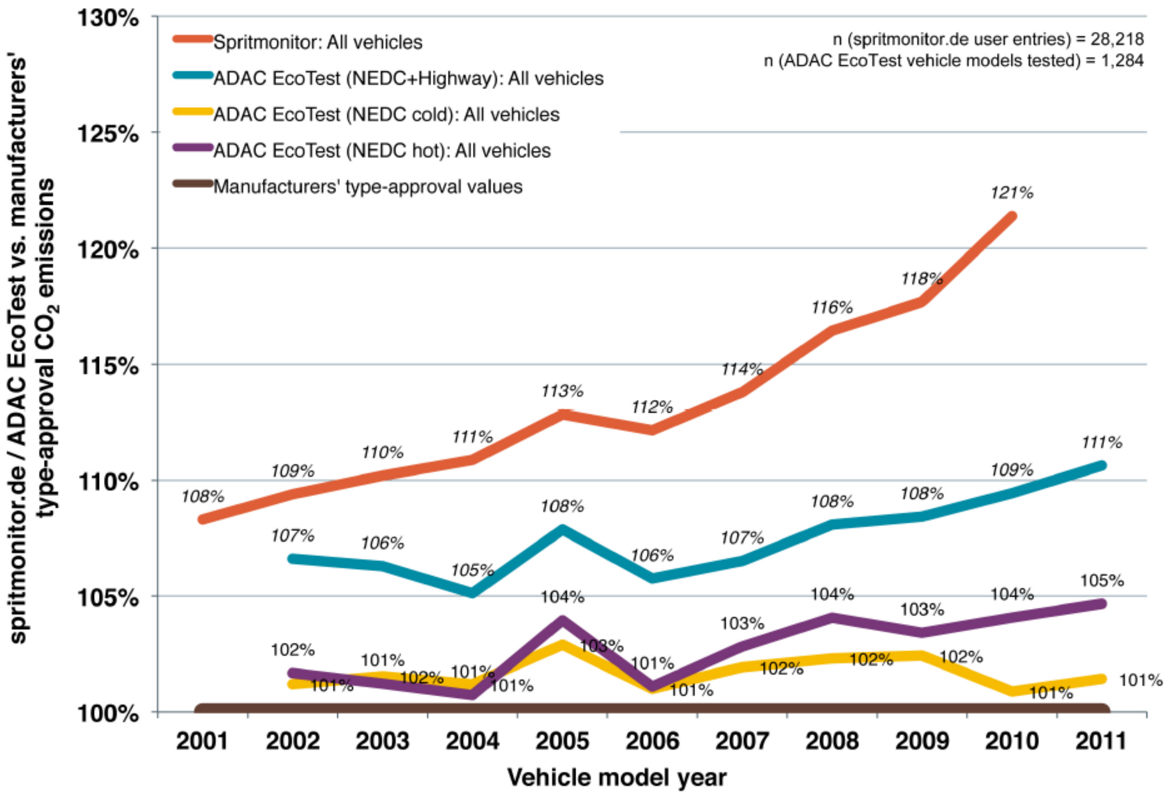
$$n \geq \frac{z^2\sigma^2}{e^2} = \frac{z^2V^2}{e^{*2}}$$

The parameter σ^2 is the variance of the investigated criteria describing the spread of the measurement values and V is the variation coefficient. The parameter z is the significance level (probability of error). The absolute error e with 1 – e* describing the accuracy with which the investigation result is representative corresponding to the stratification criteria.

The exact variance in the population is usually unknown. For the exemplary calculation of the sample size, an assumption is subsequently made based on an analysis performed by ICCT on the *Spritmonitor.de* data.

Vehicle users provide information into the *Spritmonitor.de* database entering the consumed fuel quantity and mileage per trip. According to this information, the CO_2 emission for vehicles between 2001 and 2010 is above the type approval values and the difference increases constantly for new vehicles. The average deviation of the real fuel consumption from the type approval values between 2001 and 2010 is 13.2 %.

The following figure shows the differences in the level of CO_2 emissions according to type-approval values (set at 100%) and measurements from chassis dynamometer tests and from *Spritmonitor.de* data.



The calculation of the sample size is made under the following considerations:

- The investigation criterion is the deviation of the average in-use vehicle fuel consumption from the type approval values.
- The stratification is done on model-by-model variability on CO_2 between manufacturer's type approval values. This allows drawing conclusions on the real fuel consumption difference from the type approval value for a certain vehicle model. A model is thereby described by its manufacturer, vehicle model, fuel type and the engine power.
- For estimating the variance of the measured data, it is assumed that the average in-use vehicle fuel consumption corresponds to the average CO_2 deviation between type

approval and *Spritmonitor.de* data of 13.2 %. Assuming a maximum deviation of 20 % the variation coefficient is V = 20 % / 113.2 % = 17.7 %.

- It is assumed, that the deviation of the fuel consumption corresponds to the normal distribution of the *Spritmonitor.de* values. Thus, the maximum deviations from the average *Spritmonitor.de* values can be given as follows:

Percentage of all measurements	Maximum deviation from average
50 %	$z = 0.675 * \sigma$
68 %	$z = 1 * \sigma$
90 %	$z = 1.675 * \sigma$
95 %	$z = 1.960 * \sigma$
99 %	$z = 2.576 * \sigma$

Table 3-1: Assumed maximum deviations

The following table shows the calculated minimum sample size n for each vehicle model considering different interval widths. It seems reasonable to increase the sample size (e.g. by 20%) and round the result to the closest integer number. The additional percentage is added to maintain the sufficiency and statistical validity of the results by compensating potential losses of participants during the data collection, e.g. by vehicle or data logger damages or vehicle owners leaving the project prematurely.

Variation Coefficient V = 17.7% and Relative Error e* = 5 %		
Interval Width (z)	**N**	**Model Sample Size (additional ~20%)**
50 %	5.71	**7**
68 %	12.53	**15**
90 %	35.16	**42**
95 %	48.14	**58**

Table 3-2: Calculation of sample size for stratification on vehicle model

For example, if the 75 most popular vehicle models shall be analyzed and assuming that 68 % of all measurements have a maximum deviation of 20 % from the average *Spritmonitor.de* data, it would require a total sample size of 1,125 vehicles.

As the exemplary sample size calculation shows, the resulting sample size can vary significantly, depending on the main goals of the investigation and also on the assumptions about the calculation parameters. Further estimations of the required sample size based on different assumptions show, that a smaller sample size in the range of 200 vehicles allows for example analyzing individual influences of the real vehicle fuel consumption, in general for the vehicle fleet. A size in the range of 500 vehicles allows a more detailed analysis of the deviation of the real fuel consumption from the type approval values, for example to prove the model year curve from the *Spritmonitor.de* analysis performed by the ICCT. A large sample size in the range of 1,000 vehicles or above might be suitable if the objective is a detailed investigation with an analysis of the FC behavior for popular vehicle models.

It should be noted that a detailed analysis of the *Spritmonitor.de* data would allow estimating the z parameter more precisely. Furthermore, a smaller value could be assumed for z with greater similarity of the vehicles of one model regarding fuel consumption; for example, by creating strata with similar technical properties such as engine power, gearing or tires.

To draw conclusions about the whole vehicle population, the total sample has to be compiled with multiple vehicle models representative of the population. Therefore, the vehicle population should be analyzed in more detail. The evaluation of the sample also has to consider that individual layers are represented disproportionally. Furthermore a detailed analysis of the vehicle population allows a more precise determination of the variance of the investigation characteristic and the desired significance level of the sample.

The parameter values for calculating the sample size result from the desired goals of the investigation, e.g. deviation of the real fuel consumption from type approval data on vehicle model level or the average deviation for all vehicles.

3.4 Information for Stratification of the Vehicle Population

Based on the regulations of the European Parliament (cf. 1999/94/EG etc), manufacturers and distributors of passenger cars have to provide information regarding vehicles fuel consumption, CO_2 emission and, if applicable, electric power consumption. In Germany these European regulations are implemented on national level with the “Verordnung über Verbraucherinformationen zu Kraftstoffverbrauch, CO_2-Emissionen und Stromverbrauch neuer Personenkraftwagen (Pkw-Energieverbrauchskennzeichnungsverordnung)” [Pkw-EnVKV]. According to this regulation, the information on fuel consumption has to be provided for every vehicle model in combination with the engine displacement, power, gearing mechanism, mass, fuel type or other energy sources. Different fuel types that can be used by one vehicle (such as Super or Super Plus) may be summarized and the fuel consumption has to be given for the groups: urban, highway and combined. These values have to be determined according to defined test cycles within the framework of the vehicle type approval (cf. 80/1268/EWG, 70/156/EWG). If the information is summarized for multiple variants of one vehicle model, the highest consumption value of the group has to be listed. As a result, it might be interesting to compare the collected data with the given manufacturer information.

The European Commission provides statistics on the vehicle stock via EUROSTAT (http://epp.eurostat.ec.europa.eu). The statistics available are given for the overall vehicle stock and for vehicles per 1000 inhabitants on European, national and regional level and on different characteristics describing the vehicle type.

For vehicles in the European Union, the determination of the vehicle fuel consumption is made in accordance with directive 80/1268/EWG, which follows regulation 101 of the United

Nations Economic Commission for Europe (UN/ECE). In Europe vehicles have to undergo a standardized NEDC (New European Driving Cycle) on a chassis dynamometer test. For the type approval of vehicles driven with a combustion engine, at least three vehicles are measured by an independent authority on a chassis dynamometer test stand. If the standard deviation of the production given by the manufacturer is not valued as sufficient, more vehicles have to be tested.

According to manufacturers of start-stop components and also investigations from independent authorities, start-stop systems can save up to 15 % fuel in short-distance traffic.

Tires are responsible for around 20 % of the total resistance for a vehicle. Depending on the kind of tires, the vehicle fuel consumption can vary between 5 to 10 percent for the same vehicle.

Vehicles registered in Germany are presently from more than 50 different vehicle brands, 200 manufacturers, 680 model ranges with more than 2,000 models and 15,000 model types. Manufacturers with a vehicle stock of more than 100,000 in Germany are AUDI, BMW, Chevrolet, Chrysler, Citroen, Daihatsu, Daimler, Fiat, Ford, GENERAL MOTORS, Honda, Hyundai, KIA, Mazda, MG Rover, MITSUBISHI, Nissan, Opel, Peugeot, Porsche, Renault / Dacia, Seat, Skoda, SMART, Subaru, Suzuki, Toyota, Volkswagen, Volvo. (cf. KBA, Fahrzeugzulassungen (FZ) Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Herstellern und Handelsnamen 1. Januar 2011).

In 2010, the world’s vehicle stock reached over one billion vehicles for the first time. With 238.8 million passenger vehicles, the car fleet in Europe (2010) is the biggest in the world, followed by the US with 131.7 million vehicles.

The VDA annual report 2012 indicated that 19,644,000 new passenger vehicles were registered in Europe in 2011. In Western Europe that were 14,683,000, in Eastern Europe 4,056,000 and in the new EU countries 905,000 vehicles.

The European commission provides access to a database via the Eurostat[1] online portal. The vehicle population can be analyzed in view of different characteristics, for example, performance class, empty weight and vehicle age.

The ACEA Pocket Guide 2012[2] gives an statistical overview on the vehicles in use, hereafter the average vehicles age in the European Union is 8.3 years (c.f. table 3-3) and approximately two thirds are running on gasoline (c.f. table 2-4).

[1] http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/

[2] http://www.acea.be/collection/publications/

Average	Share EU
≤ 5 years	32.2 %
5 – 10 years	32.1 %
> 10 years	35.6 %

Table 3-3: EU car fleet by age (2010)

Fuel Type	Share
Gasoline	61.5 %
Diesel	35.3 %
Other	3.2 %

Table 3-4: EU car fleet by fuel type (2010)

Detailed information on the German vehicle population is provided by the KBA. The considerations on the sample size can be done with the details and layers of the vehicle population that are provided in the KBA reports. The KBA report on registered vehicles (Fahrzeugzulassungen (FZ), Bestand an Personenkraftwagen und Krafträdern nach Motorisierung) of January 1, 2012 gives information on the vehicle population based on engine displacement and engine power. In Germany 42,927,647 passenger vehicles are registered at January 1, 2012 and around 90 % of these registered vehicles are in private property. Having a look at new registrations, the picture is different. In Germany 3,080,000 vehicles were registered in 2012, with approximately 61.2 % commercial vehicles. The share of commercial vehicles strongly depends on the vehicle segment. The share of Diesel vehicles is 48.2 %, alternative powertrains are 1.6%.

Looking to the characteristics of private vehicle owners, 33% of new vehicle owners are women, and 50% of new vehicle registrations are from people over 50 years.

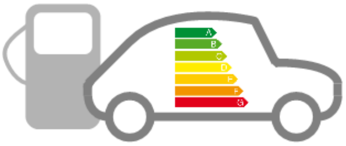
4 Vehicle Recruiting Methodology

The vehicle fuel efficiency field study requires vehicle owners that are willing to participate in the data collection over the runtime of one year. Thereby it has to be considered that the participants selected from the pool of volunteers correspond to the desired composition of the sample. The willingness of vehicle owners to participate in the data collection project is a significant unknown; the willingness might be different on people driving a different mileage per year and also for different vehicle types. Furthermore, incentives that are expected by potential participants are one important design element for carrying out the study.

4.1 Survey at TÜV NORD stations

To get an initial impression on these questions a survey was carried out as part of this pilot study with customers of five selected TÜV NORD service centers. Customers of the service centers come to execute the two year periodic general inspections of their vehicle. Having a prior appointment a customer stays approximately 20 to 30 minutes at the service center, this enables to ask to fill out a small questionnaire in that time.

The next two sides show the questionnaire in German and English language.



Umfrage

Ermittlung der realen Kraftstoffverbräuche von PKWs

TÜV NORD

Mobilität sicher genießen

Sehr geehrter Kunde,

in den Herstellerinformationen zu Ihrem Fahrzeug finden Sie Angaben zum durchschnittlichen Kraftstoffverbrauch. Diese Angaben werden anhand festgelegter Labor-Fahrzyklen ermittelt. Kenntnisse über die tatsächlichen Kraftstoffverbräuche von Fahrzeugen im realen Einsatz sind für Fahrzeugnutzer, Hersteller und Gesetzgeber nicht nur von ökonomischem Interesse, sie können auch zur Verbesserung der Umweltsituation beitragen.

Bitte beantworten Sie die folgenden Fragen und unterstützen Sie eine aktuelle Untersuchung zur Ermittlung der Kraftstoffverbräuche von Fahrzeugen im täglichen Einsatz.

1. Haben Sie den Eindruck, dass der tatsächliche Kraftstoffverbrauch Ihres Fahrzeugs im Alltag von den Angaben des Herstellers abweicht?

□ Der reale Kraftstoffverbrauch ist **höher** als angegeben

□ Der reale Kraftstoffverbrauch ist **geringer** als angegeben

□ Der reale Kraftstoffverbrauch entspricht den Angaben im Datenblatt

2. Welches Fahrzeug besitzen Sie?

Hersteller ____________________ Modell ______________________ Baujahr _________

Kraftstoffart □ *Diesel* □ *Benzin* □ *Gas* □ *Hybrid* □ *Elektrisch*

3. Welche Distanz legt das Fahrzeug durchschnittlich im Jahr zurück? __________ km

4. Unter welchen Bedingungen würden Sie an einer Studie zur Ermittlung des Kraftstoffverbrauchs von Fahrzeugen teilnehmen?

Ihr Fahrzeug wird für die Dauer von einem Jahr mit einem elektronischen Aufzeichnungsgerät ausgestattet. Die aufgezeichneten Motordaten und Routeninformationen fließen anonymisiert in die Analyse ein. Die Anbringung erfolgt über einen genormten Stecker im Innenraum Ihres Fahrzeugs und ist daher voll reversibel.

□ Ich würde teilnehmen

  □ aus Interesse dieses Vorhaben zu unterstützen

  □ und habe Interesse die Daten meines Fahrzeugs einzusehen, via

    □ Smartphone □ E-Mail □ Internet □ postalisch

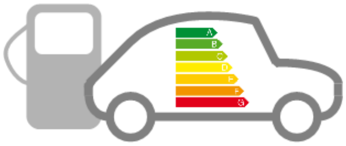
  □ bei Anreiz in Form eines Geldbetrags oder Gegenwerts in Höhe von € _________

□ Nein, ich würde nicht teilnehmen

□ **Bitte kontaktieren Sie mich unverbindlich und senden mir weitere Informationen über die Teilnahme an der Studie.**

Name ________________________ Adresse ________________________

E-Mail ________________________ Telefon ________________________



Survey

Determination of Real Vehicle Fuel Consumption

TÜV NORD

Enjoying Mobility Safely

Dear Customer,

In the manufacturer's vehicle specification you find information on the average fuel consumption. These values were determined by standardized driving cycles under laboratory conditions. Knowing the real fuel consumption of vehicles is valuable for car owners, manufacturers and lawmakers not only for economical reasons, it can also help to improve the environmental situation.

Please fill out this short questionnaire and support a current investigation for determination of vehicle fuel consumption in the daily use.

5. Do you have the impression that the real fuel consumption of your car deviates from the information given by the manufacturer?

☐ The real fuel consumption is **higher** than in the data sheet

☐ The real fuel consumption is **lower** than in the data sheet

☐ The real fuel consumption corresponds to the values given in the data sheet

6. What car do you own?

Manufacturer ____________________ Model ______________________ Construction date ________

Fuel type ☐ *Diesel* ☐ *Petrol* ☐ *Gas* ☐ *Hybrid* ☐ *Electrical*

7. What is the average mileage of the vehicle per year? ___________ km

8. Under what conditions would you participate in a study for determining the vehicle fuel consumption?

Your vehicle will be equipped with an electronic recording device for the duration of one year. The recorded motor and route data are incorporated into the analysis in anonymized form. As a matter of course, the installation in the interior of your vehicle is fully reversible and causes no inconvenience for you.

☐ I would participate

☐ and be interested to see the data of my vehicle, via

☐ Smartphone ☐ Email☐ Internet ☐ Mail

☐ if offered a financial or valuable incentive in the amount of € _________

☐ No, I would not participate

☐ **Please contact me with a non-binding inquiry about study participation.**

Name ___________________________ Address ___________________________

Email ___________________________ Phone ___________________________

In the selection of TÜV NORD service centers for the survey it was considered that these stations have a high amount of customers per day. In winter season there is generally a lower customer demand for general vehicle inspections as in the warmer months, which affects the amount of persons that can be contacted during the survey runtime. On the other hand a lower utilization of the service employees will give them the chance to call attention on the questionnaire.

The survey was executed for six weeks starting at beginning of February at the following service centers:

- TÜV-STATION Hamburg
- TÜV-STATION Hannover-Döhren
- TÜV-STATION Braunschweig
- TÜV-STATION Essen-Frillendorf
- TÜV-STATION Duisburg

During the runtime the employees at the service centers asked around 1,500 customers to fill out the questionnaire while they are waiting for their general vehicle inspection. In total 322 customers filled out the questionnaire and approximately 25 % (82) vehicle owners volunteered to participate in the fuel economy field investigation.

75 volunteers are also interested in receiving a report on their driving data while 9 people marked receiving information via post, 45 people via e-mail and 27 people via the internet. 29 volunteers desire a further incentive for participating in the field study, while people mentioned incentives in an amount of € 80 to € 100 like a tankful, a general vehicle inspection or something similar.

It seems to be obvious, that increasing the individual incentives up to € 250 would increase the participation rate and also reduce the efforts for the recruiting process. An additional task-base incentive could motivate participants to remain in the program over the whole runtime and also to perform particular activities.

The answered questionnaires contain vehicles of 29 different manufacturers. From the 203 vehicles with Otto engine there were 8 vehicles with additional gas fuel. 167 cars were built at year 2000[3] or after, 38 were built before. From the 109 vehicles with Diesel engine 90 cars were built at year 2003[4] or above, 19 before.

The following tables summarize the survey analysis.

---

[3] OBD became mandatory for Otto engine passenger vehicles in the EU (cf. 5.1)

[4] OBD became mandatory for Diesel engine passenger vehicles in the EU (cf. 5.1)

Engine Type: Diesel						
Km per Year	Answers		Vehicle Fuel Consumption			
	Total	Interest[5]	Higher	Equal	Lower	Don't Know
5.000 km	7	1	1	6	0	0
10.000 km	19	4	8	11	0	0
15.000 km	22	5	10	11	1	0
20.000 km	24	5	11	7	2	4
25.000 km	13	2	7	4	0	2
30.000 km	17	7	5	10	1	1
50.000 km	6	2	1	4	0	1
Sum	**108**	**26**	**43**	**53**	**4**	**8**

Engine Type: Otto						
Km per Year	Answers		Vehicle Fuel Consumption			
	Total	Interest5	Higher	Equal	Lower	Don't Know
5.000 km	45 (1 Gas)	12	20	16	5	4
10.000 km	87 (3 Gas)	14	48	32	1	6
15.000 km	34 (1Gas)	14	16	14	1	3
20.000 km	20	7	8	12	0	0
25.000 km	9 (2 Gas)	1	4	3	1	1
30.000 km	7 (1 Gas)	3	3	2	1	1
50.000 km	1	0	0	1	0	0
Sum	**203**	**51**	**99**	**80**	**9**	**15**

Engine Type: Hybrid						
Km per Year	Answers		Vehicle Fuel Consumption			
	Total	Interest5	Higher	Equal	Lower	Don't Know
15.000 km	1	1	1	0	0	0

Engine Type: Don't Know						
Km per Year	Answers		Vehicle Fuel Consumption			
	Total	Interest5	Higher	Equal	Lower	Don't Know
10.000 km	6	2	4	2	0	0
15.000 km	4	0	3	1	0	0
20.000 km	1	0	1	0	0	0
Sum	**11**	**3**	**8**	**3**	**0**	**0**

[5] Participant answered that he is interested to participate the field study

4.2 Evaluation of methods to recruit participants

Depending on the precise objectives to be investigated with the field study the vehicle sample has to be compiled regarding different aspects. Thus a high number of vehicle owners from different European regions might have to be recruited and different aspects as vehicle models, engine technologies and vehicle mileage per year have to be considered.

A conceivable method to recruit participants would be to cooperate with companies or organizations that have a large base of vehicle users and have also be an interest in the results of the study.

Besides the insight gained from the answered questionnaires the survey showed the possibility to recruit participants for the data collection project via TÜV NORD service centers.

Automobile clubs

There are several vehicle and traffic clubs in Europe that have a large number of members. The members are private vehicle drivers and also fleet operators.

These clubs are profit and non-profit organizations with different objectives and goals as

- Road assistance and service for drivers and vehicles
- Regulations and laws
- Environmental improvement
- Road safety

As part of the pilot study several vehicle clubs as ADAC, ACE or AVD were contacted and interviewed for cooperating the project. During the discussion with representatives of different vehicle clubs and also with the ICCT it turned out that vehicle clubs show big interest in the study and in analyzing real in use fuel economy of passenger vehicles. The main interest thereby is producing technical reliable results and investigating different aspects that influence vehicle fuel efficiency in real world driving.

The FIA (Fédération Internationale de l'Automobile) is a non-profit association and brings together over than 230 national motoring and sporting organizations from more than 135 countries on five continents. For further proceeding it was decided to cooperate with the FIA as a representative of the vehicle clubs for the fuel economy field investigation.

Fleet Operators

Although around 90 % of registered passenger vehicles in Germany are in private property, today more than 60 % of new registrations are commercial vehicles.

Thus, it might be worth to analyze the opportunity to include passenger cars from existing vehicle fleets into the sample. An additional benefit could be that fleet operators have a special interest in topics as vehicle remote diagnosis, fleet management and also vehicle fuel efficiency. Participating in the project enables gathering such experiences.

Leasing companies

Leasing companies operate large vehicle fleets and support numerous customers. Within the pilot study three big leasing companies were interviewed for a potential interested to participate in the project. Each of these companies maintains a vehicle fleet comprising one or several hundred thousand vehicles of private and business users.

For reasons of marketing policy none of the contacted leasing companies are interested to participate in the intended project.

Company Cars

Companies are operating vehicle fleets with numerous vehicles being used by the employees for business and also for private operation. Several large companies operate fleets with more than 10,000 vehicles. During the pilot study it turned out that there is a general opportunity that selected companies participate in the project and provide some of their vehicles for the data collection. But, for a detailed discussion with individual companies a concrete definition of project contents and goals is necessary.

TÜV NORD has around 700 company cars in use and most of them are also used by the employees for private purposes. Thus it would also be possible to include several of these cars into the data collection sample.

Existing Vehicle Fleets equipped with data loggers

There are currently a lot of organizations and companies working on fleet management topics and several vehicles are already equipped with OBD data loggers.

During the pilot study the mobile communications provider Vodafone was contacted for discussing the planned fuel economy investigation. Vodafone is developing a commercial M2M platform that also provides remote telematic services. The solution can be used for different use cases, for instance to implement usage based vehicle insurance products were parameters as vehicle and engine speed, GPS information are recorded from the vehicles. It turned out that it is generally possible that vehicles equipped with Vodafone M2M devices can be used for a study as the fuel economy investigation. But, when taking this opportunity into account several issues have to be clarified. Beside technical requirements to the platform and the data that shall be collected there is further discussion on costs and legal aspects necessary.

5 On Board Diagnosis (OBD)

Analyzing fuel economy based on on-board diagnostic data for a wide range of vehicle models needs to evaluate the data that is available via vehicle OBD systems and also to determine meaningful methods for estimating the fuel consumption. The following section illustrates the possibilities and limitations of OBD systems according to the common standardization and summarizes the conducted experiments to estimate the vehicle fuel consumption based on data that was collected from different vehicles when performing chassis dynamometer tests. Besides evaluating the feasibility of the desired fuel economy estimation based on OBD data, the results of this section provide a basis for deriving specific requirements of the data logging application.

5.1 OBD Standardization

The European directives [70/220/EEC] and [98/69/EC] require that a passenger vehicle must supply unrestricted and standardized access to a vehicle on-board diagnostics (OBD) system. The OBD system must provide information required for emission related diagnosis, servicing or repair of the vehicle.

An electrical vehicle diagnosis system for emission relevant data (OBD) (EOBD) system is mandatory for passenger vehicles that are powered by

- an Otto engine since model year 2000 (type approval)
- a Diesel engine since model year 2003 (type approval)

The OBD-II system is standardized in ISO 15031 and consists of 7 parts. In general, the ISO 15031 is harmonized with the SAE standardization and there are only minor deviations between the related ISO and SAE documents. The following table gives an overview of the individual parts of the ISO standard and their SAE equivalents.

ISO 15031			SAE equivalent
Part	Title	Latest Version	
1	General information and use case definition	15031-1:2010	-----------------------
2	Guidance on terms, definitions, abbreviations and acronyms	15031-2:2010	J1930: Electrical/Electronic Systems Diagnostic Terms, Definitions, Abbreviations, and Acronyms
3	Diagnostic connector and related electrical circuits, specification and use	15031-3:2004	J1962: Diagnostic Connector

4	External test equipment	15031-4:2005	J1978: OBD II Scan Tool
5	Emissions-related diagnostic services	15031-5:2011	J1979: E/E Diagnostic Test Modes
6	Diagnostic trouble code definitions	15031-6:2010	J2012: Diagnostic Trouble Code Definitions
7	Data link security	15031-7:2001	J2186: E/E Data Link Security

An OBD compliant vehicle has to provide a standardized OBD-II connector that enables communication with an external scan tool. As several pin functions of the connector are manufacture dependent, an OBD system has to provide at least one of the alternative bus systems, CAN (ISO 15765), ISO 9141, ISO 14230 or SAE J1850. If a vehicle does not support a certain bus system, the corresponding "free" pins may be used for manufacturer dependent usage, but have to be electrical compatible with the given bus systems.

Pin	Function
1	Manufacturer Dependent
2	**J1850 Bus+**
3	Manufacturer Dependent
4	**Vehicle Ground**
5	**Signal Ground**
6	**CAN High (ISO 15765-4)**
7	**K-Line (ISO 9141-2 and ISO 14230-4)**
8	Manufacturer Dependent
9	Manufacturer Dependent
10	**J1850 Bus-**
11	Manufacturer Dependent
12	Manufacturer Dependent
13	Manufacturer Dependent
14	**CAN Low (ISO 15765-4)**
15	**L-Line (ISO 9141-2 and ISO 14230-4)**
16	Permanent battery power

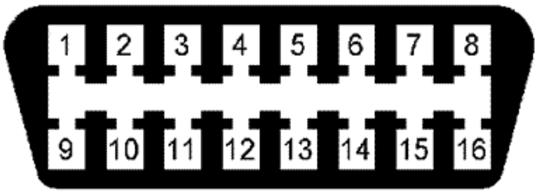


Table 5-3: Pin out of the OBD-II connector

Part 5 of ISO 15031 defines the communication interface between the vehicle diagnostics system and the external scan tool. It provides services and parameter identifiers (PIDs) for requesting emission related vehicle diagnostics data from the electronic control units (ECUs) of the vehicle.

OBD service	Definition
1	Request current power train diagnostic data
2	Request power train freeze frame data
3	Request emission-related diagnostic trouble codes
4	Clear/reset emission-related diagnostic information
5	Request oxygen sensor monitoring test results
6	Request on-board monitoring test results for specific monitored systems
7	Request emission-related diagnostic trouble codes detected during current or last completed driving cycle
8	Request control of on-board system, test or component
9	Request vehicle information

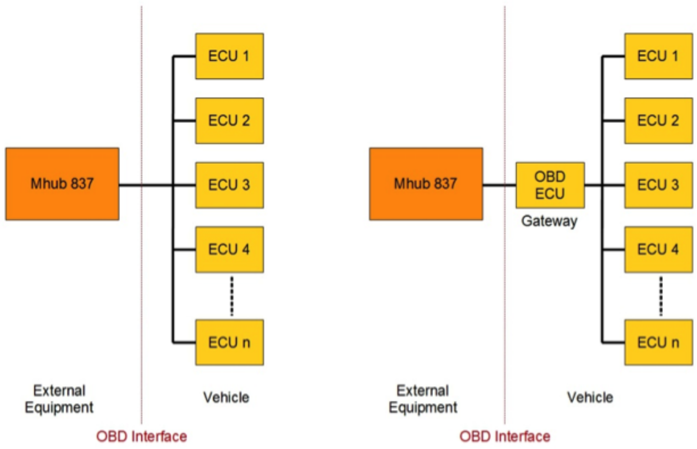
Before OBD data can be requested from vehicle ECUs, the external scan tool has to determine the bus protocols that are supported by the vehicle OBD system. According to [ISO15031-4], the external scan tool must implement an automated built in mechanism for testing the availability of the individual protocols.

After successful determination of the vehicle OBD bus protocol, diagnostic data may be requested via the specified OBD services. Thereby, the external scan tool acts as a client initiating information exchange by transmitting a service request on the OBD bus. Vehicle ECUs are acting as servers and provide the requested data by transmitting adequate service response messages. According to the OBD standard, multiple ECUs[6] that are connected to the OBD interface might send response messages to one data logger request.

The external scan tool does not know which vehicle ECU(s) responds to its requests. The request messages are thereby so-called functional messages.

[6] Today, modern premium vehicles comprise more than 80 ECUs that are connected to the vehicle network. According to OBD standards it is allowed that multiple ECUs answer one request message from the external scan tool.

Besides positive response messages containing the requested data, there are also negative response messages for the [ISO 14230-4] and [ISO 15765-4] protocols. Negative responses have to be transmitted by the ECUs in case those services are not supported or data is not available within defined time slots.



The message length for request messages is limited to seven data bytes, where the first byte holds the request service identifier followed by up to six service-specific data bytes. For OBD via CAN it is allowed to request up to six parameters in one request message. The maximum response payload length is 7 bytes for ISO 9141-2, ISO 14230-4, SAE J1850, for CAN the maximum response payload length is according to ISO 15765-2. The bus protocols allowed for an OBD system can be realized with the following variants:

Bus Protocol	Protocol Variant
ISO 15765-4 (CAN)	11 bit ID, 500 kBit/s
	29 bit ID, 500 kBit/s
	11 bit ID, 250 kBit/s
	29 bit ID, 250 kBit/s
ISO 9141-2 (K-Line)	5 Bit/s init,10.4 kBit/s
ISO 14230-4 (KWP 2000 on K-Line)	5 Bit/s init,10.4 kBit/s
	fast init,10.4 kBit/s
SAE J1850	10.4 kBit/s
	41.6 kBit/s

ISO 15031-5 defines also timing intervals for the communication elements. This implies the timing between requests from the external scan tool and responses from the ECU(s).

Depending on the used bus protocol, the bit rate and the specified timing restrictions, there are limitations in the amount of data that can be transmitted via the OBD interface in a given time interval.

K-Line (ISO 9141-2 and KWP 2000)

The OBD K-Line protocols are operating with a bit rate of 10.4 kbit/s. The bus time for transmitting OBD request and response messages depend on the timing parameters specified within [ISO 14230-4] and [ISO 9141-2] and shown in the following table.

Timing Parameter	Description K-Line	Min. Value	Max. Value
$P1_{K\text{-line}}$	Period between two consecutive bytes of ECU message	0 ms	20 ms
$P2_{K\text{-line}}$	Period between end of request message and successful transmission of response message. Also applies for subsequent response messages to same request.	25 ms for [ISO 14230-4] and key word $0808 for [ISO 9141-2] 0 ms for key word $9494 for [ISO 9141-2]	50 ms
$P3_{K\text{-line}}$	Period between end of final vehicle response and start of new scan tool request message	55 ms	5000 ms
$P4_{K\text{-line}}$	Period between two consecutive bytes of scan tool message	5 ms	20 ms

A best case scenario with respect to the transmission time of a request or response message can be drawn when assuming minimum timing parameters for the K-Line protocols (P1 = 0 ms, P4 = 5 ms); a worst case scenario can be drawn when assuming maximum timing parameters (P1 = P4 = 20 ms).

Scenario	Request Message Bus Time	Response Message Bus Time
Best Case Scenario (P1 = 0 ms, P4 = 5 ms)	30.8 ms	7.7 ms
Worst Case Scenario (P1 = P4 = 20 ms)	137.8 ms	127.7 ms

A best case scenario considering only minimum timings of P1 = 0 ms, P2 = 25 ms, P3 = 55 ms and P4 = 5 ms and assuming that each request is answered with one response message allows collecting up to 4 PID responses with a frequency of 2 Hz.

In real world operation, with real vehicles and data loggers, the timing parameters lie between the best and worst case scenario. The timing analysis pointed out that the opportunities for collecting data of multiple vehicle sensors via OBD, as intended in the fuel economy field study, is very limited for vehicles implementing OBD via K-Line protocols.

SAE J1850

The SAE J1850 interface was introduced in the US simultaneously to the K-Line interface in Europe. It comprises two variants, one with variable pulse width (VPW) bit coding and 10.4 kbit/s bit rate as for instance used by GM and Chrysler, the other variant with pulse width modulation (PWM) bit coding and 41.6 kbit/s bit rate as used by Ford. SAE J1850 is usually not used for OBD communication in European vehicles. Furthermore, using the CAN protocol for OBD communication is mandatory in the US since 2007. Thus, it is recommended to exclude vehicles having SAE J1850 OBD systems in the European data collection field study.

Timing Parameter	Description	Min. Value	Max. Value
$P2_{J1850}$	Period between end of request message and successful transmission of response message. Also applies for subsequent response messages to same request.	0 ms	100 ms

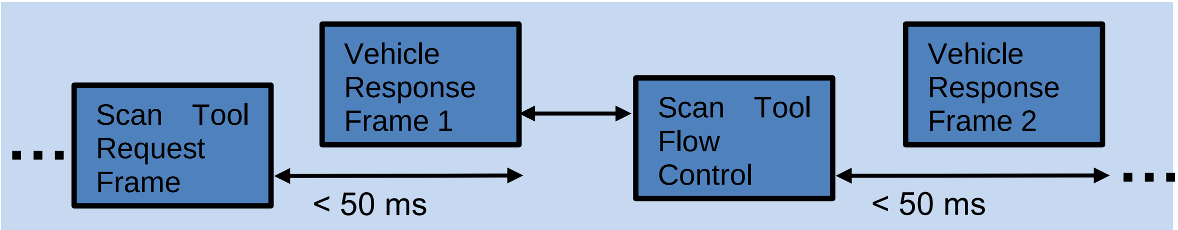
CAN

Using CAN at 500 kBit/s bit rate, transmitting a single CAN data frame containing 8 data bytes takes around 0.23 milliseconds bus time using an 11 bit identifier and around 0,26 ms using the extended ID segment.

Timing Parameter	Description	Min. Value	Max. Value
$P2_{CAN}$	Time between request message and receipt of all unsegmented response messages and all first frames of segmented response message(s). In case the vehicle network architecture uses a gateway to report emission-related diagnostic data, all unsegmented response messages and all first frames of segmented response message(s) shall be received by the external test equipment within $P2_{CAN}$.	0 ms	50 ms
$P2^*_{CAN}$	Time between successful reception of negative response message with response code $78 and next response message (positive or negative message). Negative response message with NRC 78 hex shall not be used as response message to a service $01 request.	0 ms	5000 ms

OBD via CAN allows requesting up to six PIDs with one CAN frame. For most Service 1 PIDs, the vehicle response data usually consists of one or two byte, but can also be more for different parameters. Depending on the amount of response data and the number of ECUs responding to the request, the vehicle transmits one or more response frames. The detailed specification of the transport protocol is given in [ISO 15765].

As shown in the figure below, the first ECU response frame has to be acknowledged by a flow control frame of the external scan tool before the ECU is allowed to continue transmission of the remaining response messages.



To get an impression of the number of OBD parameter responses that can be collected with a frequency of 2 Hz using CAN, the following scenario gives an example based on several assumptions:

- Six PIDs are transmitted within one request message.
- No negative response messages are transmitted by the vehicle.
- Only one vehicle ECU responds to the request.
- The response data for each request message can be transmitted with three response messages
- The response time for the first response frame of the vehicle is 50 ms (allowed maximum) and the two following consecutive frames are transmitted within additional 50 ms.

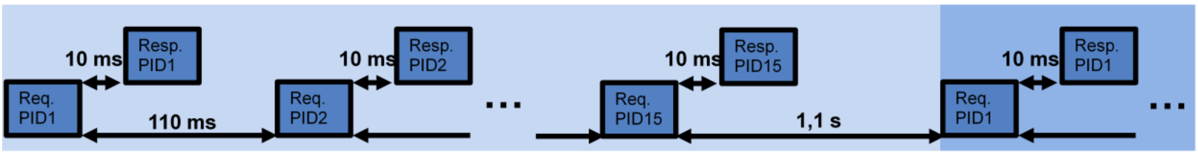
Assuming the described communication behavior, collecting data of six PIDs requires around 100 ms. It should be stressed here, that the transmission and timing behavior of real vehicle ECUs differs from the example. As the response time of vehicle ECUs is usually shorter, the possible data collection rate might be higher. But it should be considered that there are also vehicles with multiple ECUs responding to individual PID requests. Because the number of response frames from the vehicle is increased then, additional bus time is occupied and the next request message can only be transmitted after that. The previous example can be used as orientation for the preparation of the data collection strategy. Correspondingly, it is recommended not to request more than 24 PIDs (transmitted via four request frames) with a frequency of 2 Hz.

5.2 OBD Data Logger Vehicle Tests

Several devices were tested for OBD data collection with different vehicles to study data logger OBD signal requests and response rates. As a non disclosure agreement must be signed with some manufacturers for exchange details on device functionality and documentation, the following device limitations observed in the test execution are described without giving explicit device and manufacturer names. Nevertheless, all device manufacturers offered the possibility to customize their products for the usage of the field study.

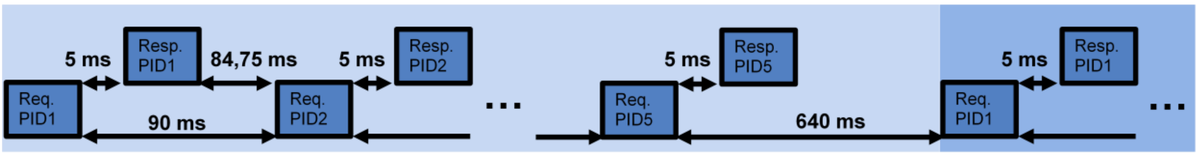
The devices were tested for collecting data from a vehicle OBD system via CAN with a bit rate of 500 kBit/s.

Device one running with its standard firmware was configured to collect 15 OBD parameters with a frequency of 1 Hz. The following figure shows the observation that was made.



It was observed that the device sends each PID request in a separate CAN message. The vehicle OBD system replies every request after up to 10 ms and it takes more than 110 ms until the device sends the next PID request in a CAN message. After all 15 PIDs are requested the device waits around 1 second until the next read cycle starts. Thus, the time between two requests of the same PID is around 3 seconds.

Device two running with its standard firmware was configured to collect 5 OBD parameters with a frequency of 1 Hz. The following figure shows the observation that was made.

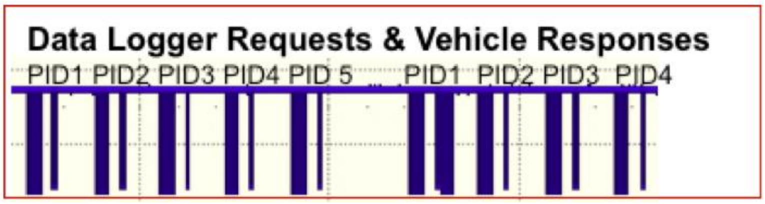


It was observed that the device sends each PID request message in a separate CAN message. For testing device two, a different vehicle was used as for testing device 1. The vehicle OBD system in testing device 2 replies every request after around 5 ms and the device starts transmission of the next PID request message after around 90 ms, which is 40 ms more than the OBD specified maximum value for P2 of 50 ms.

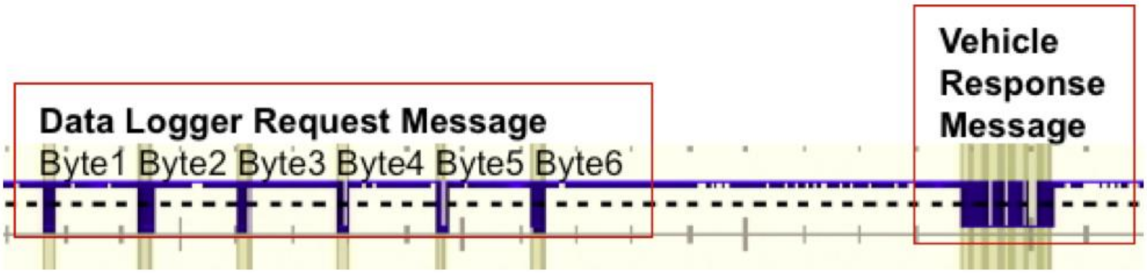
After all 5 PIDs are requested the device waits around 640 ms until the next read cycle starts. With the implemented wait time of 90 ms maximum 11 PIDs can be read within one second by this data logger. Reading more PIDs with a higher frequency could be implemented for the OBD logger by

- reducing the 90 ms wait time ($P2_{max}$ = 50 ms)
- transmitting multiple PID requests within one CAN message
- transmitting the next request directly after the last response

Analogue to the tests on the CAN protocol an additional vehicle test for the K-Line protocol was executed. The device was running with its standard firmware configured to request 5 PIDs with a frequency of 1 Hz.



For the K-Line protocols each PID has to be requested within an individual message. The messages transmitted by the data logger have a specified length of 6 byte with an inter-byte time of around 6 ms. Therefore each individual PID request has a transmission length of around 36 ms. In the test, the vehicle wait time P2 between the request and the single ECU vehicle response is around 30 ms and the single ECU vehicle response has a length of around 7 ms.



The OBD logger wait time P3 between the response and the next request is about 107 ms.

When operating the data logger on K-Line within the test, the time between two request messages was around 180 ms. This means, a maximum number of 5 PIDs per second could be requested in one second considering the vehicle response time of the used car. Reading more PIDs per seconds with a higher frequency could be implemented by

- reduction of the inter-byte time of PID request messages to 5 ms that is the minimum allowed time
- reduction of data logger wait time P3 between the vehicle response and transmission of the next request to 55 ms

For the presented case of 30 ms response time P2 of the single vehicle ECU response with a length of 7 ms, the number of PID responses that could be collected within one second could be increased to 8 when implementing both optimizations.

Conclusions

The investigation of the OBD standard and the additional tests performed with different OBD loggers and vehicles showed, that the number of parameter responses that can be collected with a defined frequency is limited by the used OBD bus protocol and also depends on the transmission behavior of the vehicle and the external scan tool.

The theoretical analysis pointed out, that for collecting data of multiple OBD parameters with a high frequency as required for the fuel economy field study, only CAN based OBD systems appear to be suitable. The K-Line protocol does not provide enough bandwidth to collect the required data.

The results of the test performed with different data loggers and vehicles confirm the theoretical considerations and additionally show that the used data loggers do not provide important features defined within the OBD standard that are required for collecting a high amount of different OBD parameters with a high frequency. In particular, the data loggers do not implement the possibility for transmitting six PIDs within one CAN request frame and are not optimized to perform a time efficient data collection process.

For executing the fuel economy field study it might be meaningful to

- use only vehicles that support CAN, in order to ensure data collection of all required parameters with a sufficient frequency
- limit the number of PIDs that are requested periodically with 2 Hz to 24 PIDs for CAN
- enhance the data logger functionality for transmitting multiple PIDs in one request frame
- reduce the data logger wait time between transmitting different request messages according to the characteristics of the OBD standard
- implement a mechanism into the data logger that initially checks the supported PIDs and message response times of the vehicle and considers the results in the data collection mechanism

To avoid an error-prone and time efficient data collection mechanism, specific requirements to the transmission and reception behavior of the data logger are determined in section 7.3 of this document.

6 Determination of the Vehicle Fuel Economy

6.1 Influences on the fuel economy

The real-world vehicle fuel economy depends on various vehicle and environmental influences. For determining fuel consumption and performing analyses with regard to different vehicle models and varying operating conditions it is important to identify these parameters and analyse how they could be considered and rated in the evaluation of collected vehicle data.

The following table depicts several influences on vehicle fuel efficiency. There are parameters that cannot be recorded via the vehicle OBD system, but might be known from the vehicle model, can be estimated or are an unknown quantity in the estimation.

Influence	Description
Motorization and engine type	Motorization and engine type of vehicles are known through vehicle and driver recruitment data.
Gearing and drive mechanism	The drive and gearing mechanism of vehicles are known. Influencing factors are • manual or automated gearbox • number of gears available • start/stop automatic • front/back or all-wheel drive If the all-wheel drive is switchable it might be necessary to consider the actual setting via a non standard PID.
Vehicle mass and loading	The empty weight of vehicles is known. Vehicle loading and trailers might be an unknown quantity.
Drag Coefficient (cw)	The basis drag coefficient of a vehicle is known. Influences by objects and loading mounted outside at vehicle body as well as influences by opened windows, sunroof and cabriolet top might be an unknown quantity.
Tyres and air pressure	Rolling resistance and air pressure of tires are unknown quantities. Modern vehicles may have a tire pressure monitoring system providing a low pressure warning. This information might be available via non-standard PIDs.

Driver behaviour	The driver behaviour with several factors such as vehicle speed, engine speed, braking and acceleration has a huge influence on the fuel efficiency. Evaluation may be done based on collecting route information and vehicle activity from GPS and OBD data such as speed, RPM and throttle opening rate.
Route	Influencing factors (gradient, curves, ...) can be evaluated based on GPS, OBD, accelerometers and gyro slope determination. Road surface (friction coefficient) might be an unknown quantity.
Climate conditions	Influences like wind, rain, snow might be an unknown quantity. Some parameters like temperature, barometric pressure or humidity might be available via the vehicle OBD system.
Fuel type and quality	General fuel type (gasoline or diesel) is known for a vehicle. Measurements on ethanol proportion might be available via OBD system of some vehicles, but could be inaccurate. The used fuel type quality may vary. Unknown quantities are for example season dependent admixtures or the fuel octane value for Otto engines and the cetane number of diesel fuel.
Auxiliary load	Load at the alternator caused by electrical energy consumers as heating, air conditioning, light, radio are unknown influences. Information might be available via non-standard PIDs.
Vehicle condition and wear parts	Influencing factors caused by vehicle age and wear are • moving parts of vehicle power train • fill level and quality of oil • fill level of cooling water
Engine temperature	The fuel consumption depends on the operating temperature of the engine. During cold start phase and in cold weather the vehicle fuel consumption increases. The influence might be considered via supported OBD parameters.

Motor management	The motor management controls systems as fuel injection, turbo charging and exhaust gas recirculation that influence fuel consumption, emissions and engine performance. Depending on the implementation and parameterization of the motor management system the fuel mixture for a particular engine operation point is adjusted with regard to engine load, engine speed, operating temperature and environmental parameters.

6.2 Data to analyse fuel efficiency

The following table depicts data that shall be collected regarding ICCT requirements [cf. RFP, TNM offer].

ID	Description
[RFP, 3.3.a.1]	At the start of each trip an identifier including the date and time shall be recorded.
[RFP, 3.3.a.2]	The vehicle speed must be recorded in a frequency of 2 Hz. It shall be inspected if the speed information that is available via the OBD-II port is accurate enough to compute acceleration or if an alternative method of determining speed is required and possible.
[RFP, 3.3.a.3]	The vehicle acceleration depending on vehicle speed, data recording frequency and accuracy should be recorded with a frequency of 2 Hz when the engine is running. This requirement is optional. The acceleration can be seen as the change of velocity in a time interval.
[RFP, 3.3.a.4]	The recorded data shall include the distance traveled. The information can be post processed from vehicle speed or GPS data.
[RFP, 3.3.a.5]	The fuel consumption shall be recorded with a frequency of 2 Hz. The ability to calculate the fuel consumption based on information from the OBD-II port shall be assessed.
[RFP, 3.3.a.6]	The recorded data must include the fuel type and an estimation of the ethanol ratio if possible.
[RFP, 3.3.a.7]	The intake air temperature must be recorded with a frequency of 1 Hz. (The value is assumed to be equivalent to ambient air temperature at a time of a cold start.)

[RFP, 3.3.a.8]	Signal that could provide an idea of engine load
[RFP, 3.3.a.9]	The data shall include the altitude recorded with 1 Hz. The measurement of the altitude requires altimeters or barometric instruments or can be based on GPS data (although the altitude accuracy of GPS is lower than the horizontal accuracy).
[RFP, 3.3.a.10]	The geographic location via GPS data must be recorded with a frequency of 1 Hz.
[RFP, 3.3.a.11]	The cabin climate control on/off information must be recorded with a frequency of 1 Hz.
[RFP, 3.3.a.12]	The air conditioning compressor on/off information must be recorded with frequency of 1 Hz.
[RFP, 3.3.a.13]	For hybrids and battery electric vehicles the battery state of charge must be recorded with a frequency of 1 Hz.
[RFP, 3.3.a.14]	For hybrids it shall be recorded with a frequency of 1 Hz if the internal combustion engine is turned on or off.
[RFP, 3.3.d]	The data logger must be able to hold the data for a full year or be capable of transmitting data wirelessly on a periodic basis.

Besides these parameters a vehicle OBD system or specific data logger may provide additional data that can be used to determine and analyze the fuel efficiency of a vehicle.

6.3 Supported OBD PIDs

A vehicle OBD interface provides a large variety of services and therefore several parameter identifiers (PIDs) for requesting services from vehicle ECUs. The PIDs specified in [ISO 15031-5] represent only a small fraction of an entire vehicle ODB interface, but vehicle manufacturers do usually not implement the set of standardized PIDs completely. Typical vehicles support only between 20 and 40 standard PIDs that are related to the emissions power train.

According to [ISO 15031-5] current power train, diagnostic data can be requested via service 1 PIDs (cf. section 6.4). The service 1 PIDs supported by a vehicle can be read via the OBD interface with the following requests.

Service 1, PID	Information on Supported PIDs
PID 0	PID 01 – 20
PID 20	PID 21 – 40
PID 40	PID 41 – 60
PID 60	PID 61 – 80
PID 80	PID 81 – A0
PID A0	PID A1 – C0
PID C0	PID C1 – E0

The following table contains a selected number of PIDs that might be recorded once per trip for each vehicle within the fuel efficiency field study. In this context a trip is defined as the time between vehicle ignition switched on and off.

ISO 15031-5 Parameter	PID
Supported PIDs Mode 1, PID $0, $20, $40, $60, $80, $A0, $C0	
Vehicle Identification Number (VIN) Service $09 (Request vehicle information) Request message: SID 0x09 (SIDRQ), INFOTYPE $02 (VIN) If the vehicle information not be available (ECU response: $FF).	
OBD requirements to which vehicle is designed	**$1C**
Information on oxygen sensors Depending on the supported PID ($13 or $1D) the location of the oxygen sensor location can be retrieved (Bank-No. and Sensor-No.). (According to ISO 15031 a vehicle shall only support one of both PIDs.) PIDs $14 to $1B each addresses a single oxygen sensor.	**$13 $1D** **$14 to $1B**
Maximum value for Equivalence Ratio (Byte A) **Maximum value for Oxygen Sensor Voltage (Byte B)** **Maximum value for Oxygen Sensor Current (Byte C)** **Maximum value for Intake Manifold Absolute Pressure (Byte D)** Required for determine the scaling factor for the corresponding sensor data.	**$4F**
Maximum value for Air Flow Rate from Mass Air Flow Sensor PID $50 is used to retrieve the scale of the air flow rate requested with PID $10.	**$50**

The maximum scaling factor is 2550 and can vary in steps of 10 per bit. The scaling factor 0 indicates an unmodified scale, i.e. the original scaling of PID $10 is used.	
Type of fuel and ethanol ratio The fuel type currently utilized by the vehicle can be read out with PID $51. ISO 15031 specifies 15 fuel types including bi-fuel types. If the utilized fuel type indicates ethanol content the alcohol fuel percentage can be read out with PID $52. The alcohol fuel percentage (PID $52) may be inaccurate, if the fuel contains less than 10% ethanol (in this case ISO 15031 allows a return value of 0%).	**$51** **$52**

The following table contains a selected number of PIDs that might be recorded periodically for each vehicle while ignition is on.

ISO 15031-5 Parameter	PID
Time Since Engine Start The time since the start of the vehicle engine can be read out with PID $1F. The time value has a precision of 1 second and is limited by 65535 seconds.	**$1F**
Vehicle speed Sensor The vehicle speed can be read out with PID $0D. Minimum value is 0 km/h, maximum value is 255 km/h and the scaling is 1 km/h per bit.	**$0D**
Engine RPM PID $0C displays the revolutions per minute of the engine with a precision of ¼ rpm per bit and a range up to 16383,75 rpm.	**0x0C**
Calculated Load Value The calculated load value indicates the percentage of maximum available torque between 0% and 100% with a scaling of 100/255% per bit. The load value reaches 100% at wide open throttle independent of altitude, temperature or rpm.	**$04** (cf. Table B.5 in ISO)
Absolute Load Value The absolute load value can be read out with PID $43 in a range of 0% to 25700% with a scaling of 100/255% per bit. For naturally aspirated engines the absolute load value ranges from 0% to approximately 95%, while it can reach 400% for boosted engines. Spark-ignition engines have to support PID $43, while compression-ignition	**$43**

(diesel) engines may not support this PID.	
Commanded Equivalence Ratio Through the commanded equivalence ratio the fuel system can modify the stoichiometric air-to-fuel ratio during open loop. The multiplication factor has a range of 0 to 1.999 with a scaling of 2/65535 per bit.	**$44**
Oxygen Sensors The oxygen sensors provide the Oxygen Sensor Output Voltage in the range of 0V to 1,275V with a scaling of 5mV per bit and the Short Term Fuel Trim associated with the sensor between -100% and 99.22% with a scaling of 100/128% per bit.	**0x14 – 0x1B**
Fuel Level Input PID $2F returns the nominal fuel tank liquid fill capacity as a percentage of the maximum, where 0% indicates “no fuel” and 100% “maximum fuel capacity”. The scaling is 100/255 per bit.	**$2F**
Air Flow Rate from Mass Air Flow Sensor (MAF) The MAF sensor provides the air flow rate, which can be read out with PID $10. The value has a scaling of 0.01 g/s in the range of 0 g/s to 655.35 g/s. If the actual sensor reading cannot be reported 0 g/s is returned by default. If PID $50 is supported the scaling for the air flow rate shall be calculated based on the reported value for PID $50.	**$10**
Intake Manifold Absolute Pressure The Manifold Absolute Pressure sensor (MAP) provides the intake manifold pressure as an absolute value with a scaling of 1kPa per bit in the range of 0 kPa to 255 kPa. A vehicle using MAP and MAF sensors shall also support both PIDs (MAP and MAF). If PID $4F is supported the scaling for the intake manifold absolute pressure shall be calculated based on the reported value for PID $4F.	**$0B**
Long Term Fuel Trim PIDs $07 and $09 report the long term correction values utilized by open-loop and closed-loop fuel control. PID $07 reports the values for the oxygen sensors of Bank 1 and 3. PID $09 reports the values for the oxygen sensors of Bank 2 and 4. The long term fuel trim value has a range from -100% to +99.22% with a scale	**$07** **$09**

of 100/128% per bit.	
Short Term Fuel Trim PIDs $06 and $08 report the short term correction values utilized by the closed-loop fuel algorithm. If the fuel system is in open loop the correction value 0% is reported. PID $06 reports the values for the oxygen sensors of Bank 1 and 3. PID $08 reports the values for the oxygen sensors of Bank 2 and 4. The short term fuel trim value has a range from -100 % to +99.22 % with a scale of 100/128 % per bit.	**$06** **$08**
Short Term Secondary O2 Sensor Fuel Trim PIDs $55 and $57 can be used to read out the correction value utilized by the closed-loop fuel algorithm based on the secondary O2 sensors. The range and scale of the value is identical to the short term fuel trim value (cf. PIDs $06 and $08).	**$55** **$57**
Long Term Secondary O2 Sensor Fuel Trim PIDs $56 and $58 can be used to read out the correction value utilized by the open-loop and closed-loop fuel algorithm based on the secondary O2 sensors. The range and scale of the value is identical to the short term fuel trim value (cf. PIDs $07 and $09).	**$56** **$58**
Intake Air Temperature The intake manifold air temperature can be read out with PID $0F. According to ISO 15031 the intake air temperature value may be obtained directly from a sensor or derived from other sensor inputs. The temperature value has a range of -40°C to +215°C with a scaling of 1°C (and an offset of -40 °C).	**$0F**
Fuel system status The fuel system status gives information if the system is working in open or closed loop. It can be read out with PID $03 to determine the validity of the short term fuel trim value, because 0% is reported by default if the fuel system is in open loop.	**$03**
Barometric Pressure The barometric pressure can be read out with PID $33 and can be used to derive weather conditions or for altitude approximation. The barometric pressure is reported as an absolute value in the range of 0 kPa	**$33**

to 255 kPa. The scaling of 1 kPa per bit allows a precision around +-100m for the determination of the geographic altitude.	

The SAE J1979 standard describes the parameter engine fuel rate (PID $5E) that shall indicate the amount of fuel consumed by the engine per unit of time in litres per hour. This PID is not contained in ISO 15031-5 and not supported by all vehicles tested within this pilot study.

The website http://www.outilsobdfacile.com/vehicle-list-compatible-obd2.php collects information on the OBD bus protocols and the supported PIDs for more than 7000 vehicles. The available data was provided by registered users. Subsequent to the pilot study it might be advisable to use this data for analyzing different vehicles for supported bus protocols and standard PIDs.

Non-standard PIDs

Beside the PIDs specified in the OBD standards (ISO 15031 and SAE 1979), a vehicle manufacturer implements various diagnostic services into the ECUs that can be requested via non-standard PIDs. These parameters are typically not publicly available and there is only very limited information in the public domain on this subject. Several vehicle manufacturers offer licensing opportunities for accessing non standardized OBD data for vehicle service and repair business. The business models, the available data and also the pricing vary on different manufacturers and also on different vehicle models.

With the ETI Tek-Net library (https://securehost.totalsol.com/Tek-Net_Data_Search/) the equipment and tool institute (www.etools.org) maintains an online database that comprises more than around eleven GB of technical data and documentation for different vehicles. The database covers the vehicle US market and contains several vehicle specific on-board diagnostic information. Accessing the database requires a full membership in the ETI which costs between 5.000 and 10.000 USD depending on the company annual sales and an additional scan tool surcharge of 2.500 USD. Nonetheless, this membership does not involve full access to data from all vehicle manufacturers and several manufacturers require separate licenses with pricing up to 50.000 USD.

No similar collection of vehicle data is available for specifically European vehicles. To realize the fuel economy study, an appropriate way would be to cooperate with an OBD scan tool manufacturer that has information on non standard PIDs available. Several tool manufacturers perform own reverse engineering activities with several vehicles. Refer to section 7.2 of this document for additional information on different data logger manufacturers.

6.4 Methods for determining fuel consumption

Manufacturers of OBD-II data loggers may implement functionality to measure the fuel consumption of a vehicle. In most of known cases details about the implemented algorithms are not disclosed by the manufacturers. Thus, the accuracy of the estimated fuel consumption and the applicability to different vehicles is unknown.

This section investigates methods to determine the vehicle fuel consumption based on data available via the vehicle standard ODB interface.

Engine Fuel Rate

The SAE 1979 specifies the Service 1, PID $5E that allows requesting the engine fuel rate in liters per hour from the vehicle ODB system. Although the SAE 1979 and the ISO 15031-5 standards are almost identical, this PID is not available in the ISO standard. All vehicles tested as part of this pilot study do not support this PID.

Fuel Level Input

A trivial method to compute the vehicle fuel consumption may be done by considering the tank capacity and the distance travelled. Based on the fuel input level (Service 1, PID $2F) and the vehicle speed (Service 1, PID $0D) the fuel consumption in a time interval can be estimated. The fuel level input indicates the nominal fuel tank liquid capacity as a percent of the maximum with a resolution of 100/255. It is assumed that this method does not guarantee a high accuracy, especially over short distances. Furthermore, estimation of the current fuel consumption while driving with a temporal resolution in a matter of seconds is not possible. Nevertheless, the fuel input level could be used additionally to investigate and improve the accuracy of other methods, in particular when collecting data of a vehicle over a whole year. It should be noted that only one of the six vehicles tested on the chassis dynamometer test stand does support Service 1, PID $ 2F for requesting the fuel level input.

Stoichiometric Air-to-Fuel-Ratio

A more complex method to determine the vehicle fuel consumption may be done based on the stoichiometric air-to-fuel ratio, which is the mixture between the mass of air and the mass of fuel necessary for a complete combustion. Furthermore the three-way catalyst of petrol vehicles works at maximum efficiency at this mixture.

Modern vehicles implement fuel injection and emission control strategies and do not solely operate on a constant (stoichiometric) air-to-fuel ratio, especially for Diesel engine vehicles, which operate under lean conditions 100 percent[7] of the time. In general, a high engine power is reached with a richer fuel mixture; a leaner fuel mixture leads to a more efficient operation. The adjusted air-to-fuel ratio depends on several parameters as the air temperature, the engine configuration or if the engine is supercharged or naturally aspired. Thus, the vehicle motor management adjusts the air-to-fuel ratio during operation in relation to different engine parameters as the engine load and engine speed.

For determining if the currently used air-to-fuel ratio is lean or rich, and by how much, the oxygen content in the exhaust stream is measured using O_2 (lambda) sensors. Operating on the stoichiometric mixture, the lambda value is one. A smaller value (lambda < 1.0) indicates richer fuel content; a larger value (lambda > 1) indicates leaner fuel content.

[7] This does not apply to vehicles equipped with a NO_x storage catalyst.

In general, the fuel system in a gasoline vehicle works in closed loop, if the motor has reached its operating temperature and adjusts the air-to-fuel ratio according to a configuration map that correlates the lambda value. If the system is working in open loop, the lambda factor is not considered.

For determining the injection time with regard to the desired air-to-fuel mixture, an engine fuel management system uses data from a mass air flow (MAF) sensor and/or an intake manifold absolute pressure (MAP) sensor.

A vehicle equipped with an OBD-II system typically supports the MAF and/or MAP sensor data via service 1 parameter IDs. The calculation of the fuel consumption FC in liters per hour using the MAF sensor data and the stoichiometric air-to-fuel ratio may be done with

$$FC_{MAFi}\,[l/h] = \frac{3600 \times MAF_i}{AF_{ratio} \times \rho_{fuel} \times 1000}$$

The total fuel consumption in liters for a time interval can be calculated with

$$FC_{MAF}[l] = \frac{1}{AF_{ratio} \times \rho_{fuel} \times 1000} \sum_{i=1}^{N} (FC_{MAFi} \times v_i \times \Delta t_i)$$

Parameter	Description
AF_{ratio}	The common approximate value for the stoichiometric air-to-fuel ratio for Otto engines lies at 14.7:1 and at 14.5:1 for Diesel engines. It should be noted that diesel engines operate always[8] lean, so additional information is required to correct the theoretical value and find the real one. The additional information may be obtained from O_2 sensors.
ρ_{fuel}	The fuel density can vary regionally, seasonally and is also temperature dependent. At 15 °C the density of conventional fuel ranges between 0.72 to 0.775 kilogram per liter for Otto gasoline and between 0,820 and 0,845 kilogram per liters for Diesel fuel.
MAF_i	The air flow rate from mass air flow sensor is available via OBD Service 1, PID $10.
v_i	The vehicle speed sensor is available via OBD Service 1, PID $0D.
Δt_i	As the sensor data values are changing quickly in real-world driving, the temporal resolution of the data recording is important for the accuracy of the fuel consumption.

[8] This does not apply to vehicles equipped with a NO_x storage catalyst.

Using additional information for estimating the vehicle fuel consumption might increase the accuracy.

MAP based calculation of fuel consumption

Several vehicles do not support the MAF sensor data via the OBD interface but the data of the Manifold Air Pressure (MAP) sensor. Theoretically, the calculation of the MAF value based on the MAP sensor can be done with equation

$$MAF_{MAP} = \frac{VE \times ED \times M_{air} \times RPM_i \times MAP_i}{2 \times 60 \times 1000 \times R \times (IAT_i + 273.15)}$$

The following table depicts the parameters used within this formula. The value of two in the denominator results from the fact that each cylinder of a four-stroke cycle engine repeats the cycle every two revolutions.

Variable	Description
MAP_i	Manifold Air Pressure (kPa) is available via Service1 PID $0B
RPM_i	Revolution Per Minute of the engine crankshaft is available via Service1 PID $0C
IAT_i	Intake Air Temperature given in Celsius is available via Service1 PID $0F
VE	Engine Volumetric Efficiency The volumetric efficiency characterizes the ratio of air volume that is filled into the cylinder for the combustion. An engine manufacturer may implement several options for improving the VE; i.e. turbocharging or supercharging might increase a volumetric efficiency over 100%. In general the VE is not a constant for an engine and varies with RPM and load. If VE considers only the quantity of intake air, respectively the mixture, the exhaust air recirculation (EGR) causes significant influences because the EGR mass is not considered. The VE values will be smaller 100 % then. Depending on the desired accuracy for estimating the long term fuel consumption using a constant VE might be sufficient.
ED	Engine Displacement given in liters is known for a vehicle
M_{air}	The molar mass of air is a constant of 28.97 g/mol
R	The ideal gas constant is 8.314 J 1/K 1/mol

Air-to-Fuel Ratio

Knowledge of the real air-to-fuel ratio that is used for the injection would allow improving the accuracy of the fuel consumption calculation in an appropriate way.

Via service 1, PID $44 the commanded equivalence ratio can be requested from the vehicle OBD system. If the fuel system utilizes conventional oxygen sensors, it shall display the inverse of the commanded equivalence ratio (lambda) while the fuel control system is in open loop. It shall indicate 1.000 while operating in closed-loop.

If the fuel system utilizes wide-range/linear oxygen sensors, it shall display the inverse of the commanded equivalence ratio (lambda) in both, open-loop and closed-loop operation.

Service 1, PIDs $24 to $2B and PIDs $34 to $3B request information on the equivalence ratio (lambda) voltage and the oxygen sensor voltage. The scaling used for determining the value depends on support of PID $4F that gives the maximum value for equivalence ratio. If the PID is not supported, a scaling per bit of 2/65535 shall be used.

To obtain the actual A/F ratio being commanded, the stoichiometric A/F ratio has to be multiplied by the inverse of the equivalence ratio that complies with lambda. Applied to the FC formula this results in

$$FC_{MAF,EQR} = FC_{MAF} \times \frac{1}{EQR}$$

If supported by the vehicle, service 1, PID $03 could be used to request the fuel system status and provides information if the fuel system is working in open loop or closed loop.

Average short and long term fuel trim data

For compensating deviations from the injection system that are caused by wearing and aging of vehicle parts, the engines fuel management system uses short and long term fuel trim tables for the calculation of the quantity of fuel injected. When the fuel injection system drifts to a leaner or richer mixture the injection trim tables counteract.

If long term fuel trim data $LONGFT$ is available via Service 1, PID $07 and $09 and short term fuel trim data $SHRTFT$ is available via Service 1, PID $06 and $08, this data might be used for estimating the fuel consumption. As the consideration of fuel trim data is unknown for a vehicle, the vehicle experiments investigated this data with the following formulas:

$$FC_{MAP,LFT} = FC_{MAP} \times (1 + \frac{LONGFT}{100})$$

$$FC_{MAP,SFT} = FC_{MAP} \times (1 + \frac{SHRTFT}{100})$$

$$FC_{MAP,LFT} = FC_{MAP} \times (1 + LONGFT \ / \ 100) \times (1 + SHRTFT \ / \ 100)$$

Calculated Load Value

The calculated load value is defined in ISO 15031-5 with service 1, PID $04. The standard also reveals that various manufacturers implement the calculation in a variety of ways. The previously definition of CLV in the OBD regulation was

- (current airflow / peak airflow at sea level) * (BARO at sea level / BARO) * 100 %

The standard also gives a more restrictive definition with

- LOAD_PCT = [current airflow] / [(peak airflow at WOT @ STP as a function of rpm) * (BARO/29,92) * SQRT(298/(AAT+273))]

where

- STP = Standard Temperature and Pressure = 25 °C, 29,92 in Hg BARO, SQRT = square root
- WOT = wide open throttle, AAT = Ambient Air Temperature and is in °C

The ISO standard contains also a note that the calculated load value shall be determined by substituting fuel flow in place of airflow in the calculation for diesel applications.

Within the experiments for calculating the fuel consumption for the tested vehicles, the calculated load data supported by the vehicle OBD system was considered for estimating the fuel consumption as followed:

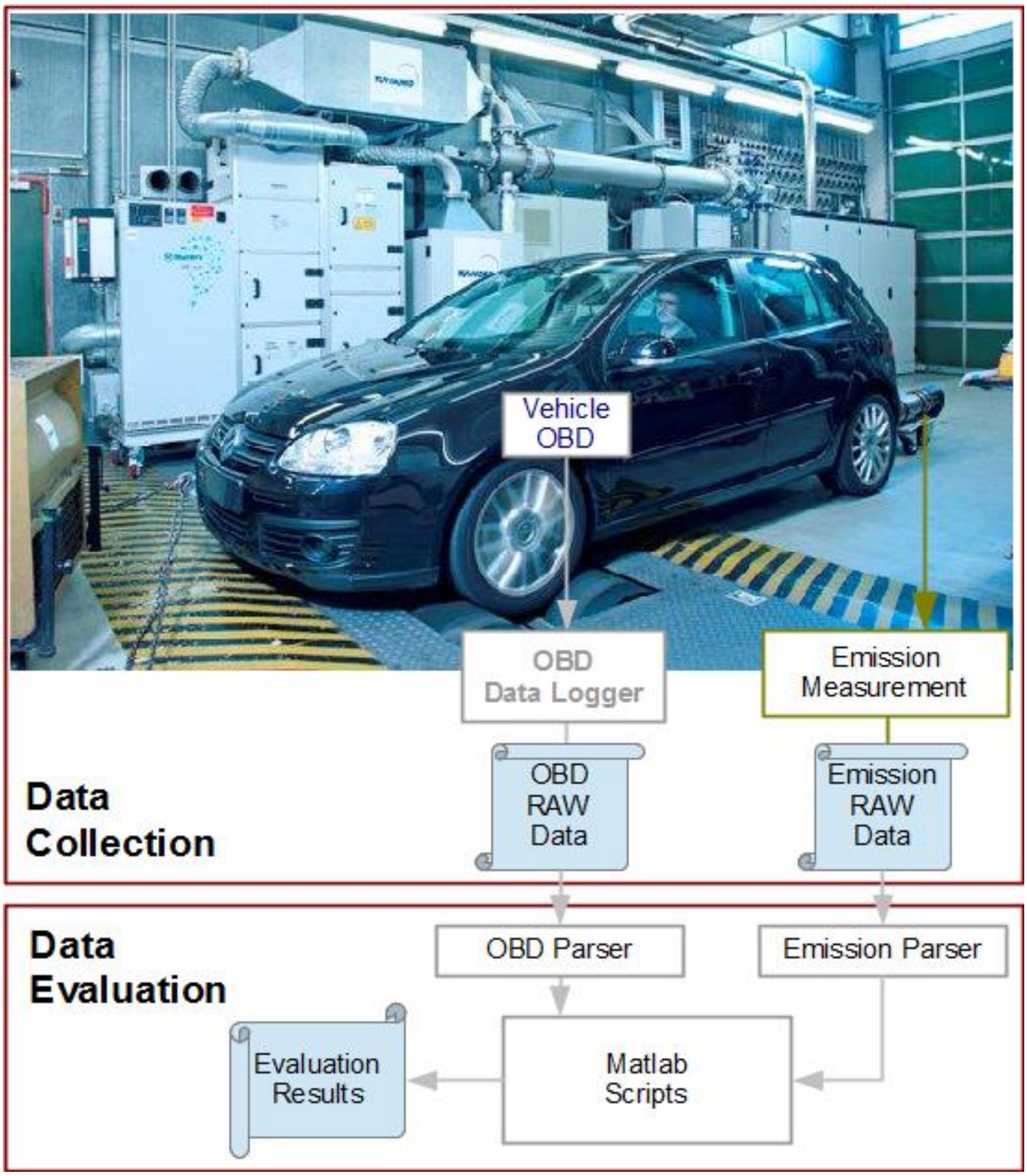
$$FC_{MAF,CLV} = FC_{MAF} \times \frac{CLV}{100}$$

The fuel management system of a Diesel vehicle is not operating at constant air-to-fuel ratio. If the current air-to-fuel ratio decreases, the load increases. Thus, applying the CLV to the FC calculation leads to an appropriate correction to the air/fuel ratio.

For gasoline vehicles, the MAF is linear with the engine load. When the MAF value is combined with the air-to-fuel ratio, the load effect is fully included. Thus, the CLV was not considered in the FC estimation for Otto engine vehicles.

6.5 Chassis Dynamometer Vehicle Tests

For analyzing the options and evaluating the accuracy of calculating the fuel consumption based on OBD parameters, vehicle data was collected from passenger cars of different manufacturers on a chassis dynamometer test stand. The vehicles were equipped with an emission measurement system and an OBD data logger.



Vehicle OBD
OBD Data Logger
Emission Measurement
Data Collection
OBD RAW Data
Emission RAW Data
Data Evaluation
OBD Parser
Emission Parser
Evaluation Results
Matlab Scripts

The measurement equipment delivers a record-file containing masses of the vehicle emission pollutants (HC, HC_{Diesel}, CH_4, NOX, NO, CO, CO_2) given in milligram per second as well as the corresponding vehicle speed in kilometers per hour and the power given in Newton. Based on these measurement values the vehicle fuel consumption was calculated according to the equations given in [ECE_R101]:

a) For Otto engine vehicles

$$\mathbf{FC(Emission) = (0{,}118/D) \cdot [(0{,}848 \cdot HC) + (0{,}429 \cdot CO) + (0{,}273 \cdot CO_2)]}$$

b) For Diesel engine vehicles

$$\mathbf{FC(Emission) = (0{,}116/D) \cdot [(0{,}861 \cdot HC) + (0{,}429 \cdot CO) + (0{,}273 \cdot CO_2)]}$$

with

FC = fuel consumption in liters per 100 kilometers
HC = measured hydrocarbon emissions in gram per kilometer
CO = measured carbon monoxide emissions in gram per kilometer
CO 2 = measured carbon dioxide emissions in gram per kilometer
D = density of the test fuel

For collecting vehicle on-board diagnostic data it was initially planned to use one of the data loggers selected for the evaluation. Experiments with the available devices showed that the data loggers are generally capable to fulfill this purpose, but each of the devices require specific adaptations that could not be delivered by the manufacturers within the project runtime and also the budget of the pilot study. Details on the data logger evaluation can be found in section 7.2.

Nonetheless, to analyze the methods for determining fuel efficiency an ELM327-based hardware interface was connected to the vehicle OBD system and the RS232 serial interface of a laboratory PC. The corresponding PC application was configured to request a set of PIDs with a frequency of two Hertz. The PID request messages where transmitted via CAN to the vehicle OBD system where one CAN frame contains up to six PIDs. The data of the vehicle response messages was stored in a record-file on the PC hard disk. After completion of a test run the recorded data was parsed and transferred to a spreadsheet for further processing in Matlab.

Synchronization of measurement values

For analyzing the measurement data, several MATLAB scripts (m-files) were written that import the record-files containing emission and OBD data into MATLAB, preprocess the data and plot several diagrams for interpretation of the test results. The OBD measurement was executed with a 2 Hz sample rate and the chassis dynamometer test stand delivers emission data with 1 Hz. To perform the comparison of data values, the preprocessing algorithm transforms the OBD data to 1 Hz values by calculating mean values. Furthermore, the time stamps of the emission and OBD measurements had to be synchronized. This was done by means of the measured vehicle speed via dynamometer test stand and OBD logger. All other measurement values use the same time synchronization.

Tested Vehicles

Several vehicles that were initially selected for testing implement OBD over the K-line protocols. As section 5 showed, the bus load of these bus systems does not provide a sufficient bit rate to collect the intended amount of data from multiple sensors with a high frequency. Thus, the tests were executed only with vehicles that provide OBD via ISO 15765-4 CAN.

The following table shows the vehicles that were tested on the chassis dynamometer test stand.

Vehicle Model	AUDI A5	VW Golf	Opel Astra	BMW X3	Ford Focus	VW Passat
Build Year	2012	2010	2010	2011	2010	2010
Engine Type	Otto	Otto	Otto	Diesel	Diesel	Diesel
Engine Displacement [cm^3]	1798	1390	1398	2993	1560	1968
Service 1[9] PIDs supported	not read	38	39	31	26	24
set (MAP, IAT, RPM, CLV, Speed) supported	Yes	Yes	Yes	Yes	Yes	Yes
MAF supported	No	No	Yes	Yes	Yes	Yes
set (LFT, SFT) supported	Yes	Yes	Yes	No	No	No
CER supported	No	Yes	Yes	No	No	No

[9] Service 1 PIDs are used to request current power train diagnostic data.

Lambda supported	unknown	Yes	Yes	Yes	No	Yes

Excluding the AUDI A5 the set of supported PIDs for Service 1 were read from the vehicle OBD system. It showed that the vehicle manufacturers do not implement the standard OBD interface completely in their passenger cars and the set of supported PIDs differs even on different vehicle models of one manufacturer.

But all tested vehicles support the MAP, IAT, RPM, Calculated Load, Engine and Vehicle Speed sensor data. Four vehicles, the BMW X3, the Ford Focus, the Opel Astra and the VW Passat also support the MAF sensor data.

Major differences appear on the data that might be used to estimate the current air-to-fuel ratio. Only the Opel Astra and the VW Golf supports the commanded equivalence ratio, the BMW X3, VW Passat and Golf support different oxygen sensors.

As the experiments with the methods to estimate vehicle fuel consumption started with the stoichiometric air-to-fuel ratio, not all of the supported PIDs that were discussed in 6.1 were collected within the initial vehicle tests. After analyzing and interpreting the data, it seems to be meaningful to continue the analysis of the methods for determining fuel consumption with further vehicle tests and also with analyzing existing data bases that show supported PIDs of different vehicles.

The following table lists all standard PIDs for service 1. If the PID is supported by the vehicle it is marked with an “X”.

S1 PID [hex]	Description	AUDI A5[10]	VW Golf	Opel Astra	BMW X3	Ford Focus	VW Passat
0	Determine PIDs supported (range 01h to 20h)	X	X	X	X	X	X
1	Trouble codes and on board test information		X	X	X	X	
2	Freeze frame trouble code						
3	Fuel system status		X	X			
4	**Calculated load value**	X	X	X	X	X	X
5	Engine coolant temperature		X	X	X	X	X
6	Short term fuel trim Bank 1 & 3	X	X	X			
7	Long term fuel trim Bank 1 & 3	X	X	X			
8	Short term fuel trim Bank 2 & 4						
9	Long term fuel trim Bank 2 & 4						
0A	Fuel rail pressure			X			
0B	**Intake Manifold Absolute Pressure**	X	X	X	X	X	X
0C	**Engine RPM**	X	X	X	X	X	X
0D	**Vehicle speed**	X	X	X	X	X	X
0E	Ignition Timing Advance for #1 Cylinder		X	X			
0F	**Intake air temperature**	X	X	X	X	X	X
10	**Air Flow Rate from Mass Air Flow Sensor**			X	X	X	X
11	Absolute Throttle sensor position		X	X	X	X	X

[10] Note: The complete set of supported service 1, PIDs was not read from the AUDI A5 OBD system.

12	Commanded Secondary air status						
13	Oxygen sensor locations bank/sensor		X	X	X		X
14	Oxy. sensor			X			
15	Oxy. sensor		X	X			
16	Oxy. sensor						
17	Oxy. sensor						
18	Oxy. sensor						
19	Oxy. sensor						
1A	Oxy. sensor						
1B	Oxy. sensor						
1C	Design OBD requirements		X	X	X	X	X
1D	Location of oxygen sensors						
1E	Auxilliary input status						
1F	Time since engine start		X	X	X	X	
20	Determine PIDs supported (range 21h to 40h)		X	X	X	X	X
21	Distance traveled while MIL is activated		X	X	X	X	X
22	Fuel rail pressure relative to manifold vacuum						
23	Fuel rail pressure		X		X	X	X
24	Bank 1 - sensor 1 (wide range O2S)				X		X
25	Bank 1 - sensor 2 (wide range O2S)						
26	Bank 1 - sensor 3 (wide range O2S)						
27	Bank 1 - sensor 4 (wide range O2S)						
28	Bank 2 - sensor 1 (wide range O2S)						
29	Bank 2 - sensor 2 (wide range O2S)						
2A	Bank 2 - sensor 3 (wide range O2S)						
2B	Bank 2 - sensor 4 (wide range O2S)						
2C	Commanded EGR				X	X	
2D	EGR error				X	X	
2E	Commanded evaporative purge		X	X			
2F	Fuel level input			X			
30	Number of warn-ups since DTCs cleared		X	X	X	X	X
31	Distance traveled since DTCs cleared		X	X	X	X	X
32	Evap system vapor pressure						
33	Barometric pressure		X	X	X	X	
34	Bank 1 - sensor 1 (wide range O2S)		X				
35	Bank 1 - sensor 2 (wide range O2S)						
36	Bank 1 - sensor 3 (wide range O2S)						
37	Bank 1 - sensor 4 (wide range O2S)						
38	Bank 2 - sensor 1 (wide range O2S)						
39	Bank 2 - sensor 2 (wide range O2S)						
3A	Bank 2 - sensor 3 (wide range O2S)						
3B	Bank 2 - sensor 4 (wide range O2S)						
3C	Catalyst Temperature bank 1, sensor 1		X	X	X		
3D	Catalyst Temperature bank 2, sensor 1						
3E	Catalyst Temperature bank 1, sensor 2						
3F	Catalyst Temperature bank 2, sensor 2						

40	Determine PIDs supported (range 41h to 60h)		X	X	X	X	X
41	Monitor status this driving cycle		X	X	X	X	X
42	Control module voltage		X	X	X	X	X
43	Absolute load value	X	X	X			
44	Commanded equivalence ratio		X	X			
45	Relative throttle position		X	X	X	X	
46	Ambiant air temperature		X	X	X		
47	Absolute throttle position B		X	X			
48	Absolute throttle position C						
49	Accelerator pedal position D		X	X	X		X
4A	Accelerator pedal position E		X	X	X	X	
4B	Accelerator pedal position F						
4C	Commanded throttle actuator control		X	X	X	X	
4D	Engine run time while MIL is activated						
4E	Engine run time since DTCs cleared						
4F	Maximum value for sensor data 1						X
50	Maximum value for sensor data 2						
51	Type of fuel currently being utilized by the vehicle						
52	Alcohol fuel percentage						
53	Absolute evap system vapor pressure						
54	Evap system vapor pressure						
55	Short term secondary O2 sensor fuel trim - bank 1 & 3						
56	Long term secondary O2 sensor fuel trim - bank 1 & 3		X				
57	Short term secondary O2 sensor fuel trim - bank 2 & 4						
58	Long term secondary O2 sensor fuel trim - bank 2 & 4						
59	Fuel rail pressure (absolute)						
5A	Relative accelerator pedal position						
5B – FF	ISO/SAE reserved						

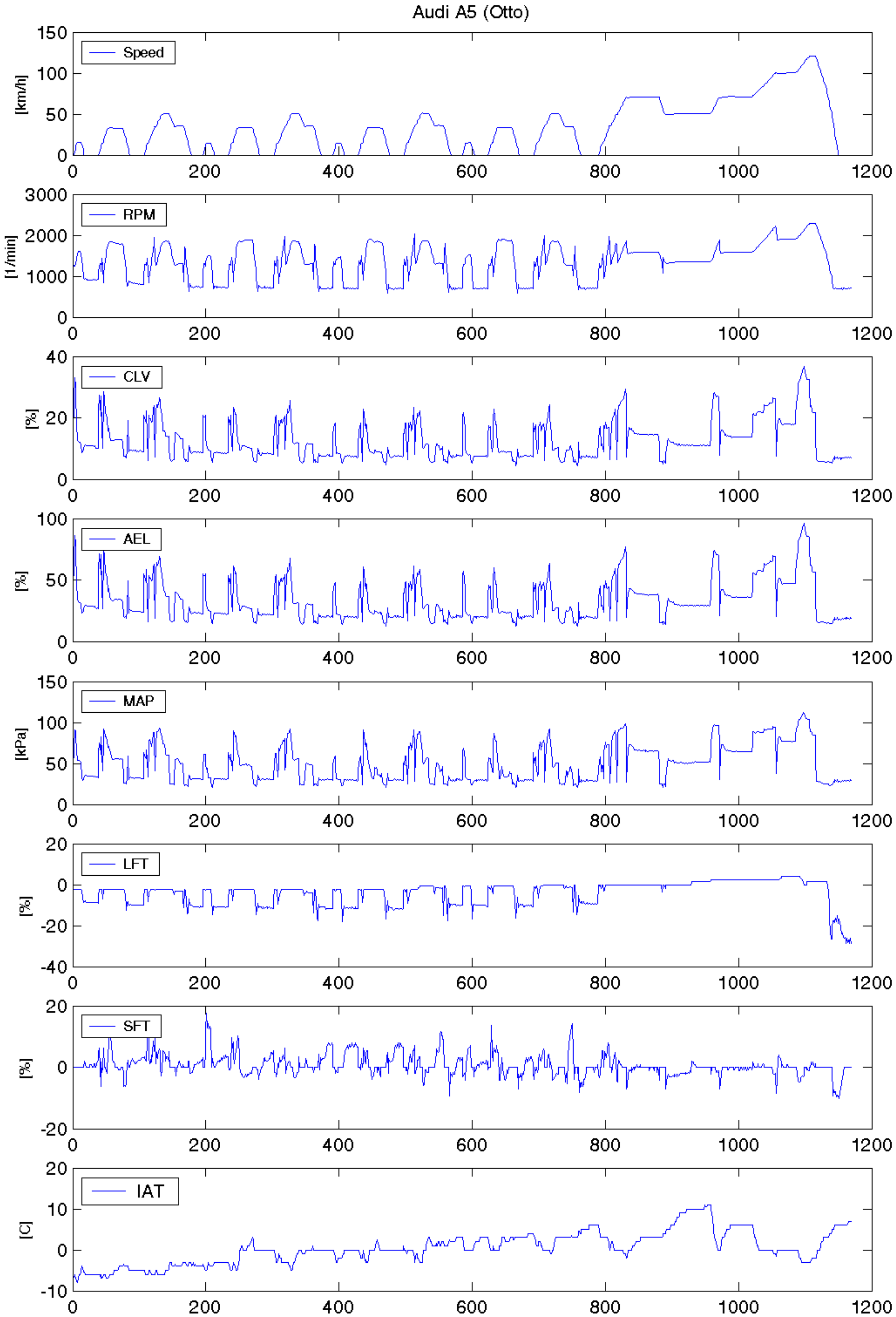
Note: The following pages show plots of the collected OBD data and the applied methods to calculate the fuel consumption. The data is always plotted over the whole driving cycle. Nevertheless, the existing MATLAB scripts are easily configurable to plot specific time sections in more detail or to add further calculations and diagrams. It is also possible to provide the plots in vector graphic format (EMF), which allows zoom into certain areas of the diagrams.

6.5.1 AUDI A5 – Otto Engine

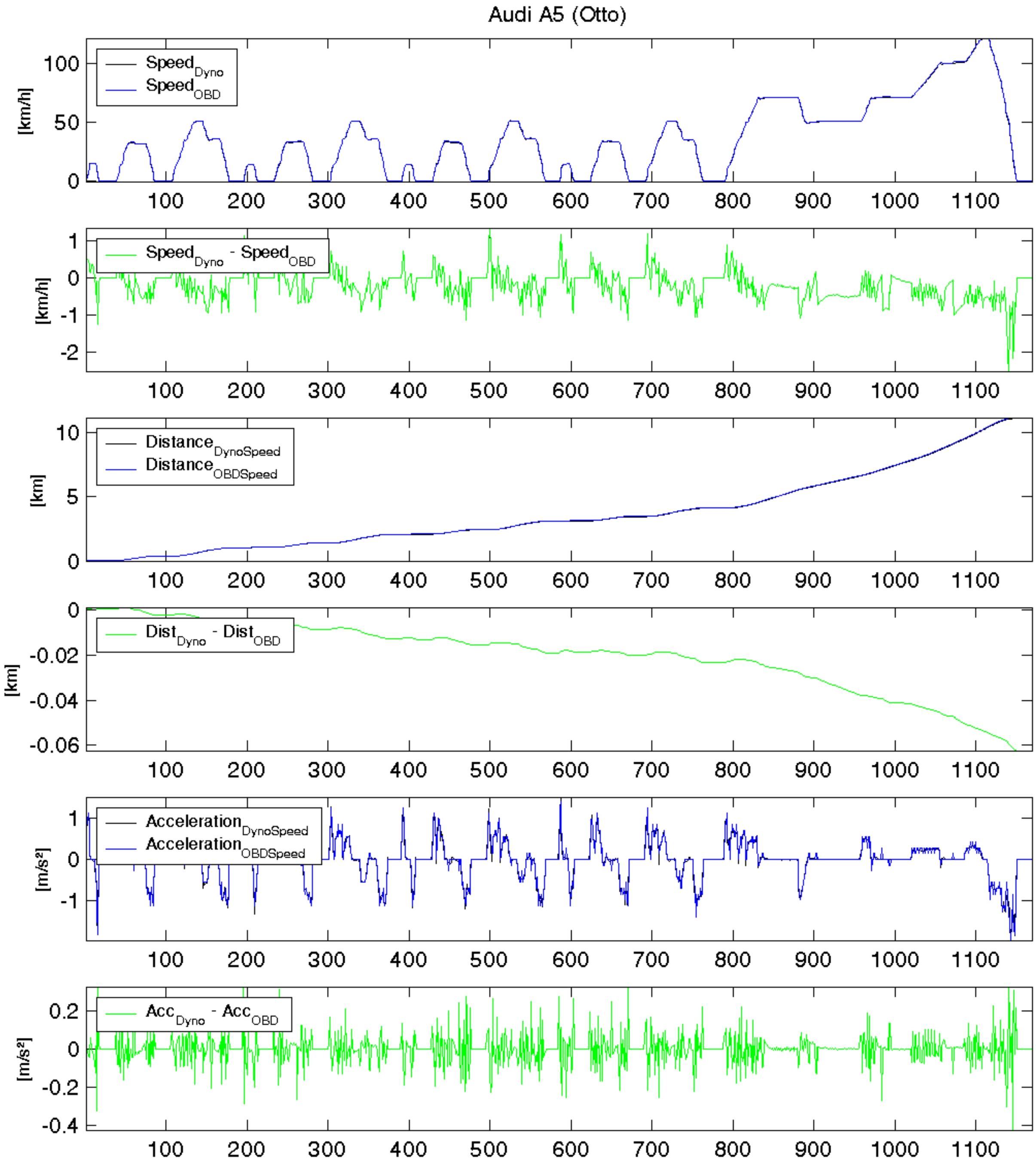
The following data was collected from the OBD system of an AUDI A5 with Otto engine:

- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Absolute Engine Load
- Intake Manifold Absolute Pressure
- Long Term Fuel Trim Data
- Short Term Fuel Trim Data
- Intake Air Temperature

The test was executed with the NEDC (New European Driving Cycle) at an environmental temperature of -7 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.74 kg/l and an air-to-fuel ratio of 14.7:1 was applied.


Audi A5 (Otto)
Speed
[km/h]
RPM
[1/min]
CLV
[%]
AEL
[%]
MAP
[kPa]
LFT
[%]
SFT
[%]
IAT
[C]

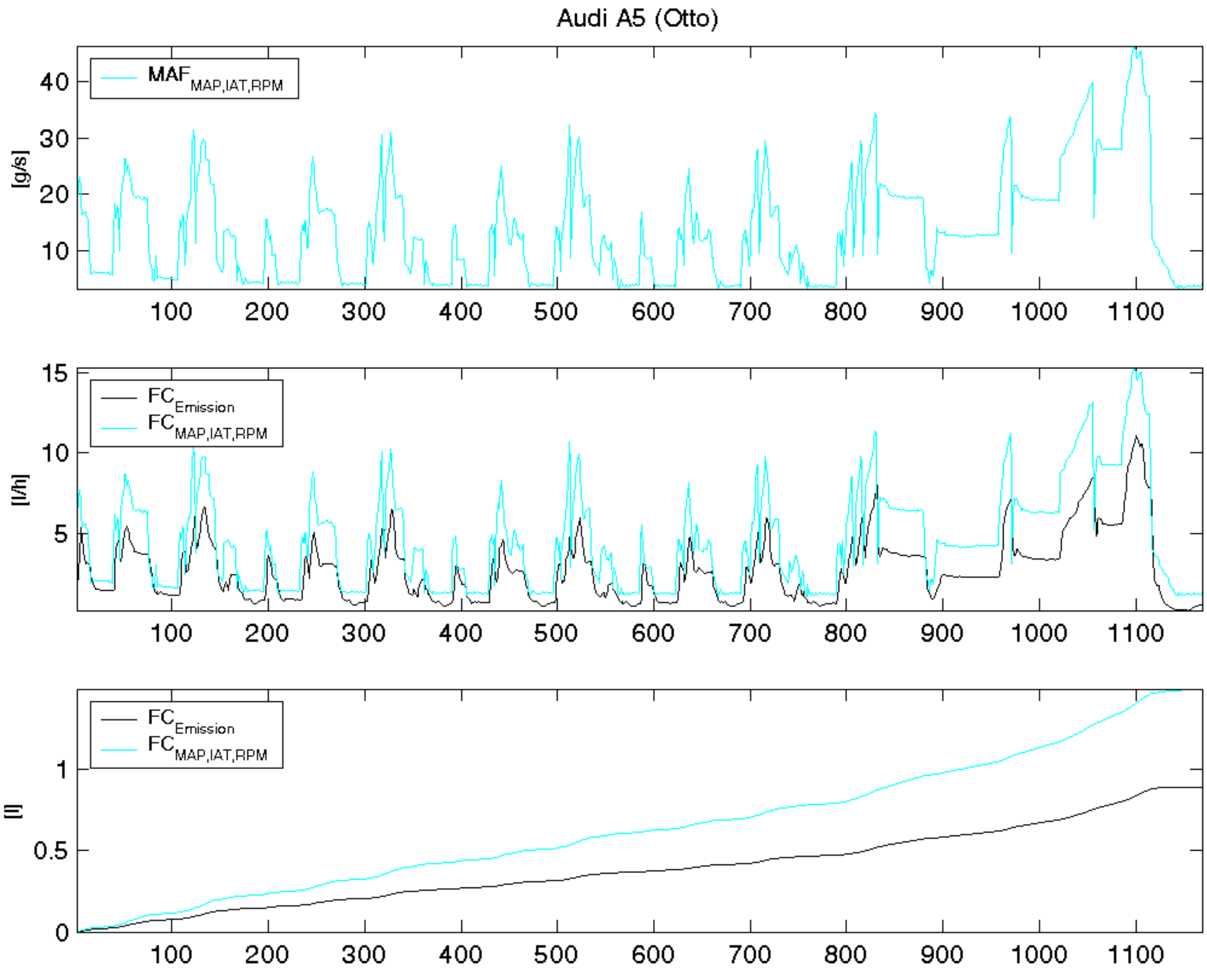
The following plot shows the vehicle speed measured by the OBD interface and the dynamometer test stand. The synchronization of data in time shows that both data flows are relatively close together. The subtraction of the OBD speed from the Dyno speed shows that the OBD speed is a bit below the Dyno speed in positive acceleration phases and a bit higher at constant speed and during negative acceleration phases.



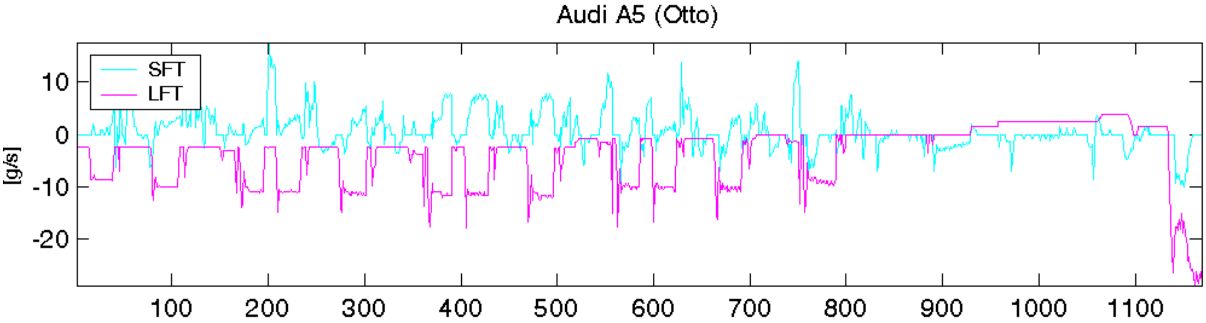
As the deviations in the range of +/-1 km/h are relatively small and also compensate over the whole driving cycle, the calculated distance does not show considerable deviations. Nevertheless the deviations influence the calculation of the total fuel consumption.

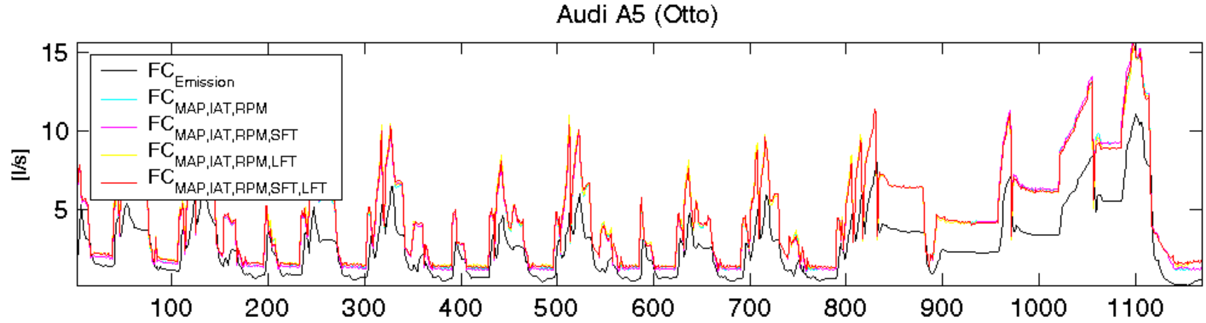
The measured acceleration values vary between -2 and +1 m/s^2 within the driving cycle. The relative deviation of the acceleration is equal to the deviation of the speed, since the acceleration is derived from the speed values.

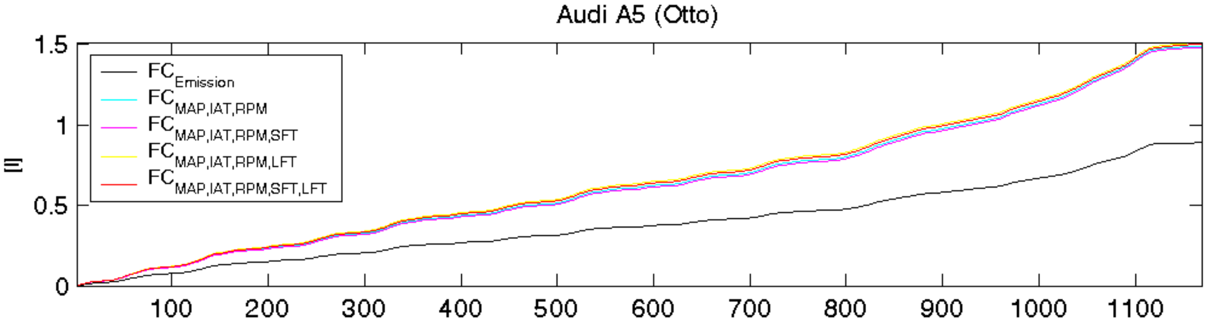
As the MAF sensor data was not available in the AUDI A5 measurement data, calculation of the fuel consumption was done only by estimating the air flow rate based on the MAP. As for all other vehicles of these experiments, the volumetric efficiency was set to 100 % and the stoichiometric air-to-fuel ratio was used within the OBD based calculation. The data plots indicate that the curve shapes of the OBD and Dyno data show parallels but also that there is a significant offset between both results. The FC_{OBD} curve based on MAP is above FC_{Dyno} for almost all values.



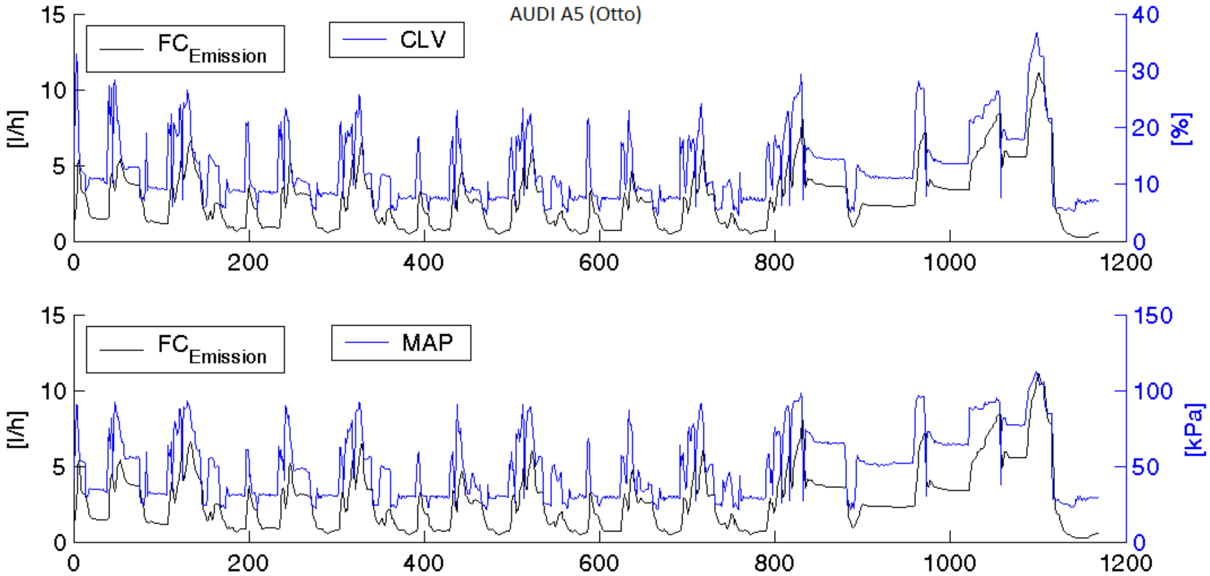
The experiment to improve the $FC_{MAP,IAT,RPM}$ results with consideration of the long term and short term fuel trim values are visualized in the following diagrams. SFT and LFT modify the air-to-fuel ratio over time, which is set to the constant value of 14.7:1. The plots of the FC_{OBD} values with different combinations of SFT and LFT show only marginal improvements compared to the deviation to the FC_{Dyno} curve.







The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.

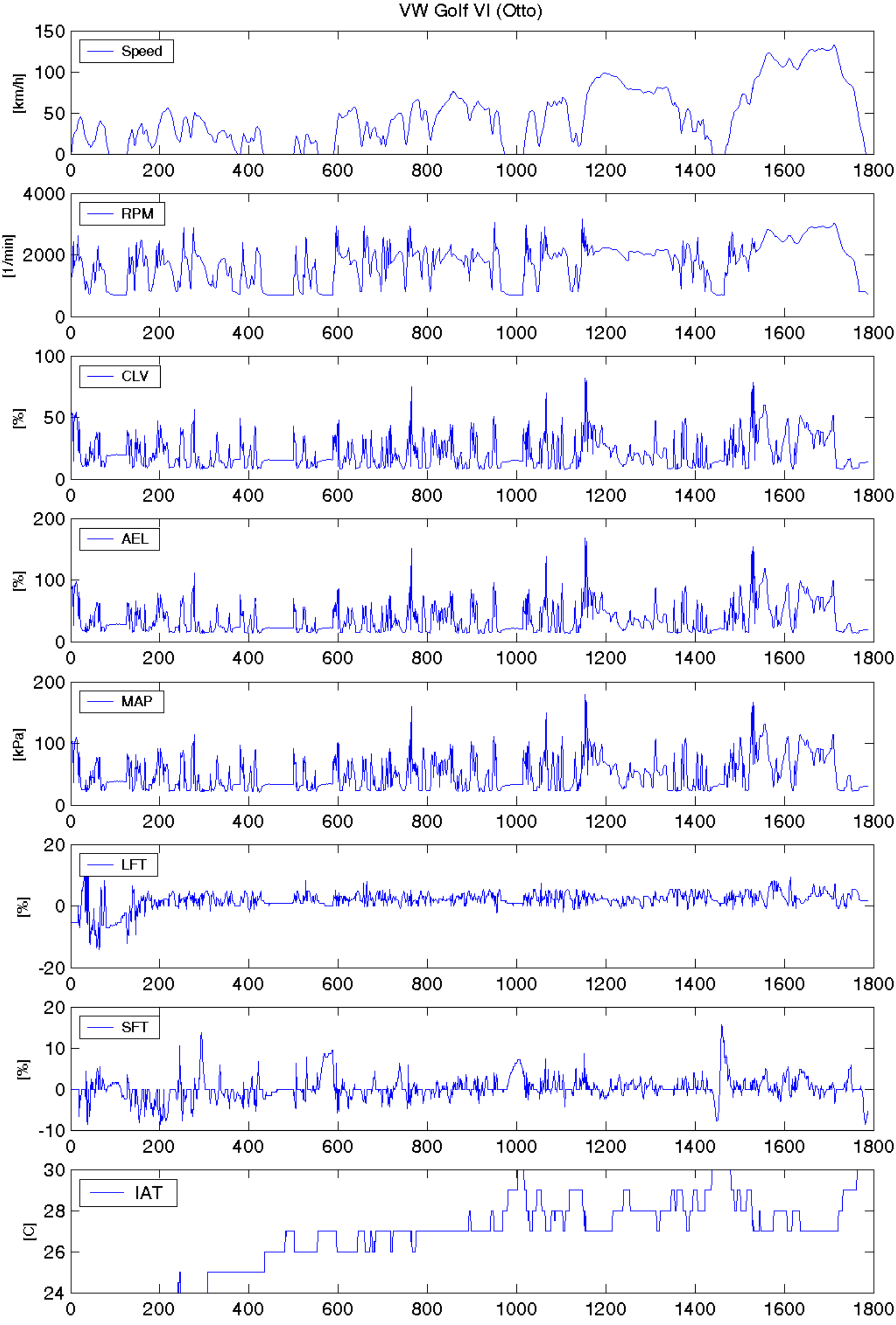


6.5.2 VW Golf – Otto Engine

The following data was collected from the OBD system of a VW Golf with Otto engine:

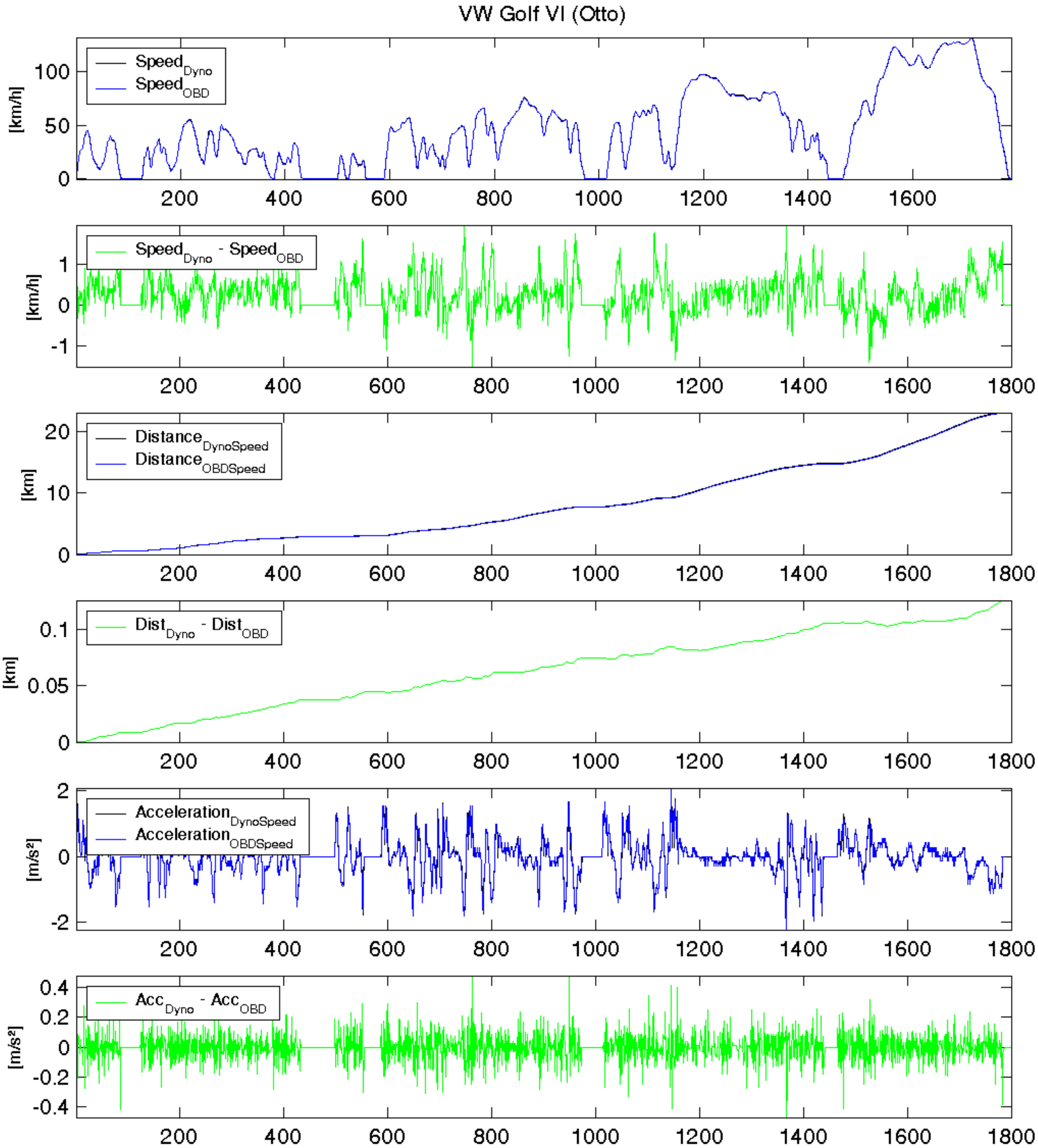
- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Absolute Engine Load
- Intake Manifold Absolute Pressure
- Long Term Fuel Trim Data
- Short Term Fuel Trim Data
- Intake Air Temperature

The test was executed with the WLTP (Worldwide Harmonized Light Duty Test Procedure) at an environmental temperature of 22 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.74 kg/l and an air-to-fuel ratio of 14.7:1 was applied.

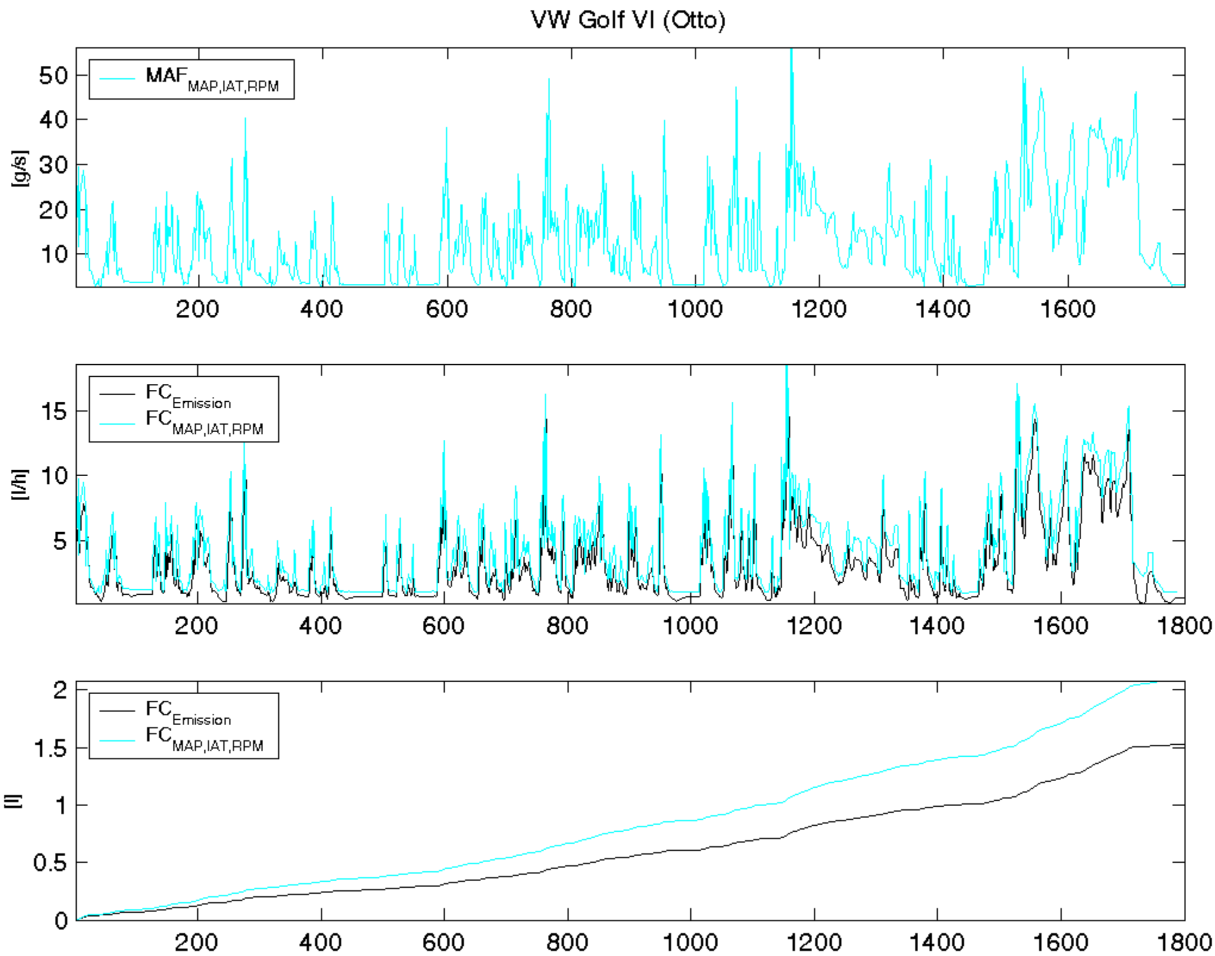

VW Golf VI (Otto)
Speed
[km/h]
RPM
[1/min]
CLV
[%]
AEL
[%]
MAP
[kPa]
LFT
[%]
SFT
[%]
IAT
[C]

The comparison of vehicle speed and acceleration with the dyno values shows a result quite similar to the AUDI measurement.

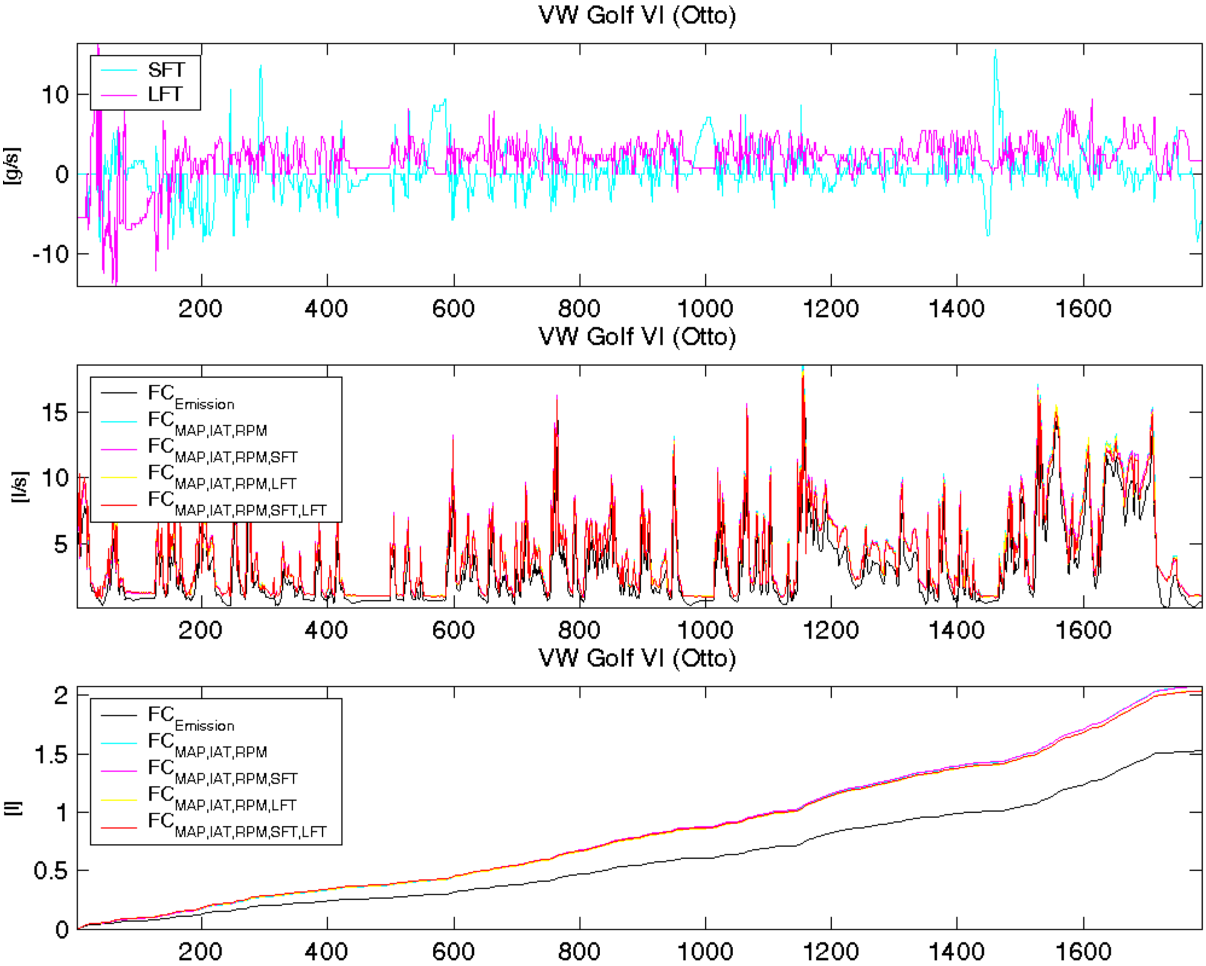
As the deviations within +/-1 km/h are relatively small and compensate over the whole driving cycle, the calculated distance does not show considerable deviations. Nevertheless, the deviations influence the calculation of the total fuel consumption.



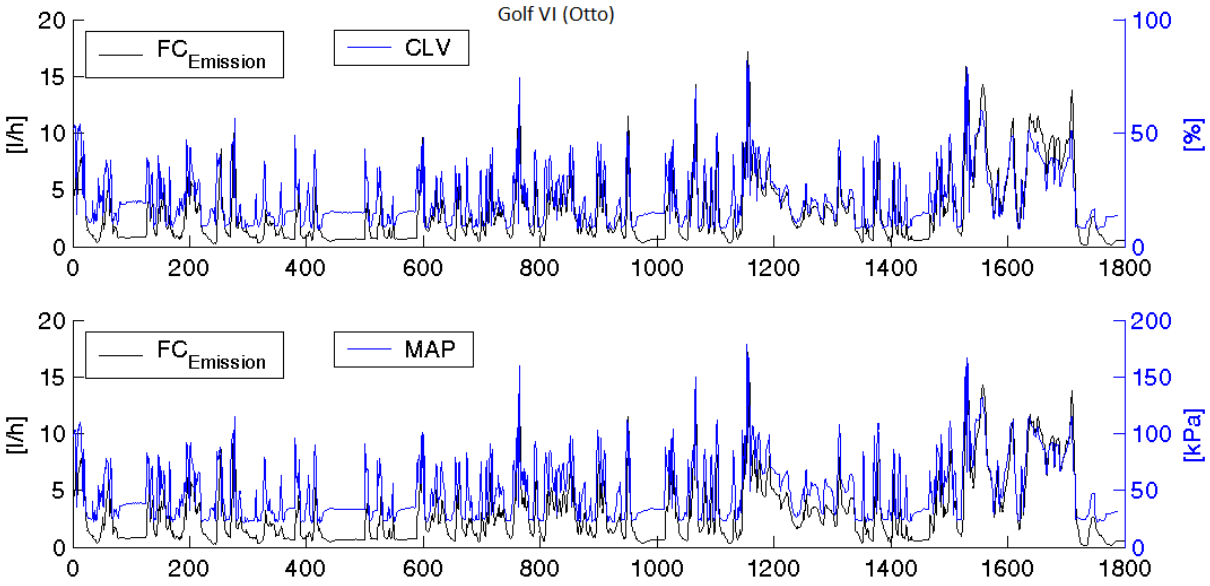
Similar to the AUDI A5, the tested VW Golf does not provide MAF sensor data via the OBD interface. Therefore, the fuel consumption was calculated with an estimation of the air flow rate based on the MAP sensor data. The plots show parallels of the OBD and Dyno data but also a large offset between both curves.



If the long term fuel trim data and short term fuel trim data are applied to the FC calculation, the results are similar to the results from the experiment with the AUDI vehicle. Applying the fuel trim data show no considerable improvement in view of the deviation to FC_{Dyno}, although the fuel trim values show different characteristics over the driving cycle.



The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.

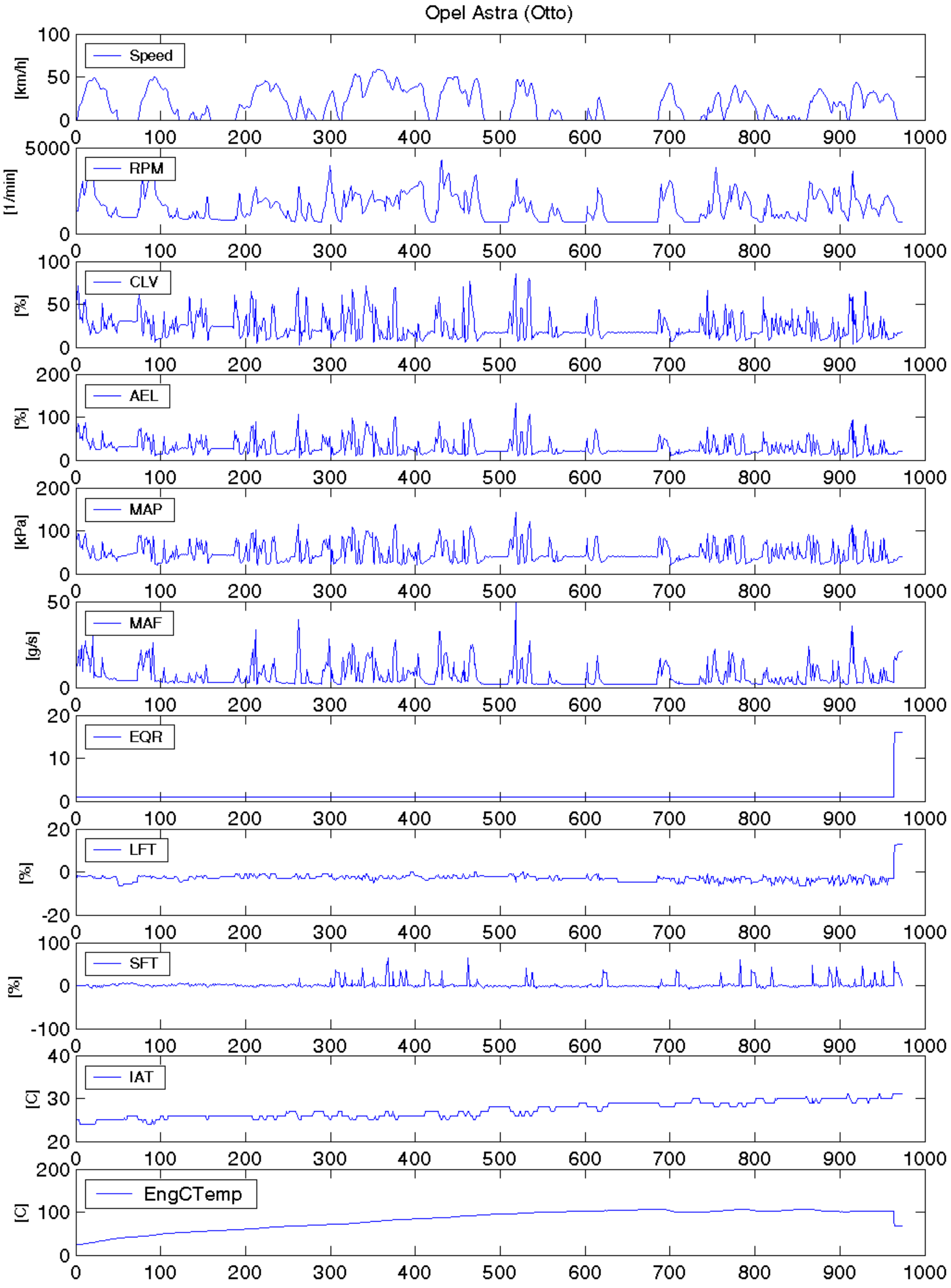


6.5.3 Opel Astra – Otto Engine

The following data was collected from the OBD system of an Opel Astra with Otto engine:

- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Absolute Engine Load
- Intake Manifold Absolute Pressure
- Long Term Fuel Trim Data
- Short Term Fuel Trim Data
- Intake Air Temperature
- Mass Air Flow
- Commanded Lambda
- Engine Coolant Temperature

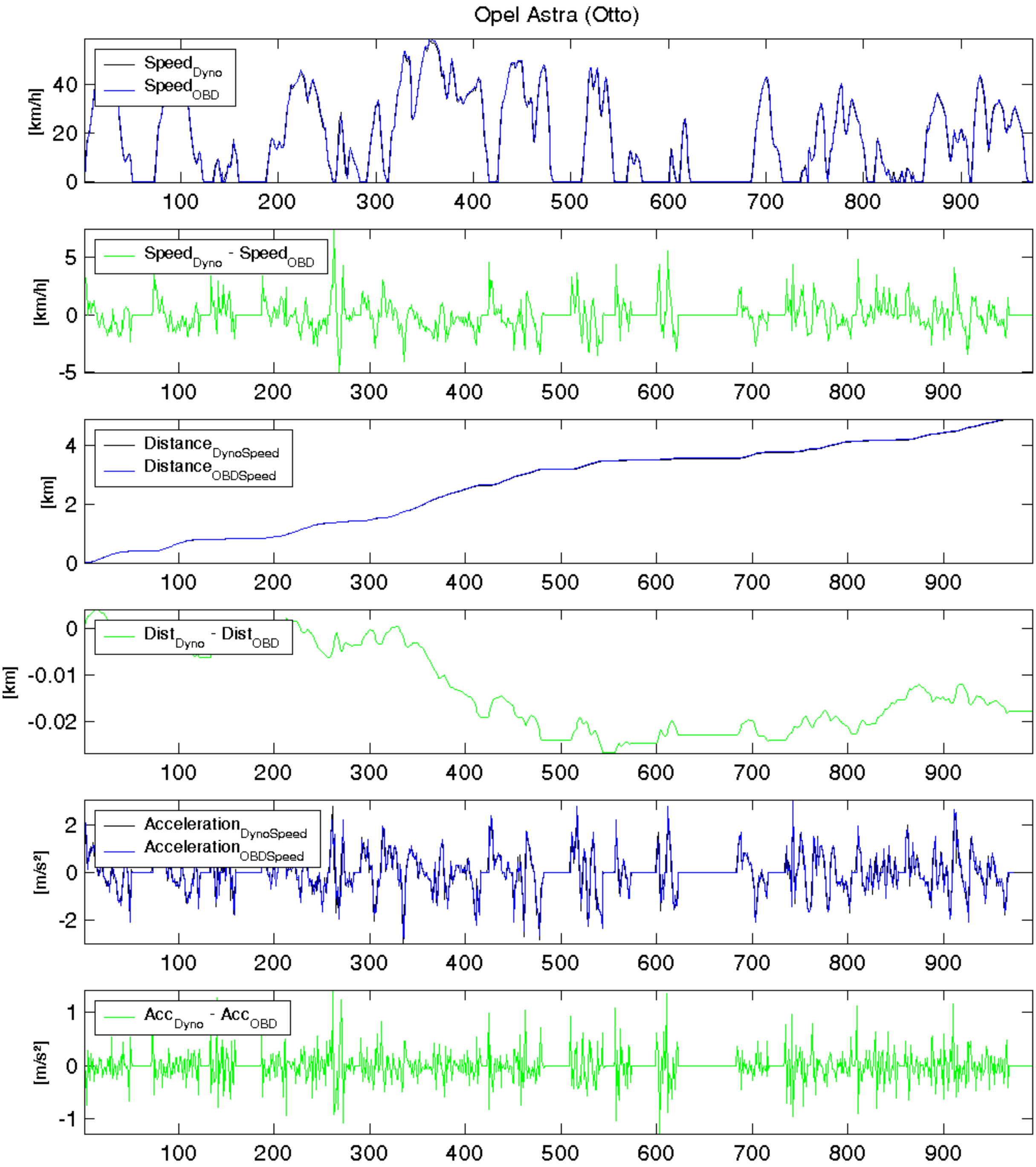
The test was executed with the CADC (Common Artemis Driving Cycle) at an environmental temperature of 22 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.74 kg/l and an air-to-fuel ratio of 14.7:1 was applied.



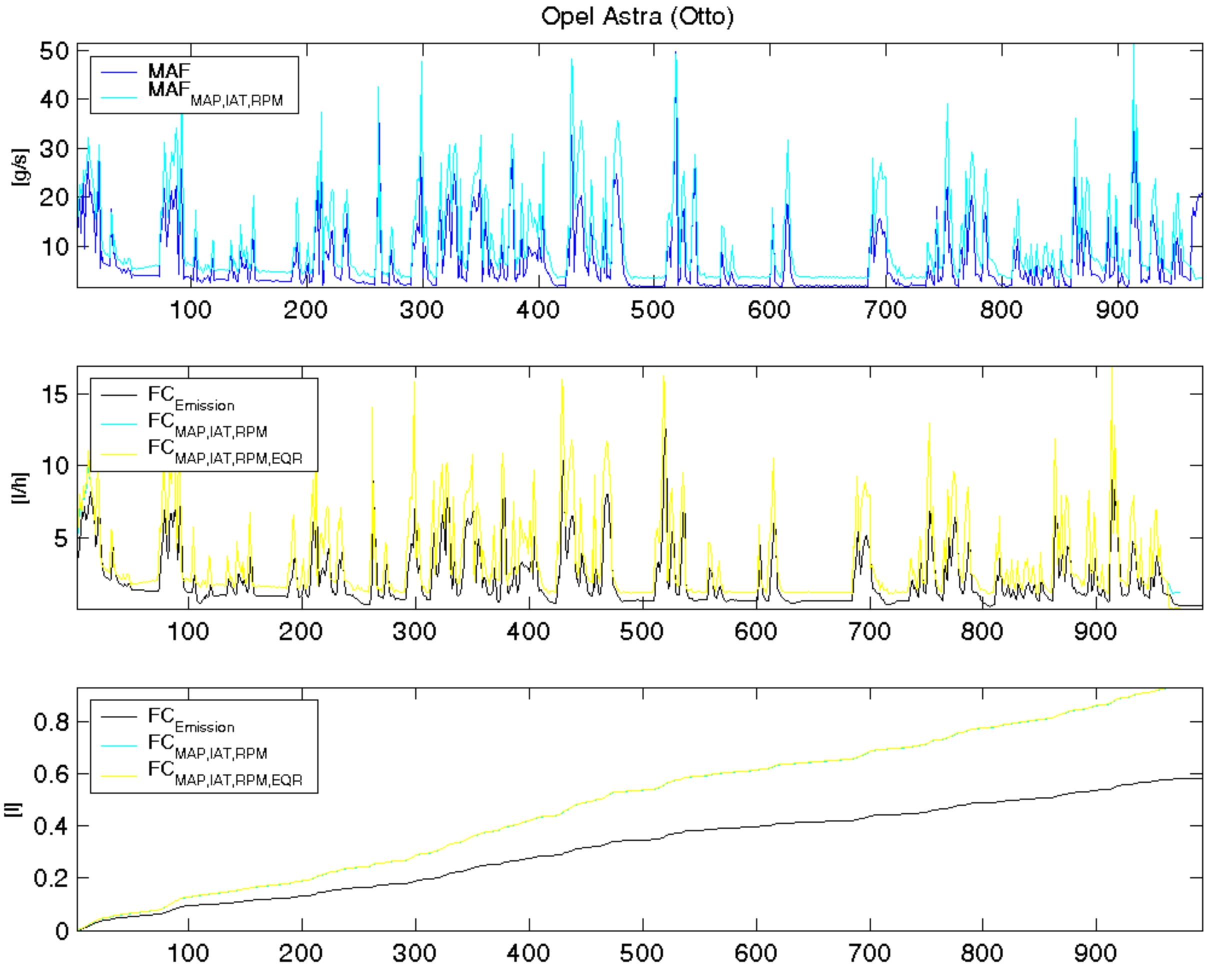
Opel Astra (Otto)
Speed
[km/h]
RPM
[1/min]
CLV
[%]
AEL
[%]
MAP
[kPa]
MAF
[g/s]
EQR
LFT
[%]
SFT
[%]
IAT
[C]
EngCTemp
[C]

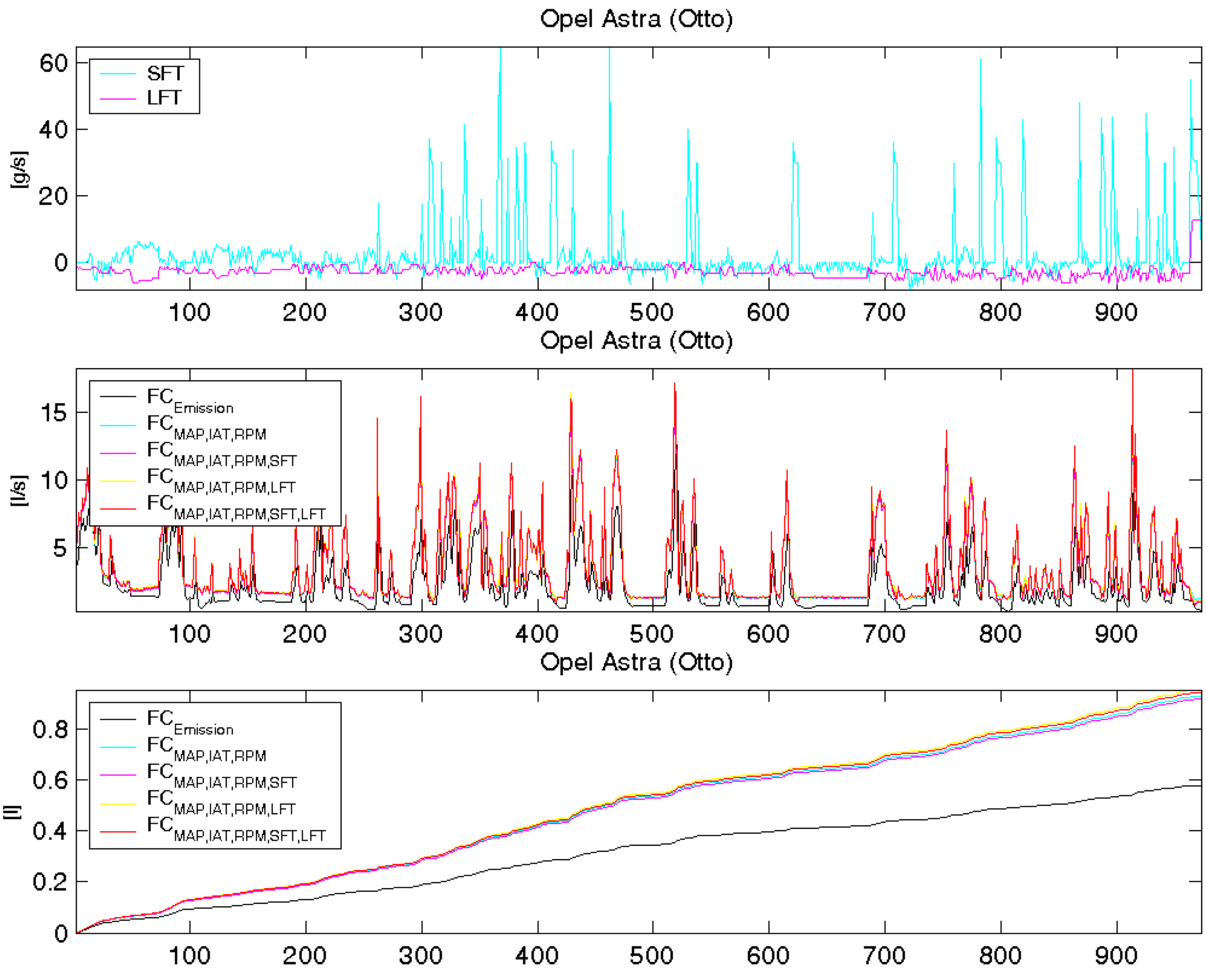
The comparison of vehicle speed and acceleration with the dyno values shows a result quite similar to the previous vehicle measurements.

As the deviations within are relatively small and compensate over the whole driving cycle, the calculated distance does not show considerable deviations. Nevertheless, the deviations influence the calculation of the total fuel consumption.



As observed with the other Otto engine vehicle experiments, calculating the fuel consumption with an estimation of the air flow rate based on the MAP show a large offset to the emission based result.



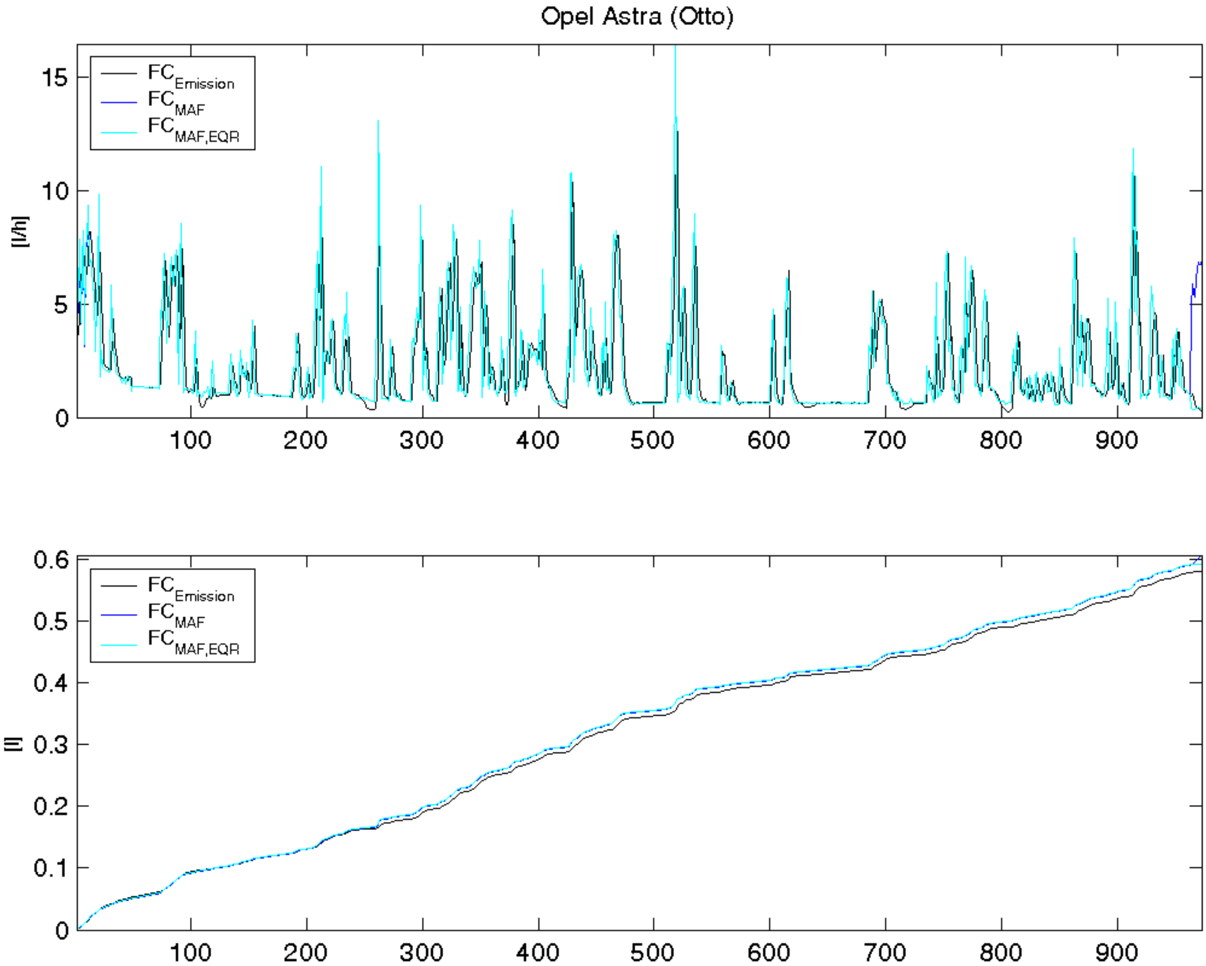


Opel Astra (Otto)
SFT
LFT
[g/s]
60
40
20
0
100
200
300
400
500
600
700
800
900
Opel Astra (Otto)
$FC_{Emission}$
$FC_{MAP,IAT,RPM}$
$FC_{MAP,IAT,RPM,SFT}$
$FC_{MAP,IAT,RPM,LFT}$
$FC_{MAP,IAT,RPM,SFT,LFT}$
[l/s]
15
10
5
100
200
300
400
500
600
700
800
900
Opel Astra (Otto)
$FC_{Emission}$
$FC_{MAP,IAT,RPM}$
$FC_{MAP,IAT,RPM,SFT}$
$FC_{MAP,IAT,RPM,LFT}$
$FC_{MAP,IAT,RPM,SFT,LFT}$
[l]
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
800
900

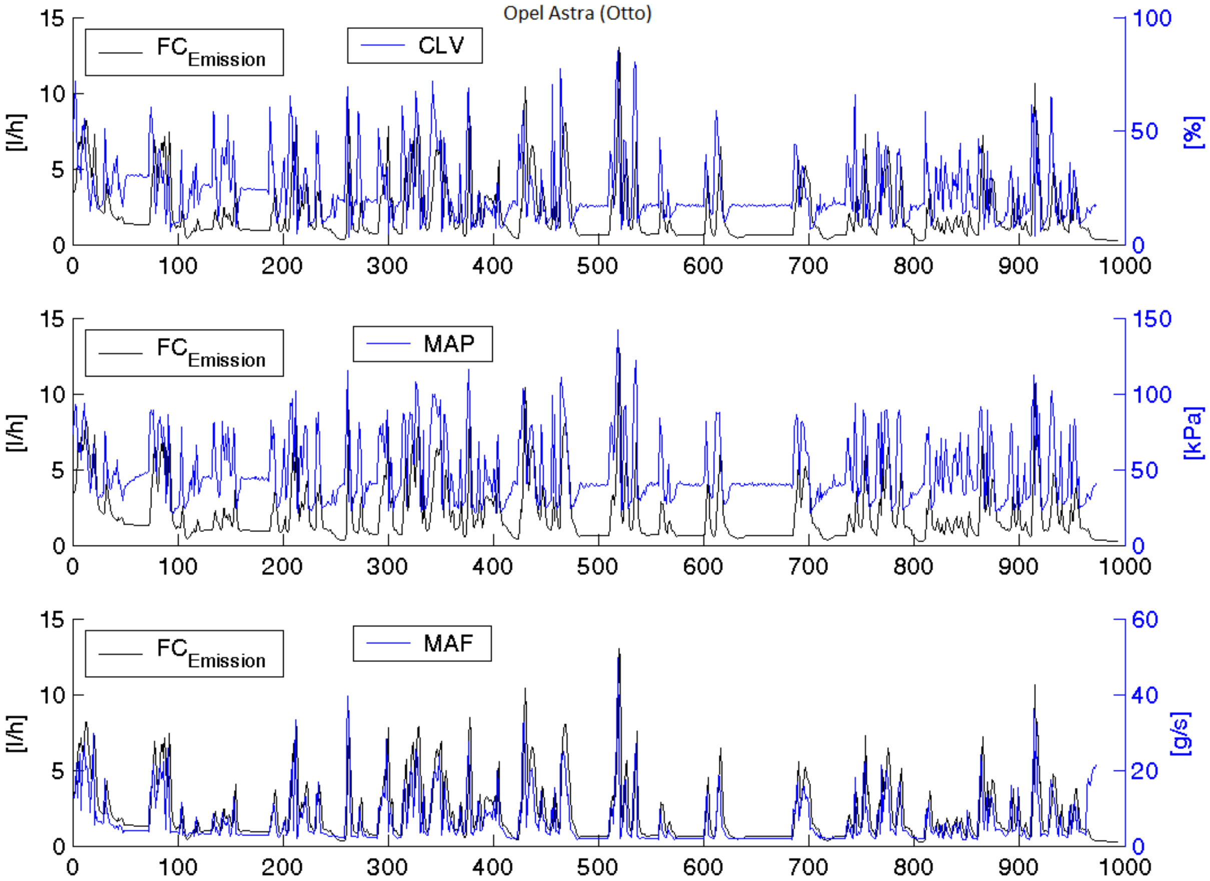
Contrary to the two other Otto engine vehicles that were tested, the Opel Astra provides the MAF sensor data via the OBD interface.

Calculating the fuel consumption based on the MAF sensor (cf. FC_{MAF}) results in a curve shape that is quite similar to $FC_{Emission}$, calculated based on the emission measurements. It can be observed that a small deviation in the estimation of the total fuel consumption of around 0.01 l occurs in the range of 260 to 265 seconds.

Founded by the reason that the commanded equivalence ratio is one during the whole driving cycle (only negligible small deviations in the first 20 seconds are observed), consideration of this parameter does not influence the calculated value (cf. $FC_{MAF,EQR}$).



The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.



6.5.4 VW Passat – Diesel Engine

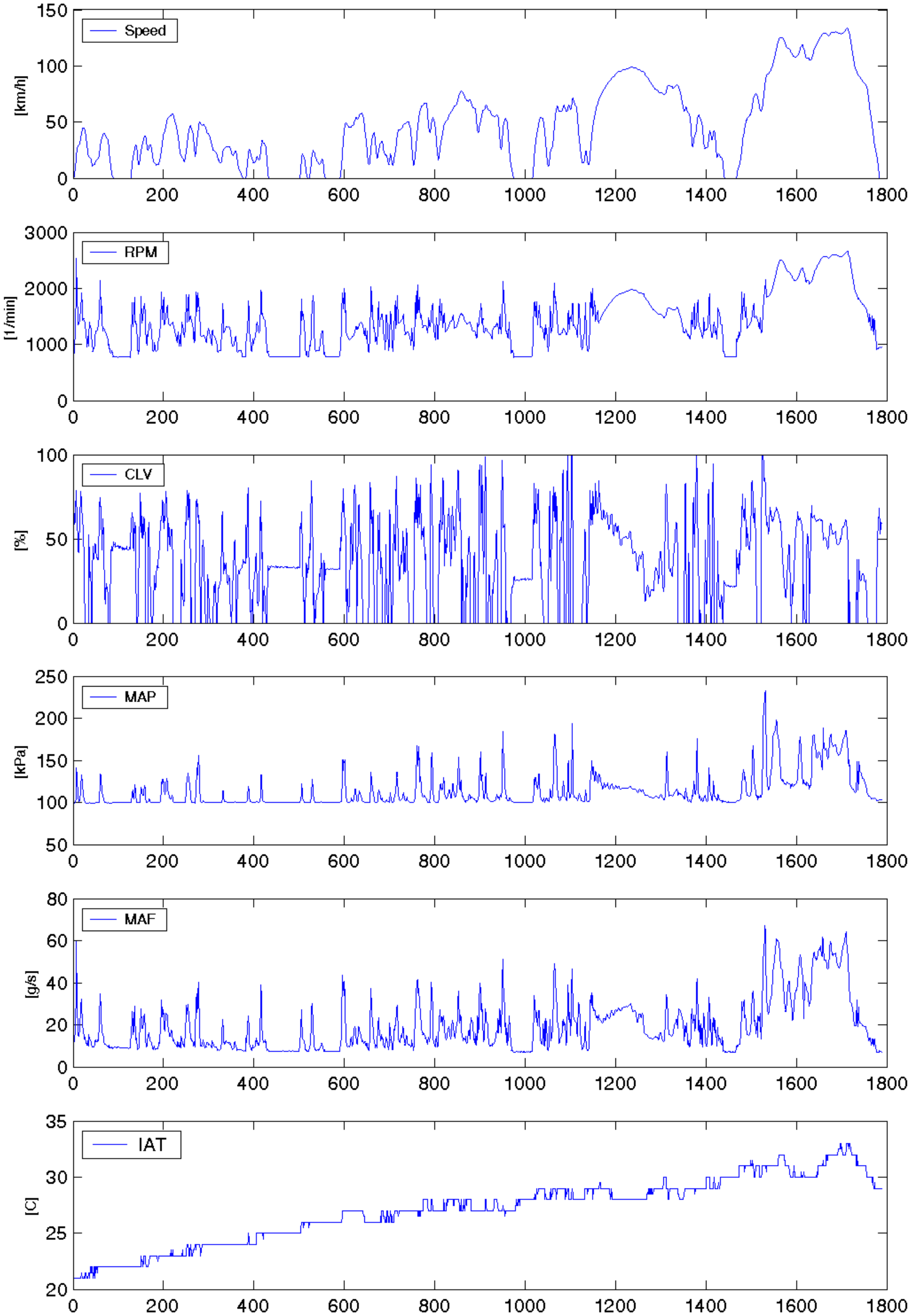
The following data was collected from the OBD system of a VW Passat with Diesel engine:

- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Intake Manifold Absolute Pressure
- Mass Air Flow sensor
- Intake Air Temperature

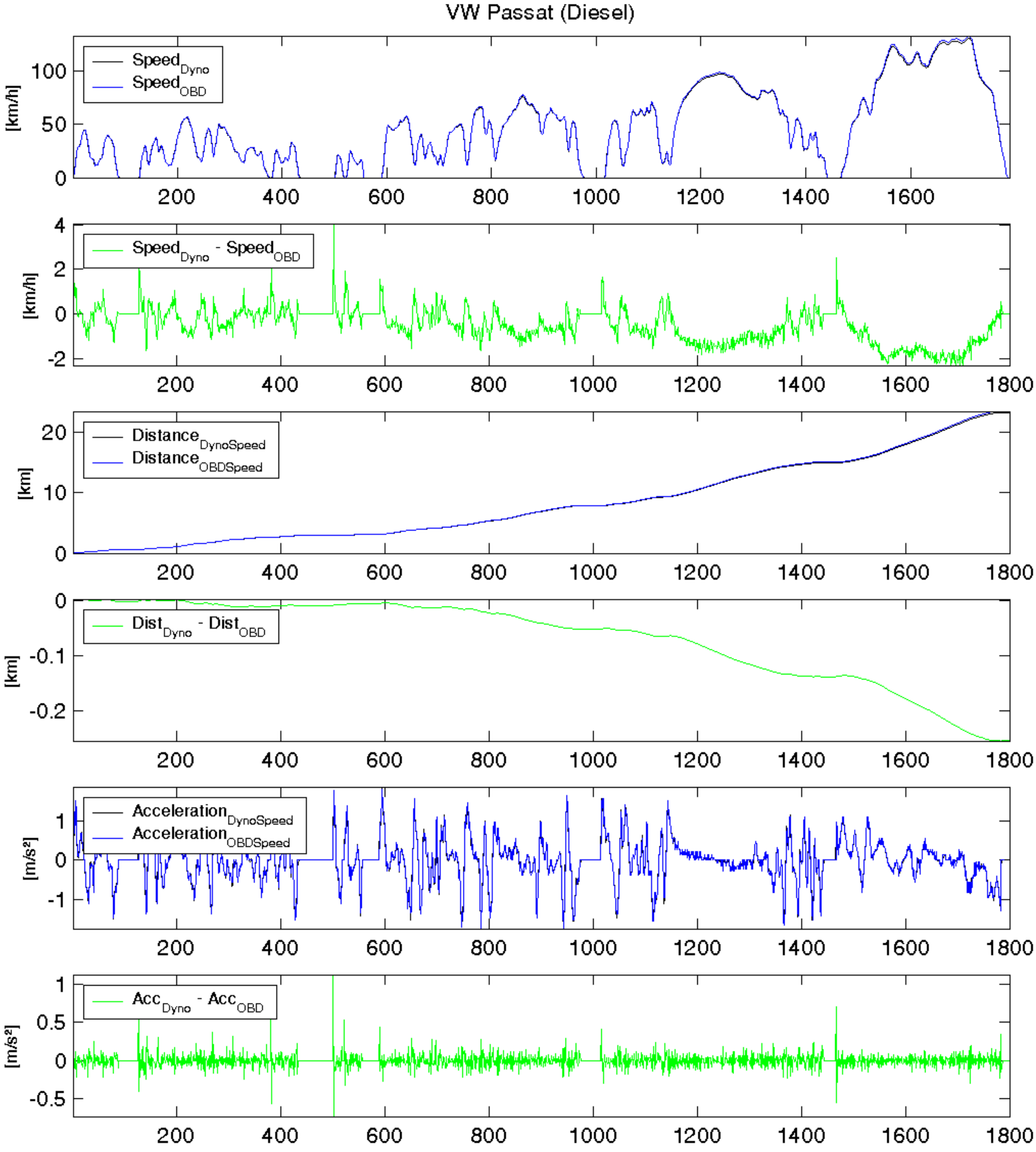
The test was executed with the WLTP (Worldwide Harmonized Light Duty Test Procedure) at an environmental temperature of 22 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.835 kg/l and an air-to-fuel ratio of 14.5:1 was applied.

As the fuel management system of a Diesel vehicle is not operating at constant air-to-fuel ratio, applying the CLV to the FC calculation should lead to an appropriate correction to the air/fuel ratio.

VW Passat (Diesel)

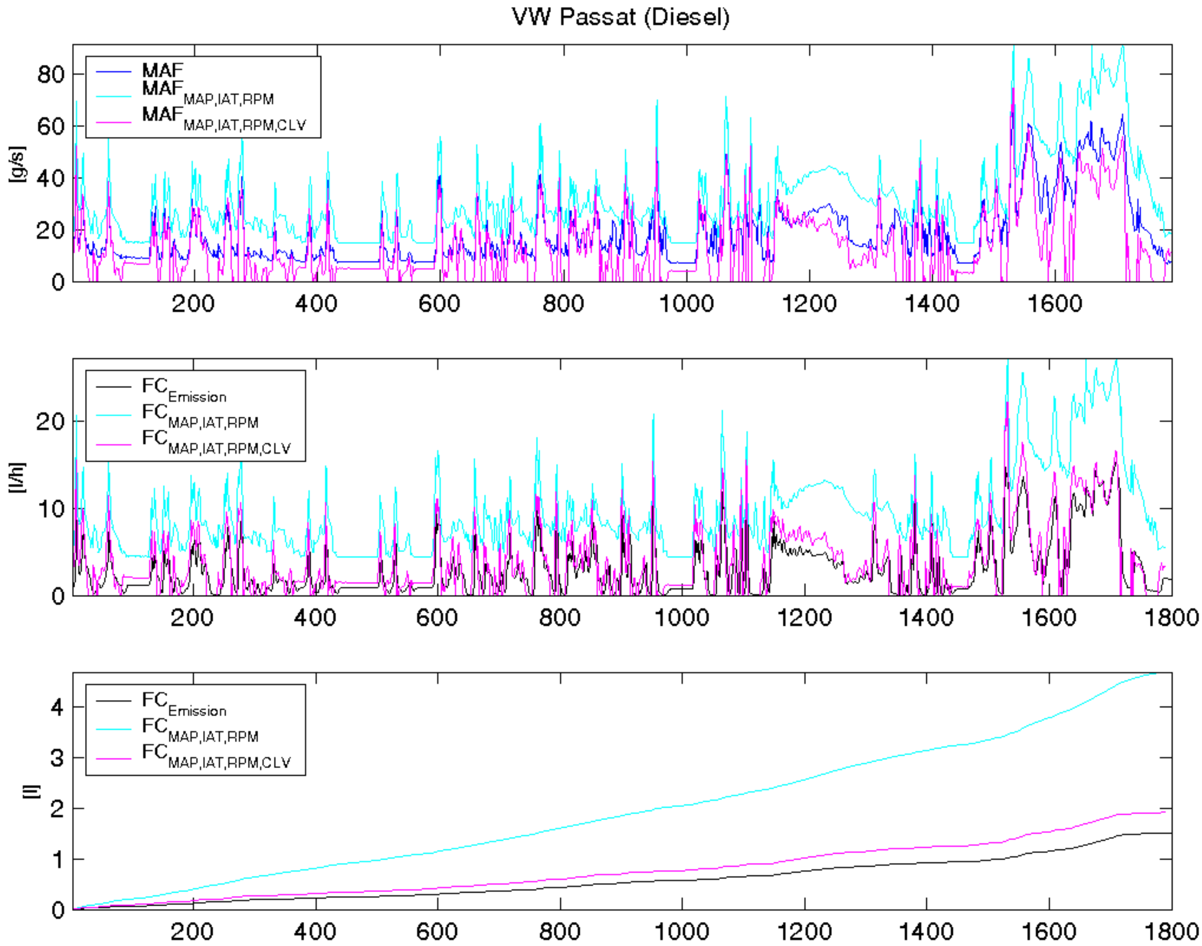


Comparing the vehicle speed measured by the OBD interface and the dynamometer test stand shows that both data flows are relatively close together. The subtraction of the OBD speed from the Dyno speed shows that the OBD speed value is up to 2 km/h above the Dyno speed at higher speed. The small deviations are compensating in the acceleration and brake phases but for phases with higher speed the accuracy of the calculated total fuel consumption may be influenced by the imprecision of the OBD vehicle speed. The plot shows that the deviation can reach up to 2 % in range 100 to 120 km/h and will presumably increase at higher speed.

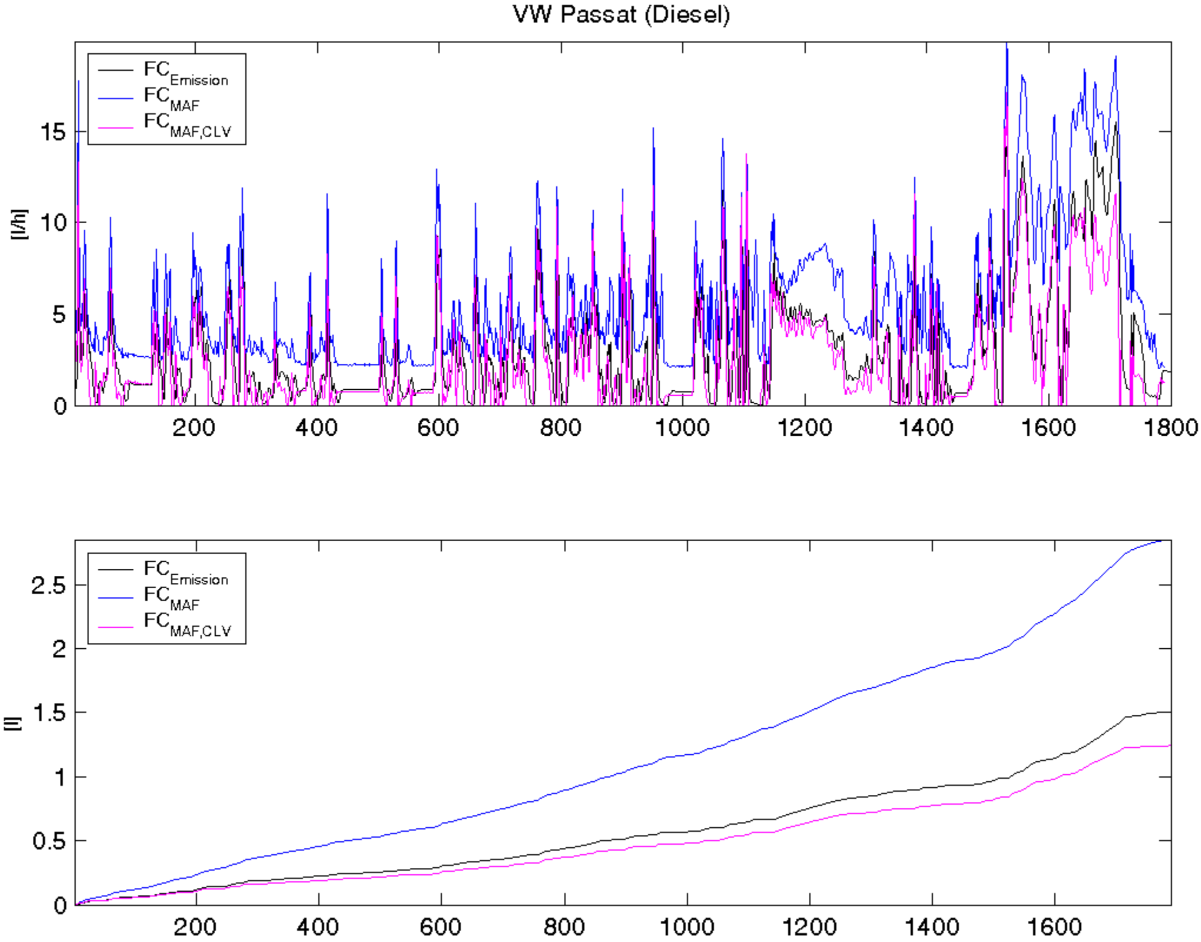


Calculating the air flow based on MAP, IAT and RPM sensor data with an assumed volumetric efficiency of 100 % shows that the resulting value is higher than the air flow measured directly with the MAF sensor, especially at higher speed. By multiplying the calculated load value based on MAP data, the deviation to $FC_{Emission}$ can be reduced significantly, although the total fuel consumption based on MAP and CLV is still higher over the driving cycle.

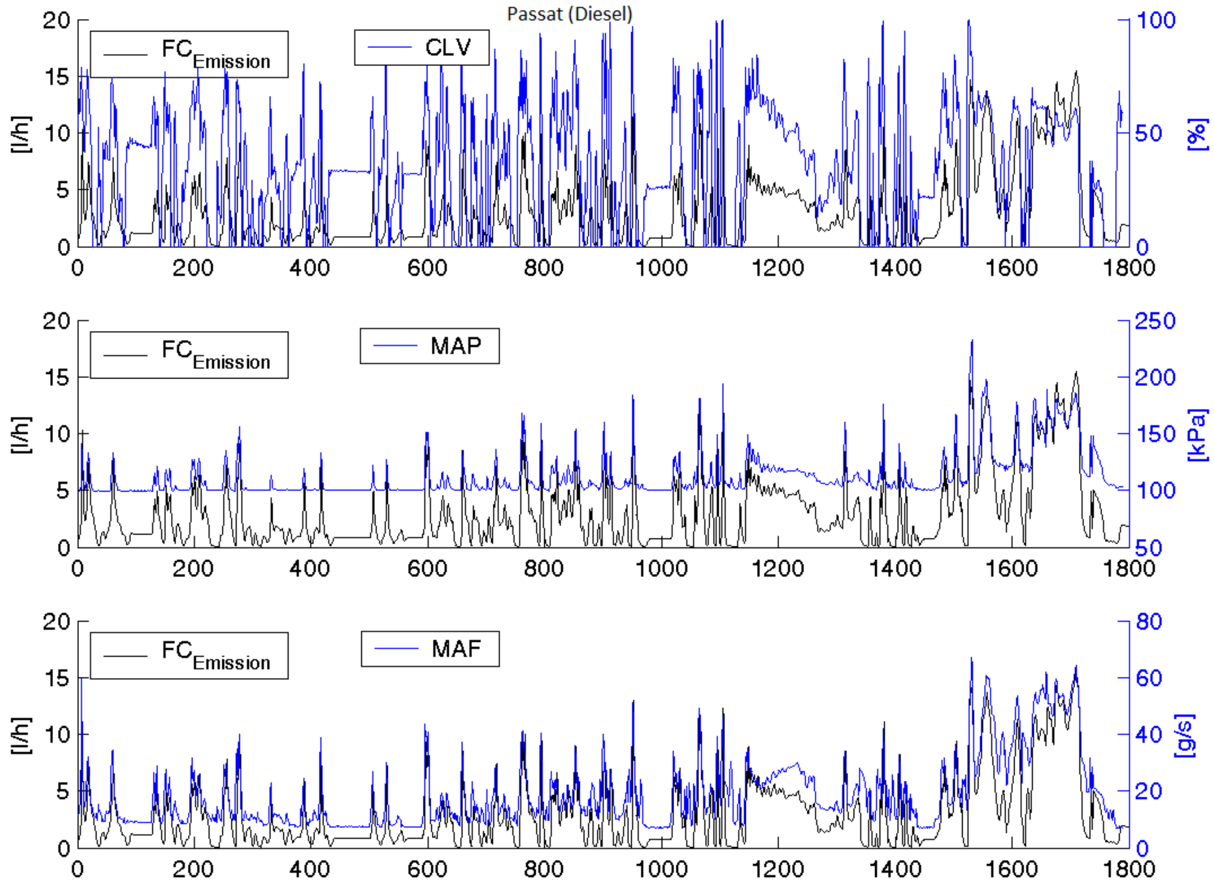
Compared to the Otto vehicles, the total fuel consumption is much closer to $FC_{Emission}$. But, it has to be considered that there are larger deviations in some periods and the result is influenced by adding higher and lower values of current FC_{MAP}.



The FC calculation based on the MAF sensor results in values much larger than $FC_{Emission}$, but with smaller deviations compared to the MAP based calculation. The product of the MAF and the calculated load results in a curve shape that is much closer to the emission based calculation. Nevertheless, there are deviations in both curve shapes that add up in the total fuel consumption. At higher speeds as seen at around 1600 to 1800 seconds the deviation increases.



The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.



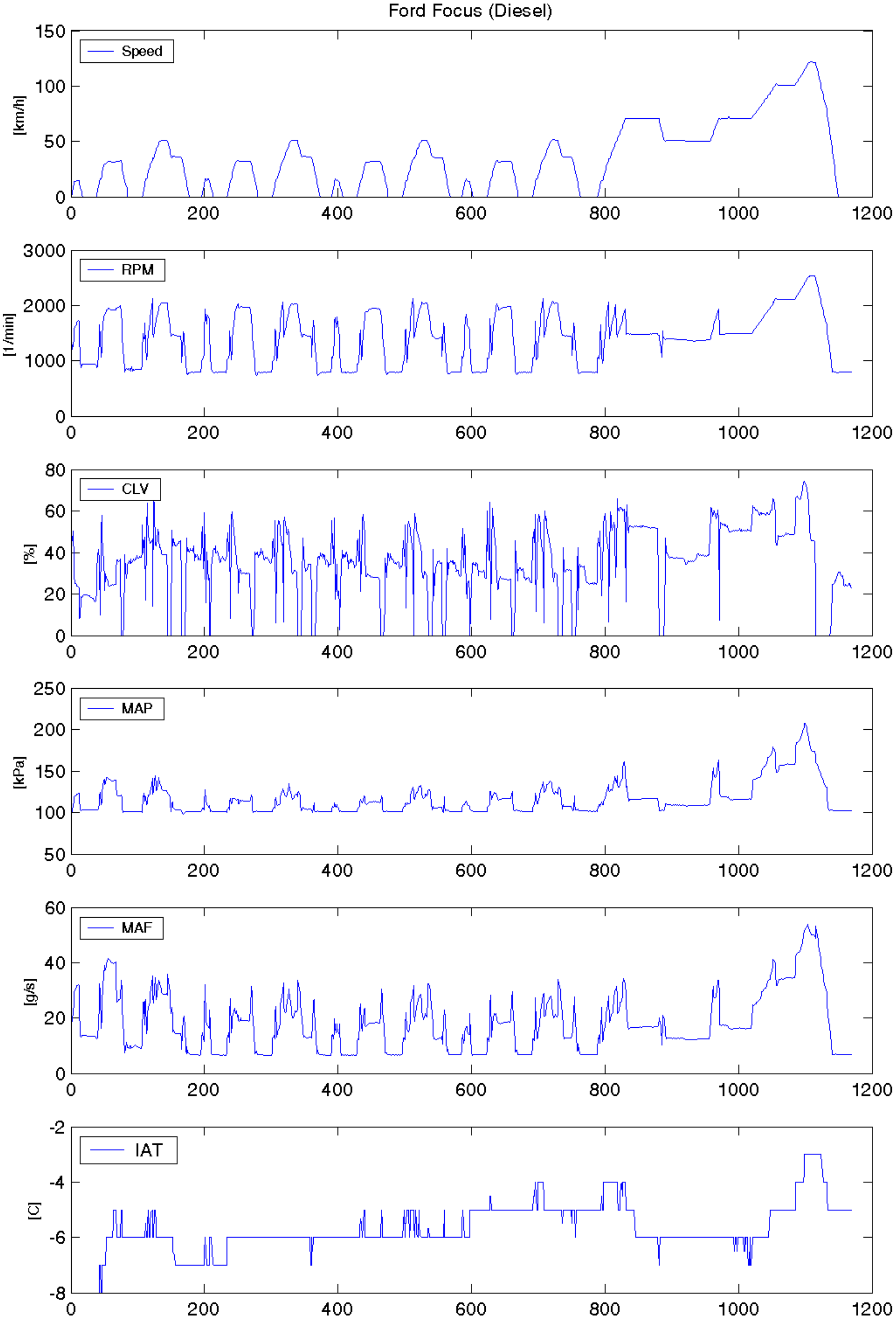
6.5.5 FORD Focus – Diesel Engine

The following data were collected from the OBD system of a Ford Focus with Diesel engine:

- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Intake Manifold Absolute Pressure
- Mass Air Flow sensor
- Intake Air Temperature

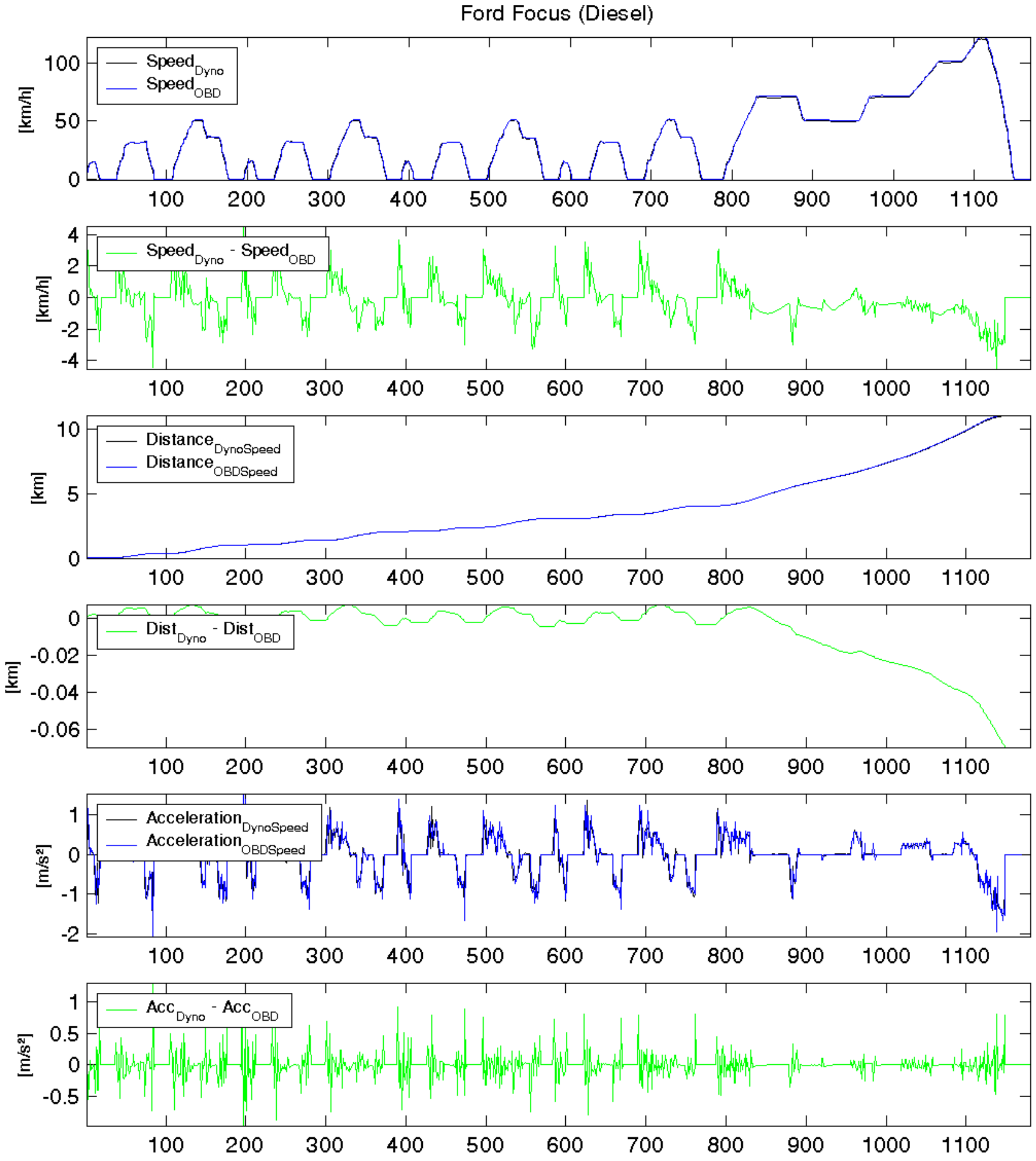
The test was executed with the NEDC (New European Driving Cycle) at an environmental temperature of -7 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.835 kg/l and an air-to-fuel ratio of 14.5:1 was applied.

As the fuel management system of a Diesel vehicle is not operating at constant air-to-fuel ratio, applying the CLV to the FC calculation should lead to an appropriate correction to the air/fuel ratio.


Ford Focus (Diesel)
Speed
[km/h]
RPM
[1/min]
CLV
[%]
MAP
[kPa]
MAF
[g/s]
IAT
[C]
0
200
400
600
800
1000
1200

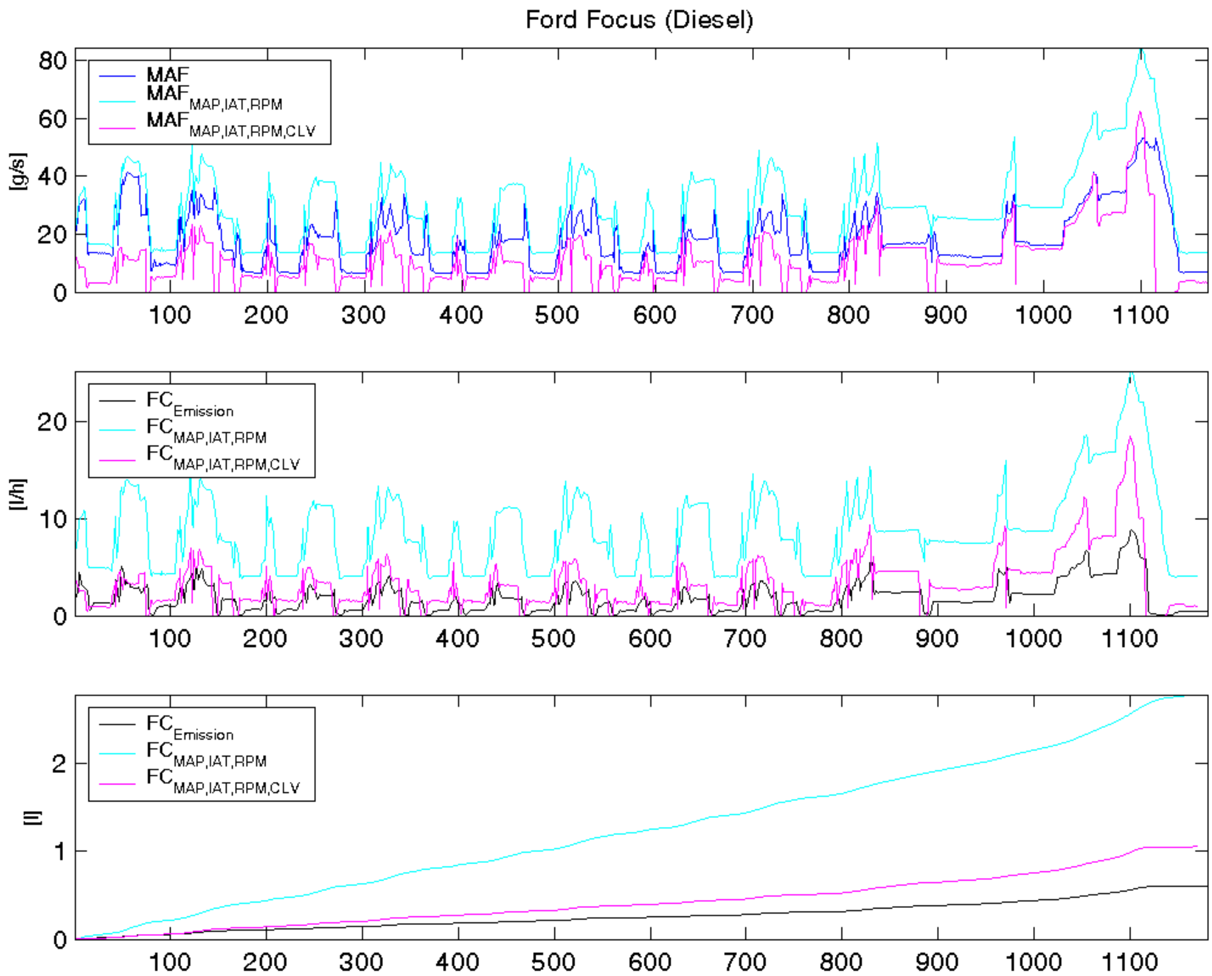
The comparison of the measured speed and acceleration values shows that the OBD values and the Dyno values are relatively close together.

The subtraction of the OBD speed from the Dyno speed shows that the Dyno speed is up to 4 km/h higher than the OBD speed during acceleration phases and up to 4 km/h lower during brake phases. But, over the whole driving cycle the deviations of the acceleration and brake phases are compensating. When driving constantly at higher speeds, the accuracy of the calculated total fuel consumption might be influenced caused by the increased imprecision of the measured OBD vehicle speed.

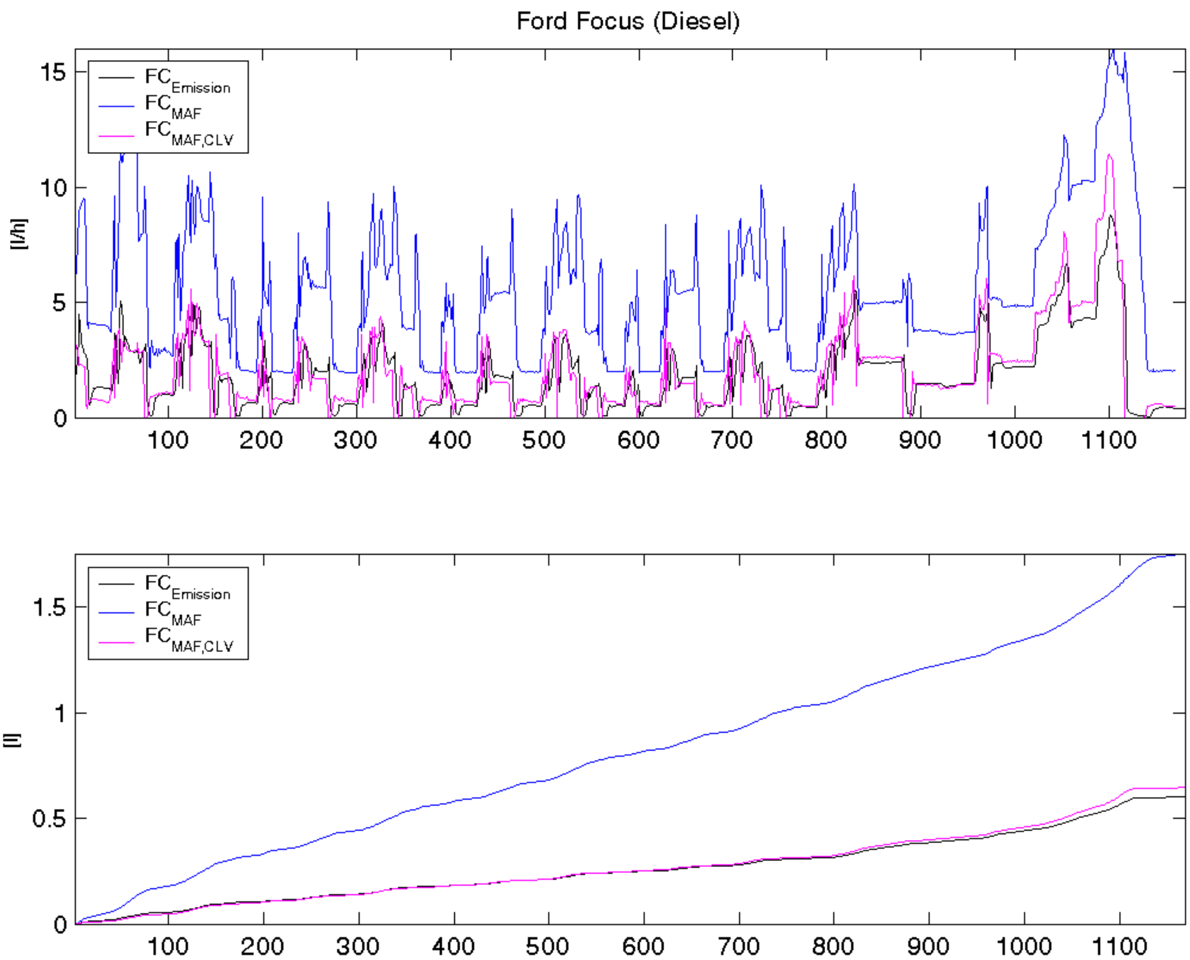


The results of the MAP based FC calculation are similar to the VW Passat results. The calculation of the air flow based on MAP, IAT and RPM sensor and a volumetric efficiency of 100 % shows that the resulting value is higher than the air flow measured directly with the MAF sensor, but can be adjusted by applying the calculated load value to the calculation.

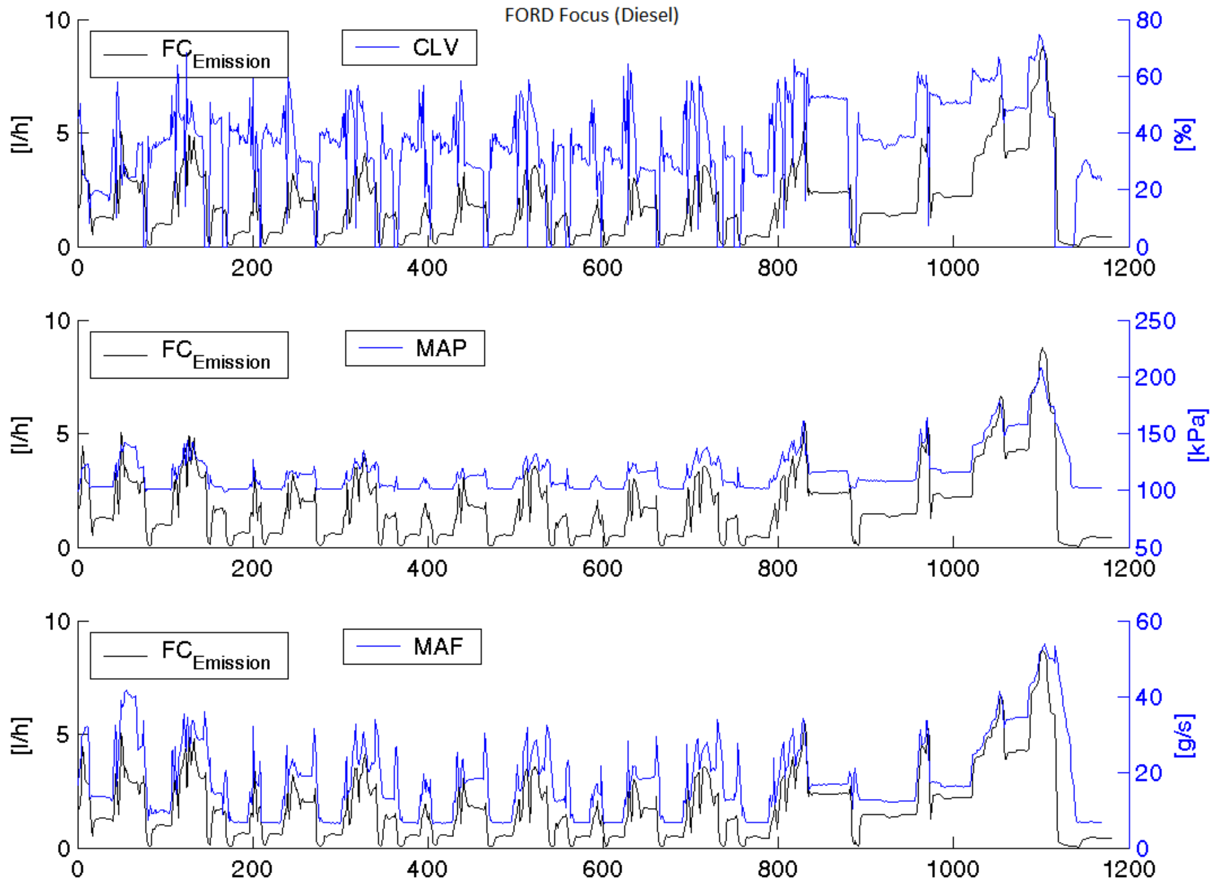
Similar to the MAP based calculation of the other vehicles, the estimation of the total fuel consumption is less accurate than the estimation based on MAF.



The calculation based on the MAF sensor leads to a much larger values compared to the emission based calculation. But, considering the calculated load value results in a curve shape that is very close to the emission based calculation, although at higher speeds the deviation increases. The curves of the total fuel consumption in liters show a very good matching especially at speeds below 100 km/h.



The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.



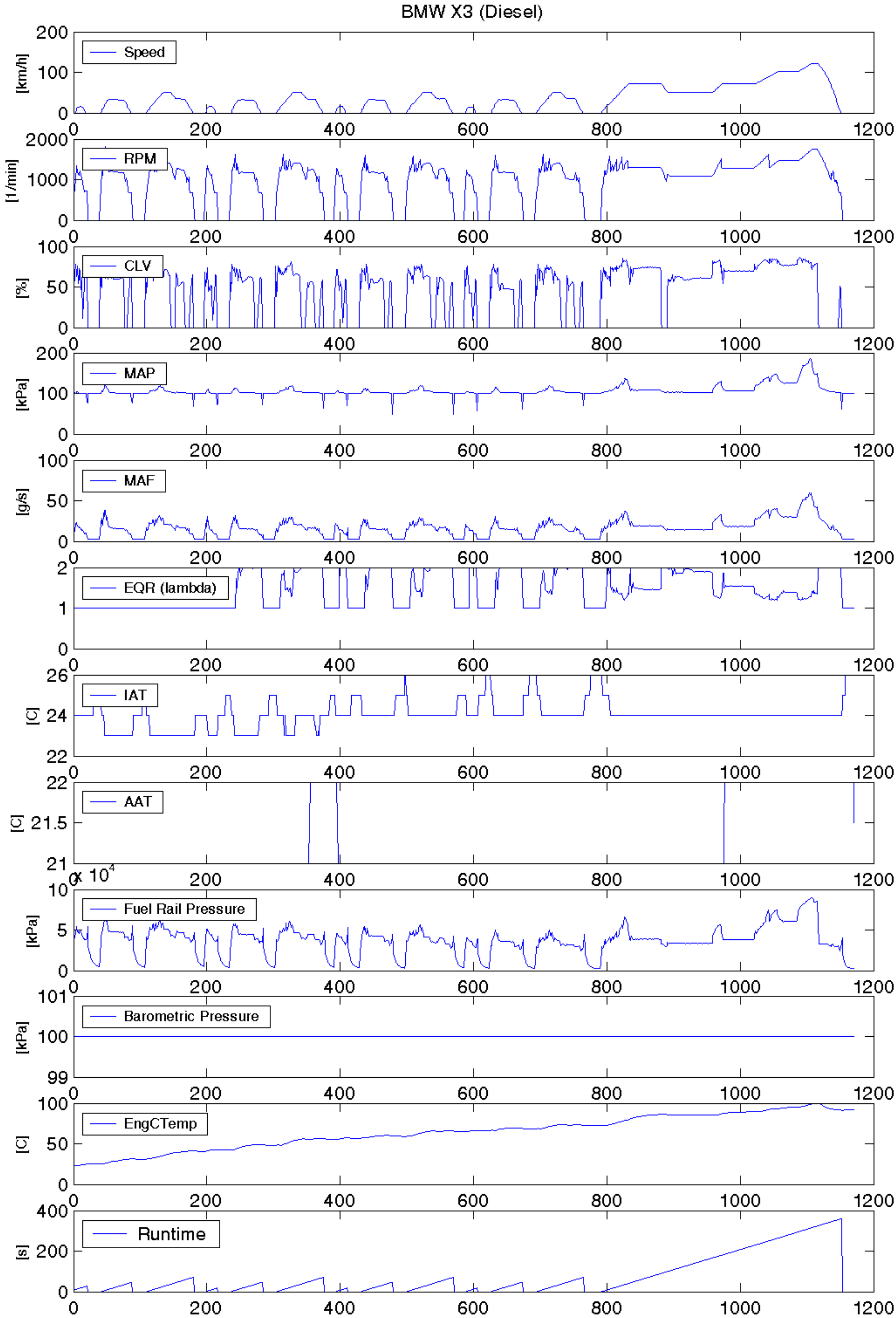
6.5.6 BMW X3 – Diesel Engine

The following data were collected from the OBD system of a BMW X3 with Diesel engine:

- Vehicle Speed Sensor
- Engine RPM
- Calculated Load
- Intake Manifold Absolute Pressure
- Mass Air Flow sensor
- Equivalence Ratio (via Service 1, PID $24)
- Intake Air Temperature
- Ambient Air Temperature
- Fuel Rail Pressure
- Barometric Pressure
- Engine Coolant Temperature
- Time Since Engine Start

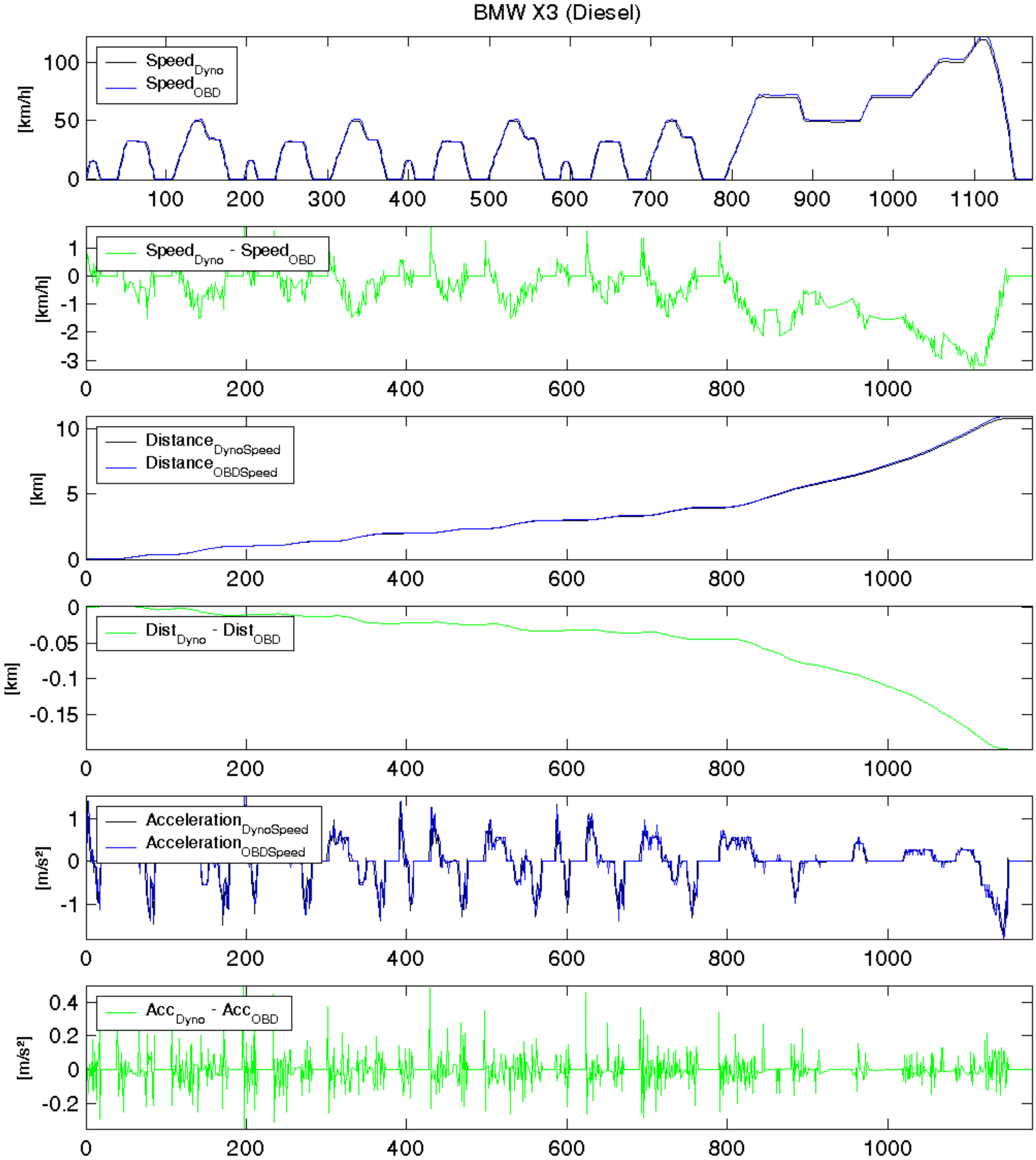
The test was executed with the New European Driving Cycle (NEDC) at an environmental temperature of 22 °C. For calculating fuel consumption based on emission and OBD data a fuel density of 0.834 kg/l and an air-to-fuel ratio of 14.5:1 was applied.

As the fuel management system of a Diesel vehicle is not operating at constant air-to-fuel ratio, applying the CLV to the FC calculation should lead to an appropriate correction to the air/fuel ratio.

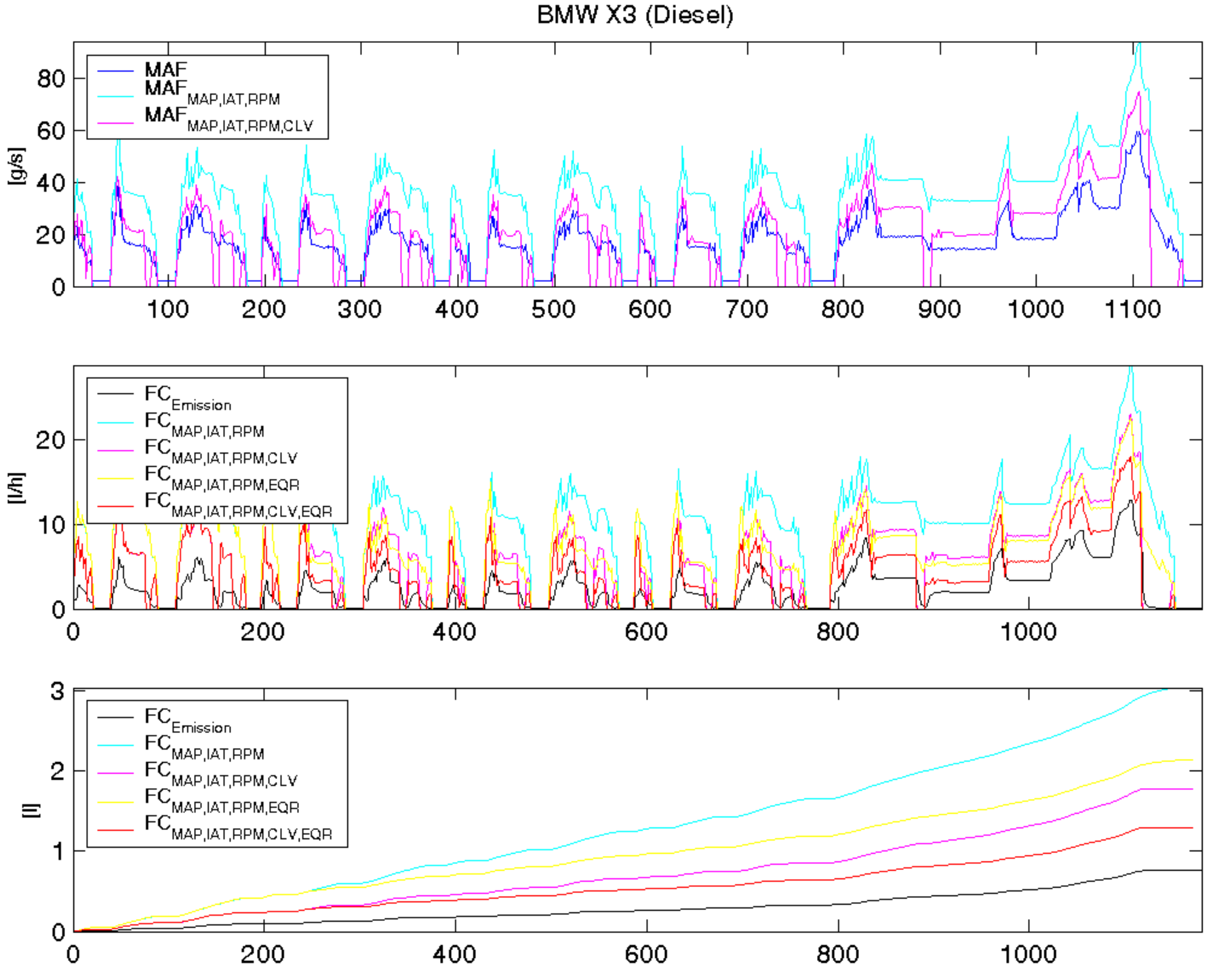


BMW X3 (Diesel)
Speed
[km/h]
RPM
[1/min]
CLV
[%]
MAP
[kPa]
MAF
[g/s]
EQR (lambda)
IAT
[C]
AAT
[C]
x 10^4
Fuel Rail Pressure
[kPa]
Barometric Pressure
[kPa]
EngCTemp
[C]
Runtime
[s]
0
200
400
600
800
1000
1200

The comparison of the measured speed values shows that the deviations of the OBD and the Dyno measurement lies in the range of +/-2 km/h in the lower speed area and increase up to -3 km/h at 120 km/h. The calculated distances show only low deviations, but would presumably increase on longer distances at higher speeds.

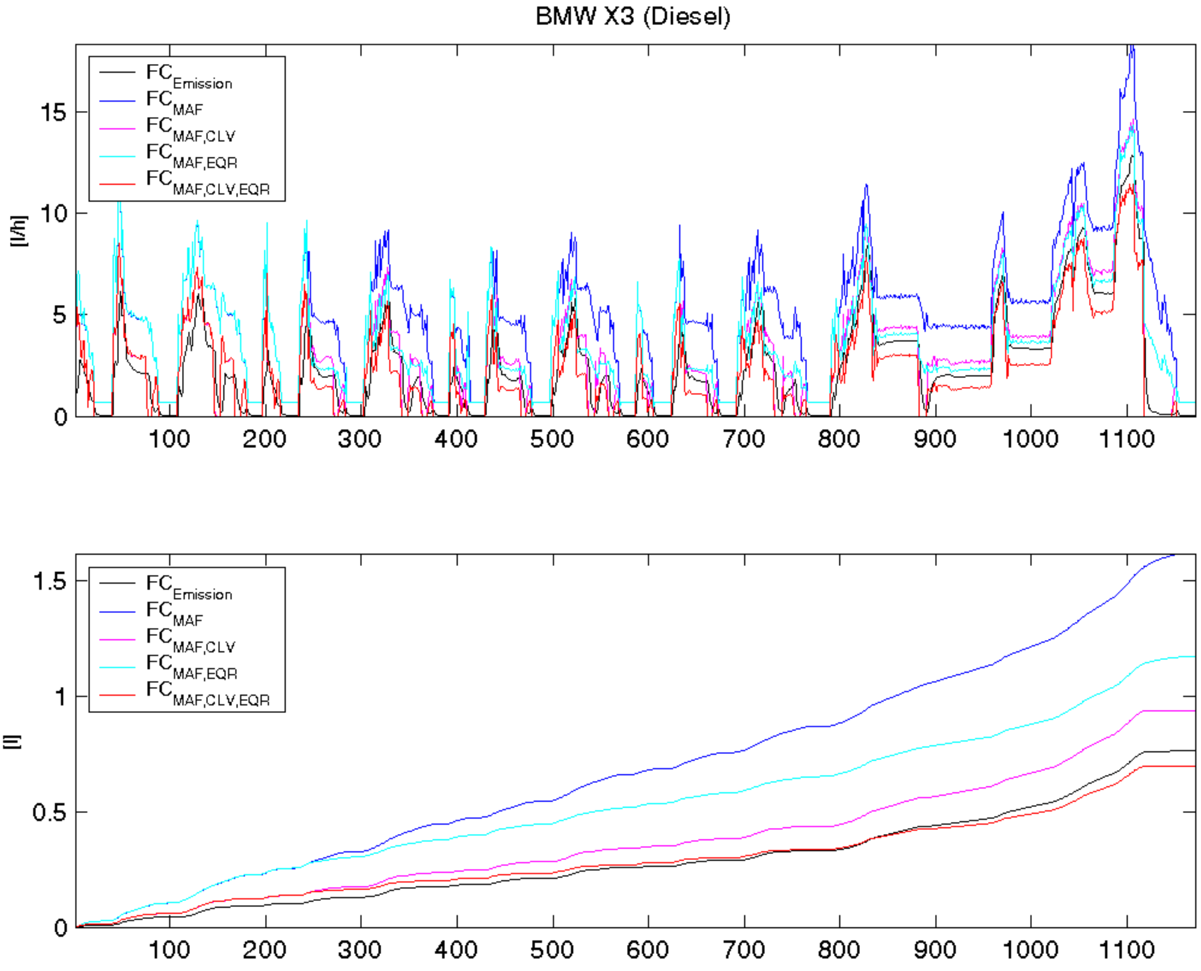


Similar to the other vehicle measurements the calculation of the air flow based on the MAP sensor leads to much higher values compared to the values of the MAF sensor. Deriving the fuel consumption from the MAP sensor does not lead to a matching with the emission data. Considering the calculated load value or the equivalence ratio in the formula leads to an improved accuracy, with best results if both CLV and EQR are applied (cf. red lines).

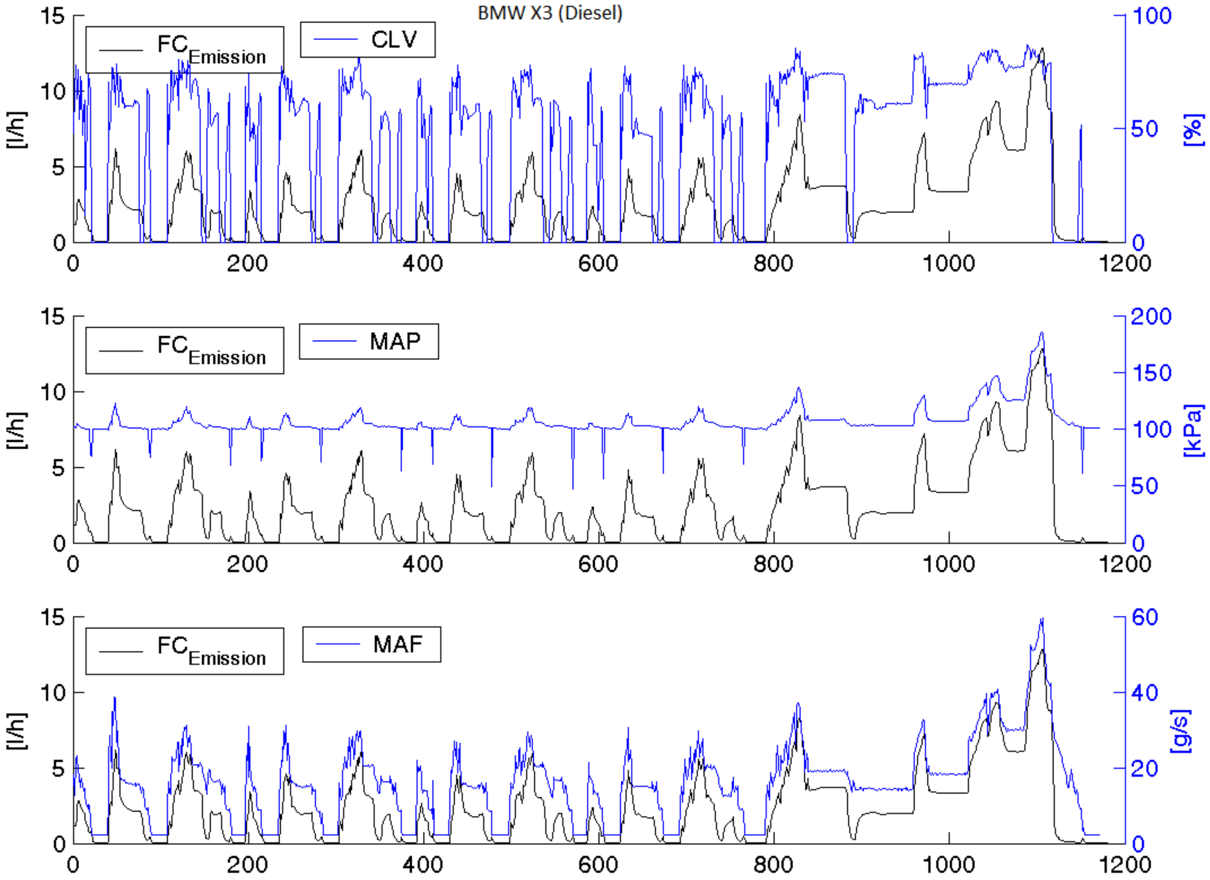


Similar to the results from the other vehicle measurements the calculation based on the MAF sensor leads to a higher accuracy when considering the calculated load value. The deviation of the total fuel consumption to $FC_{Emission}$ is similar to the Ford Focus vehicle measurements but in the opposite direction. While FC_{MAF} is lower than $FC_{Emission}$ for the Ford Focus, it is higher for the BMW.

Considering the equivalence ratio in the denominator of the formula improves the standard MAF formula, but only in conjunction with the calculated load value both curves (black and red) match quite well. However, there is an increasing deviation in the total fuel consumption curves at higher speed.



The following diagrams show the emission based calculation of the fuel consumption FC_{Dyno} against the calculated load value and the manifold air pressure values provided by the vehicle OBD system. Subsequently to the initial experiments of this study, the investigation of further methods for estimating the vehicle fuel consumption based on the CLV could show if the accuracy could be improved, in particular if the vehicle does not support the MAF sensor data.



Chapter Conclusions

The experiments showed that estimating the fuel consumption for the tested Otto engine vehicle that supports the MAF sensor data via the OBD system leads to a result that is quite close to fuel consumption based on the dynamometer emission measurement. For the tested driving cycle, the total deviation is less than 2 %, but it should be noted that the deviation is not constant during runtime.

For the tested Diesel vehicles, the accuracy of the fuel consumption using the MAF sensor data and the stoichiometric air-to-fuel ratio is not sufficient, as expected. The vehicle tests show that the accuracy of the FC estimation can be improved significantly, if additional OBD parameters are considered that are related to the current air-to-fuel ratio, commanded by the fuel management system. Using additional parameters supported by an OBD system as the calculated load value and the equivalence ratio lead to an improved accuracy of the MAF based FC estimation.

Within the next steps preparing the data collection study, further investigations with different vehicles should be executed. These tests could investigate the consideration of oxygen sensors in the fuel rate estimation, and also take their positions along the exhaust line (placed after exhaust manifold or DOC) into account.

Estimating the air flow based on the MAP sensor data requires consideration of further OBD parameters such as the engine speed and the intake air temperature and also knowledge on the engines volumetric efficiency. The volumetric efficiency is usually unknown for a specific vehicle engine and also varies for one engine in different operation conditions. Thus, the MAP based FC estimation seems not to be a sufficient method for the indented data collection study either for Otto or Diesel engine vehicles.

If a vehicle supports the engine fuel rate via its OBD system, for example via a manufacture dependent PID or via $5E as described within SAE J1979, such parameter could be used to achieve an increased accuracy of the FC estimation, in particular for vehicles that do not provide the MAF sensor and the equivalence ratio. The accuracy of calculating fuel consumption using engine fueling rate OBD data should be evaluated as a step before starting the main study.

7 In Vehicle Data Logger Evaluation

For collecting vehicle data on the road, each vehicle has to be equipped with an in vehicle data collection device. A certain device used for this purpose has to fulfill several technical requirements. The following section discusses several preliminary considerations and based on the insights to the OBD functionality described in section 5, the investigation on determining vehicle fuel consumption as described in section 6 and also the experiences made with data loggers summarized in section 7.2, a list of necessary data logger requirements was created and pictured in section 7.3.

7.1 Preliminary Considerations and Requirements

7.1.1 Data Collection and Processing

In the field study vehicle data and route information shall be collected with a frequency between 1 and 2 Hz during each trip over the runtime of one year. Depending on the number of vehicles, the amount of parameters that are recorded for each vehicle and the implementation of the storage format there might be a large amount of data that have to be collected, stored and processed.

Assuming 1,000 hours of vehicle operation during the one year data collection runtime and requesting 20 OBD PIDs with a 2 Hz frequency, the data of 144,000,000 parameter requests have to be processed for this vehicle. The amount of data collected for one vehicle during the project runtime also depends on the number of response bytes for each PID, the set of additional parameters as GPS location and timestamps and also the data logger storage format. Thus, the amount of storage data has to be particularly concerned in the selection of data loggers. A first rough estimation showed that during the planned study the amount of stored data unlikely exceeds two gigabyte for one vehicle.

In general, there are two approaches to handle the data, storing the data records locally into the device memory or transmitting data via mobile connection to a data storage server.

With regard to unit prices and operation costs storing data locally into the device might be a cost benefit compared to a solution that uses a mobile connection. But, there are some main disadvantages with that approach as storing data locally into the device require a large internal memory and possibilities for detecting malfunctions is limited.

Data can be read out from the devices periodically, after one year when the device is reinstalled or when a participant quits the program. Periodically read out of memory require changing memory cards or whole devices. This would cause additional effort for implementing a process handling hardware exchange, copying data and also requires integrating the vehicle drivers.

It might be necessary to implement simple and effective procedure to detect a malfunction during the project runtime. If the device is not working correctly for example caused by a hardware defect, OBD disconnection or because of the vehicle is simply not used for a longer time period this shall be detected at an early stage to avoid incomplete data is available for analysis. Using local data storage only has the effect data collection cannot be evaluated in detail parallel to the runtime of the project.

A solution that allows transmitting data periodically via a mobile communication network enables several opportunities. The devices do not have to store data internally over a long time, because collected data may be transmitted if a mobile connection is available. The mobile connection allows observing the operation status of every vehicle without contacting the driver. In case the device is not accessible via mobile connection or a malfunction detection message is received from one of the devices the vehicle driver could be contacted. In case additional vehicle parameters shall be read out or any software update is available during project runtime, an over the air update of the data loggers could be performed. Evaluation of the collected data already during the project runtime allows drawing conclusions on the data and taking meaningful measures timely. For example, it would be possible to add participants, if less data is collected with regard to investigated criteria. Beside these advantages a decisive factor could be the costs for mobile data traffic, in particular if the number of vehicles and frequency for data read out is high. An opportunity would be to store the collected vehicle data internally into the device memory and using the mobile connection only for checking correct operation of the data collection and for updating the device software if necessary.

7.1.2 Device Handling and Operation

Numerous vehicles from the US and Europe shall be equipped with the data collection device. Thus it would be advantageous if vehcile owners are able to perform the installation and reinstallation on their own with help of a simple installation guide. A device that can be connected to the OBD-II port directly without any cabling for OBD, external antennas and power supply may be most practicable and could increase the acceptance for vehicle owners to participate over the runtime for one year. Furthermore this kind of solution should be less prone against mechanical defects and guarantee a fully reversible reinstallation.

An important aspect in the selection of the data logger is the power consumption. It has to be guaranteed that the device does not empty the vehicle battery even if the car is not used for a long time.

7.1.3 Safe and Secure Operation

Operating a data collection device connected to the electrical system of the vehicle and also to a mobile communication platform needs to consider safety and security aspects. In automotive context safety does thereby mean functional safety and fail safe operation during the whole life cycle. Main goals of the methods applied in safety context are the protection against random hardware failures and systematic failures in the development phase. The main goals of security are to guarantee confidentiality, privacy, trust and robustness against unauthorized attacks and manipulation attempts.

A worst case scenario would be an impact to safety-relevant vehicle functions caused by an invalid interference of the data logger.

The main safety relevant interface is the OBD interface which connects the device to the vehicle network. Via this interface it is possible that the device influences automotive network communication in an illegal way by transmitting erroneous signals on the OBD protocol lines. Illegal signals transmitted by the data logger can be any kind of noise or undesired communication elements that force the vehicle ECUs to an unintended reaction.

As the device in general supports flashing of its firmware over-the-air, a possible risk scenario would be the manipulation of the device configuration or the installation of erroneous or unauthorized software. Besides malicious or unintentional attacks of unauthorized persons these impacts could appear by erroneous software updates of the device manufacturer or the service provider.

To minimize the risk it is highly recommended to perform suitable test and validation measures related to the used system and any updates on device configuration and firmware during the data collection runtime.

7.1.4 Conformity Declariations

The data collection device shall be connected to the vehicle network and safe operation in road traffic must be guaranteed in every case. In case an accident or a vehicle malfunction appears, it must be ensured that the data collection device is not the cause. It should be highly recommended that the functionality of the devices is validated with available and common tests.

The vehicle shall be equipped with the data logger for one year, thus the correct operation must be granted under changing conditions. The following aspects have to be considered:

- Error-free operation under changing climate and temperature conditions
- Secure mechanical mounting even in case of vibration
- Electromagnetic emissions below legal limits
- Resistant response to electromagnetic interferences
- Secured communication at the cabling, device complies with communication protocols, no disturbances to the vehicle network
- Obstruction of the driver must be excluded

Since the early 50s the technical regulations for motor vehicles are harmonized on international level. Currently there are 49 contracting parties and most of the regulations from the Economic Commission for Europe (ECE) are accepted and integrated into national rights. The regulations of the ECE consider parts and equipment of motor vehicles that are relevant for issuing a type approval. These regulations are continuously adapted to new developments in technology. Vehicles and items that have an ECE Approval are marked with an *E* and a following number, where the number indicates which country approved the item.

Further information on the international harmonization of the technical regulations for motor vehicles can be found at:

http://www.bmvbs.de/SharedDocs/DE/Artikel/StB-LA/internationale-harmonisierung-der-technischen-vorschriften-fuer-kraftfahrzeuge.html?nn=58354

The German versions of the ECE regulations can be found at:

http://www.bmvbs.de/SharedDocs/DE/Artikel/StB-LA/ece-regelungen.html?nn=58354#doc20394bodyText5

Access to the European right is available via:

http://eur-lex.europa.eu/

It is highly recommended that the data logger device that is connected to the vehicle OBD system have common type approvals as according to ECE R10 for electromagnetic compatibility.

Beside the common type approvals there might be additional qualification methods available to guarantee faultless operation. A communication device as an OBD data logger implements functionality on several abstraction layers. The communication between the data logger and the vehicle ECUs has be error-free and conform with the used bus system as CAN or K-Line and also with the existing OBD standards. Communication modules used within vehicle ECUs usually undergo a conformance test that confirms the correct functionality of the device with respect to the related communication standards. The individual conformance tests are usually not prescribed by law but demanded from vehicle manufacturers in their individual supplier release processes. Thus it is highly recommended that the communication modules of the used data loggers passed the common conformance tests.

Within the [ISO 15031-4] standard a specified conformance test for external OBD test equipment is available that defines several tests which have to be passed in order to certify external OBD test equipment as ISO conform. The [ISO 15031-4] conformance test has initially been specified for standalone devices comprising a display and an interface to accept user input like dynamic selection of the requested PID. Nevertheless, general parts of this test can be adopted for testing the functionality of a telematic OBD device. Based on these scenarios a functionality test for ODB data loggers was implemented at TÜV NORD and could be used for testing the selected devices.

7.2 Data Logger Evaluation

Numerous OBD scan tools and telematic devices of different manufacturers are available on the market. The products range from cheap data loggers with limited functionality to professional equipment for particular use cases, e.g. fleet management, service repair, system test, etc.

Within the pilot study several data logger manufacturers were interviewed to their products and selected devices were evaluated for its technical and functional capabilities and limitations. Access to detailed technical information from data logger manufacturers required singing of non-disclosure agreements. With this in mind, the names of the manufacturers are kept undisclosed, and only website available information is summarized here. The reader is invited to contact the authors of this report for specific data logger and manufacturer information. Only a summary of our detailed data logger market evaluation is presented here.

Data Logger 1

Device Description

Data logger 1 is designed for advanced telematic applications with high data reliability. The device provides an OBD interface for logging vehicle data and a GPS tracking unit for monitoring vehicle positions, driving and mileage.

The device supports connection to the vehicle OBD system only via CAN bus. During the runtime of the pilot study, support of the whole instruction set defined in ISO 15031-5 is not implemented, but planned in a later firmware release. Reading non-standard PIDs is also not supported, but could be implemented on customer request.

As an extension to the data logger, the manufacturer offers a solution to calculate the CO_2 emission which allows also estimating the vehicle fuel consumption. Detailed information on the accuracy and the mechanism was requested but not provided. For some vehicles they monitor the fuel level input before and after each trip for calculating the fuel consumption.

The device contains a memory for recording collected data and also a SIM card slot for data transmission via mobile networks. Within the evaluation it turned out that the present version does not support storing OBD data into the device memory. Therefore the device was not used for the planned chassis dynamometer testing. For the planned field study local buffering of collected data is essential to continue data collection when a mobile network is temporarily not available. The manufacturer offers to implement buffering OBD data into the internal memory on request. Furthermore they offer a method to save data in a histogram of the unit, where the gathered data is filtered to a matrix of preset values.

To perform over the air software updates and device configuration a tool is available for the data logger.

The manufacturer provides a development package including a Java based software development kit for implementing customized applications. This would allow implementing specific mechanisms required for the fuel economy field investigation.

The device was delivered with an OBD connector cable that provides only CAN High and CAN Low bus signals. For power supply of the device a separate power cable with 9 V plug was delivered. A new OBD cable was currently under development during the runtime of the pilot study that includes also a power supply via the OBD connector (Pin 16). For collecting GPS and/or GLOSNASS data the device was delivered with an external antenna.

Conformity Declarations

The device has the following type approvals:

- ECE 10.03
- 1999/05/EC (RTTE)
- GOST-R (A9 GLONASS)
- 2004/108/EC (EMC directive)

- CE marking

Prices

Given prices are taken from an exemplary offer including data logger device, SIM card, external GPS antenna and OBD-(CAN) cable.

Purchased Units	Unit Prices
100	€ 121,70 (excl. tax); monthly fee for 2 MB SIM is € 0,95 (excl. tax)
1000	€ 115,20 (excl. tax); monthly fee for 2 MB SIM is € 0,85 (excl. tax)
5000	€ 110,55 (excl. tax); monthly fee for 2 MB SIM is € 0,65 (excl. tax)

Data Logger 2

Data logger 2 was designed to provide a complete solution for vehicle telematics service providers.

Device Description

At the runtime of the pilot study the device support the bus protocols CAN, ISO 9141-2, KWP2000. J1850 VPW and J1850 PWM were not supported but implementation can be offered.

The standard firmware currently supports OBD services 1, 2, 3, 7 and 9 as defined in ISO 15031-5.

The embedded platform architecture offered by the manufacturer includes a data recorder and a data emitter as independent components. The device can be configured to record PIDs with a particular frequency. Using the device version without GPRS connectivity the frequency to record the data is currently the same for all PIDs. The version supporting GPRS allows updating the configuration file remotely including changing PIDs and recording frequency.

The manufacturer offers a Java based development kit that allows developing customized device software. The API also allows transmitting CAN messages with a configurable ID and payload data. This enables transmission of additional standard and non-standard requests.

The device is directly connected to the OBD-II port. No external connector or antennas are required for operation.

The manufacturer provides a package including hardware, SIM cards and cloud connect services. They are currently working on new device management tools to offer a complete plug-and-play package.

Recorded data can be stored into the internal memory. The data can be downloaded afterwards or transmitted via a mobile connection. The unit is equipped with 1 MByte storage reserved to the recorded data. The memory is implemented as circular buffer, thus the last data recorded will automatically replace old data once the memory is full.

The manufacturer is working on an implementation to determine fuel consumption with their devices. No information was available during the runtime of the pilot study, but sharing information is planned in future. Furthermore they are working on new firmware updates and additional features to analyse driver behaviour including measuring deceleration / acceleration / left cornering / right cornering.

Conformity Declarations

The device has ECE R10 type approval (E24) and a CE mark following R&TTE Directive 1999/5CE with requirements covering EMC Directive 2004/108/EC and LV Directive 2006/95/EC. Conformity with appropriate standards:

- ETSI EN301 489-1 V1.8.1 2008
- ETSI EN301 489-3 V1.8.1 2002
- ETSI EN301 489-7 V1.8.1 2005
- IEC 60950-1: 2005 (2nd Edition)/A1: 2009
- EN 60950-1: 2006/A11:2009/A1:2010/A12:2011
- ETSI EN 300 440-1 V1.6.1 2010
- ETSI EN 300 440-2 V1.6.1 2010
- ETSI EN 301 511 V9.0.2 2003
- EN 62209-2: 2010

Prices

The communicated prices for the OBD data logger are given in the following table.

Purchased Units	Unit Prices
100	137 €
1000	100 - 120 € per unit depending on number of batches and payment terms.
5000	80 – 100 € per unit depending on number of batches and payment terms.

The SDK for implementing project specific applications is offered for a fix amount of 4000 €, including the full SDK and a mandatory two day training with up to three persons and technical support via mail and phone for one year.

Data Logger 3

The manufacturer offers vehicle data logging solutions and provides tailored solutions. They currently supply loggers to a number of companies as Jaguar Landrover, Ford Europe, Ford North America, Ford India, Bentley, McLaren, SAIC, BP, Lubrizol, Ricardo amongst others.

Device Description

The data loggers support CAN and K-Line protocols. Compatibility of the J1850 protocol is not provided but can be developed on request. The OBD services defined in ISO 15031-5 are completely supported and the device also allows transmitting non standard PIDs request messages. Influx Technology has experiences with development of engine management systems and also with determining vehicle fuel consumption via manufacture dependent CAN bus information.

The manufacturer provides tools for device configuration and data management. This allows processing of recorded data and automated report generation. A standard development kit for implementing specific device software is not available, but would be negotiable if required.

The devices use a 32 GB SD card for storing data records. Data exchange is via USB, Bluetooth, Wi-Fi or GPRS. Beside transmission of recorded data it is also possible to adapt the device configuration of the standard firmware remotely.

Conformity Declarations

An ECE R10 type approval for EMC conformity is not available at the time of request, but obtaining is planned.

Prices

The product range of the manufacturer comprises different data loggers. The unit price for the top of the range, including GPRS connectivity is £2320 and additional £51 for a combined GPS/GPRS Antenna. Connecting the device to a vehicle requires a cable that is offered for £120.

The device configuration software costs £900 and can be used for multiple data loggers.

Depending on the specific project requirements the manufacturer offers different data logging solutions. The following table gives an overview on the unit prices of their products in dependence on the purchase quantity.

Purchased Units	Unit Prices
100	Between £ 648 and £ 1856 + £ 15 for antenna
1000	Between £ 540 and £ 1450 + £ 15 for antenna
5000	Between £ 432 and £ 1260+ £ 15 for antenna

The following tables list different data logger manufacturers and data loggers of their product ranges that might be suitable for the data collection field study. For a precise valuation of the applicability of individual products the data logger requirements (as listed in section 7.3) have to be discussed with the manufacturers.

Manufacturer	Device	GSM/GPRS	GPS	Memory	Power Supply	PC connection
Aplicom	A9	Yes	Yes	internal 1.7 MB Flash 400 KB RAM	External 9 V plug in current version, upcoming via OBD connector (<100mA, <3mA sleep) Li-Ion battery	Serial Interface
Auterraweb	DashDyno SPD	No	yes	SD card (max. 2 GB)	OBD or AC adapter	USB
Caflor	IOSiX-100 IOSiX-150	Yes	yes	SD card (max. 2 GB)		Yes
Danlaw	Danlaw DL750 DL755 (Bluetooth)	Yes	yes	n/a	OBD connector (<100mA, <3mA sleep)	n/a
Enfora	N4A Spider MT 3000/3050	Yes	yes	n/a	OBD connector (GSM: <190mA, <=90mA idle, <=8mA sleep)	n/a
HEM Data	DAWN OBD Mini Logger	No	yes	SD card (max. 32 GB)	OBD connector (<=200mA WiFi, 34mA idle, 3mA sleep)	USB
Influx Technology	Rebel XT	Yes	yes	SD card (max. 32 GB) internal 32 GB Flash	external (4.7V-33V) (<3mA sleep)	USB, Bluetooth
Mobile Devices	C4	Yes	Yes	1 GB Flash for data records 64 - 128 MB RAM	external (8-18V) 900 mAh Li-ion battery & charger (optional)	Mini-USB
Scope Technologies	MHub837	Yes	Yes	n/a	(60mA, 2mA sleep), 4h battery backup	

Car Media Lab	Flea 3	Yes	Yes	128 SDRAM, 512 Flash	Sleep (Systemcontroller only) < 0,5 mA Run Mode: 300 mA	USB
Vector Informatik	GL 1000	No	no	SD/SDHC memory card (2GB – 32 GB)	55 mA at 12 V DC Sleep Mode: 160 µA	USB, RS232, Bluetooth, WLAN (optional)

Device	OBD-II Protocols	OBD Parameters	Sensors	Form Characteristics
Aplicom A9	ISO 15765 (CAN)	Configurable via management tools, freely programmable via SDK	accelerometer	(112x61x15mm), 70g, OBD cable, external power supply
Auterraweb DashDyno SPD	J1850 (VPW, PWM), ISO 9141, ISO 14320 (KWP), ISO 15765 (CAN bus)	supports 280 OBD parameters, extended parameters available		Touch screen OBD cable
Caflor IOSiX-100 IOSiX-150	SAE J1850 PWM, SAE J1850 VPW, ISO 9141-2, ISO 14230-4 (KWP), ISO 15765-4 (CAN)	supports 150 OBD parameters	accelerometer (IOSiX-150)	
Danlaw DL750 DL755 (Bluetooth)	GMLAN, FNOS, ISO 15765, ISO-9141-2, J1850 PMW, J1850 VPW, KWP-2000, ISO-14230-4		accelerometer	compact (43x46x23mm), 31g
Enfora N4A Spider MT 3000/3050	J1850 PWM, J1850 VPW, ISO-9141-2, ISO-14230 KWP2000, and ISO-15765 CAN		accelerometer	compact (55x49x29mm), 37g (45g with battery)
HEM Data DAWN OBD Mini Logger	ISO 15765-4 (CAN) (others may be available)	includes 100 OBD parameters, custom messages configurable	accelerometer, cabin temperature, vehicle battery voltage	compact (48x18x38mm)

Influx Technology Rebel XT	ASAM CCP, xCP, ISO15765/ISO14229/ISO14230/J1939, DBC, A2L, ODX/MDX/GDX		accelerometer	OBD cable, display and buttons
Mobile Devices C4	ISO 15765 CAN, ISO 9141-2, ISO 14230 KWP2000	freely programmable, extended PIDs supported via MULTI-STACK technology	3D accelerometer, 3-axis gyroscope (optional)	compact (27x48x50mm)
Scope Technologies MHub837	ISO-9141, ISO-14230, VPW, PWM, CAN			With OBD connector: 27x60,5x49,5 mm Without OBD connector: 27x48x49,5 mm
Car Media Lab Flea 3	1 x K-Line/ LIN, 4 x CAN High Speed, 1 x CAN High Speed/Low Speed switchable			
Vector Informatik GL 1000	Support of CAN and LIN protocols, no dedicated OBD implemented			138 mm x 106,7 mm x 36,1 mm inkl. antenna and main-connector

Chapter Conclusions

Within the pilot study different data loggers were evaluated for the applicability to the data collection project. As the data loggers had some functional limitations, the next section lists several requirements that could be discussed with the manufacturers in the next steps preparing the data collection study. With the detailed feedback of the manufacturers a ranking for the selection of different devices could be created.

7.3 List of Data Logger Requirements

Numerous vehicle bus interfaces for different operation scenarios are available on the market. For application to the field economy pilot study a telematic solution seems to be most suitable because these devices generally provide the required functionality at a relatively low unit price.

Nevertheless, for realizing the fuel economy data collection successfully the used data logger has to fulfill certain technical requirements. Based on experiences gained within the investigation of this pilot study the requirements to the in vehicle data logging solution are specified within this section. The requirements list is created under the aspect to setup a basis for choosing the most suitable data logger solution for the fuel economy field study. The list might be given to the data manufacturers for requesting required product features and prices.

It shall be noted that the following list describes the main features the vehicle data logging solution has to provide. This section does not represent a fully complete requirements specification.

The following list implies that the collected vehicle data shall be transferred via mobile communication network to a remote data collection server. If the data logger solution shall be realized with storing data records only locally into the internal device memory, the data logger shall transmit operation status messages to the remote server periodically. The set of status data, e.g. vehicle identification number, internal device memory fill level, malfunction detected, etc., has to defined separately as well as the size of the internal device memory.

ID	Data Logger Power Modes
1	The data logger shall provide a Normal Operation Mode. In this state the average current flow into the data logger may not be exceed 250 mA.
2	The data logger shall provide a Low Power Mode. In this state the average current flow into the data logger may not be exceed than 15 mA.

ID	Data Logger Interfaces
3	The data logger shall provide an interface for direct connection to the vehicle OBD port according to ISO 15031-4. Any additional cabling for OBD signaling and also to e.g. an external GPS antenna or power supply shall not be necessary for data logger operation. Mechanical mounting of the device shall be performed only by plugging the device into the OBD port of the vehicle.

4	The data logger shall provide an internal rechargeable battery with a capacity for at least one hour operation when the device is disconnected from the vehicle OBD connector.[11] The battery shall be rechargeable from the vehicle battery voltage.
5	The data logger shall provide an internal GPS module including an internal GPS antenna that allows recording vehicle position by means of position, altitude and timestamp.
6	Optional: The data logger has to provide an internal acceleration sensor.
7	The data logger shall provide a serial interface for uploading firmware updates, logger configuration and debugging.
8	The data logger shall provide an internal memory of at least 32 MB flash memory (e.g. SD card) for storing collected data. Each data record stored into the data collection memory shall be furnished with a unique timestamp.
9	The data logger shall provide an interface to a remote data collection server via mobile communications networks.
10	The data logger software application shall be configurable for the requirements listed below via a configuration tool and/or a software development kit.

ID	**Data Logger Processing while Vehicle Ignition Off and data logger is in Sleep Mode**
11	The data logger shall monitor the acceleration sensor data and the vehicle battery voltage. If the acceleration is greater than zero or the vehicle battery voltage is 0 V, the data logger shall store the monitored data with a unique timestamp into the internal device memory. If the vehicle battery voltage signals a switch from ignition Off to On (13.7 V) the device shall enter Normal Operation Mode.

ID	**Data Logger Initialization Phase**
12	The data logger shall execute an initialization phase once after first connection to the

[11] In case of unintended disconnection of the data logger from the vehicle OBD port, a disconnection message and also the recorded vehicle data could be transmitted to the server.

	vehicle and data logger is in Normal Operation Mode.
13	The initialization phase shall also be executable via control message received from the remote data collection server.
14	Within the Initialization Phase the data logger shall provide a built in mechanism according to ISO 15031-5 that automatically detects the bus protocol variant supported by the vehicle OBD system. The mechanism shall be executed directly after data collection initialization phase is entered. Information on the supported bus protocol shall be stored into the internal device memory.
15	Within the Initialization Phase and after a supported bus protocol has been detected the data logger shall • request the supported ISO 15031-5 PIDs from the vehicle OBD system • check if the configured non-standard PIDs are supported by the vehicle OBD system • check if multiple ECUs response messages are transmitted to a any data logger PID requests The collected information shall be stored into the internal device memory.
16	Within the Initialization Phase the data logger shall not transmit unsupported PIDs in all further request messages of the initialization and data collection phase.
17	Within the Initialization Phase the data logger has to check if in dependency of the number of ECUs responding to individual request messages if the desired frequencies for PID requests can be fulfilled. If the required timing is not feasible the device shall store this information within the internal device memory and send a status message to the remote data collection server as soon as a mobile connection is available.
18	Within the Initialization Phase and after determination of the PIDs supported by the vehicle OBD system, the data logger has to request specific data (e.g. VIN) via the OBD interface. The set of OBD requests shall be freely configurable. The collected data shall be stored into the internal device memory.
19	Within the Initialization Phase and after the initialization phase is executed successfully the data logger shall execute the data collection phase. Executing initialization phase shall not take more than 20 seconds.

ID	Data Logger Processing while Vehicle Ignition On and data logger is in Normal Operation Mode
20	The data logger shall monitor the vehicle battery voltage.

	If the vehicle battery voltage is 0 V, the data logger shall store the monitored data with a unique timestamp into the internal device memory.
21	Directly after the data logger entered Normal Operation Mode, the VIN shall be requested via OBD. If the VIN matches the data recorded during initialization, the data logger shall execute the data collection phase. Otherwise the logger the data logger shall store the monitored data with a unique timestamp into the internal device memory and not start data collection.
22	Within the data collection phase the data logger shall periodically request specific data via the OBD interface. The set of OBD requests and the frequency of individual PIDs shall be freely configurable. As the OBD PIDs supported by a vehicle vary on different models, the data logger shall at least support requesting the VIN as well as the OBD service 1 PIDs supported by the vehicle. The collected data shall be stored into the internal device memory.
23	Within the data collection phase the data logger shall periodically monitor the data of the GPS and acceleration sensor in a frequency of at least 1 Hz. The collected data shall be stored into the internal device memory.
24	Within the data collection phase the data logger shall periodically monitor status data, e.g. fill level of internal device memory, application failures or OBD malfunction detected, etc. The data shall be stored into the internal device memory. The set of monitor data and the storage frequency shall be freely configurable.
25	The data logger shall transmit the data records stored in the internal device memory to the remote data collection server via mobile connection.
26	The data logger shall delete the transmitted data records from the internal device memory after receiving a positive acknowledge message from the server.

ID	Data Logger Processing while Vehicle Ignition Off and data logger is in Normal Operation Mode
27	The data logger shall transmit the data records stored in the internal device memory to the remote data collection server via mobile connection.
28	The data logger shall delete the transmitted data records from the internal device memory after receiving a positive acknowledge message from the server.
29	The data logger shall monitor the acceleration sensor and the vehicle battery voltage. If the acceleration is greater than zero or the vehicle battery voltage is 0 V, the data logger shall store the monitored data with a unique timestamp into the internal device

	memory.
30	The data logger shall enter Low Power Mode after a configurable time interval expired.

ID	Data Logger Configuration Mode
31	The data logger has to provide a Configuration Mode which allows uploading firmware updates and device configuration.
32	The Configuration Mode shall be reachable via mobile connection and the serial interface. When Configuration Mode is entered the data logger shall interrupt data logging activities (e.g. initialization phase and data collection phase)

ID	Data Logger OBD capabilities
33	The data logger shall support the CAN bus protocol variants for OBD communication: • CAN 500 kBit/s, 11 bit identifier field • CAN 250 kBit/s, 11 bit identifier field • CAN 500 kBit/s, 29 bit identifier field • CAN 250 kBit/s, 29 bit identifier field
34	Optional: The data logger shall support the K-Line protocols.
35	The data logger shall support transmitting ISO 15031-5 conform request messages to the vehicle CAN based OBD system. The device shall support requesting all data defined in • Service $01 (Current powertrain diagnostic data) • Service $03 (Emission-related diagnostic trouble codes) • Service $09 (Vehicle information)
36	The data logger shall support transmitting request messages containing non-standard PIDs, (e.g. CAN data field of request message is freely configurable)
37	The frequency for periodic OBD requests shall be configurable for each PID. At least a frequency of 2 Hz for each PID shall be configurable.
38	The data logger shall support transmitting up to six PIDs in one CAN request message.
39	The data logger shall be capable to start transmitting a request message at least 50

	ms after receiving the end of a final vehicle response message.
40	The number of CAN request frames transmitted by the data logger shall be as little as possible with regard to the device configuration.

ID	Optional Features on estimating Vehicle Fuel Efficiency
41	The data logger solution implements a method to estimate the vehicle fuel consumption. The data is available with a temporal resolution of at least 1 Hz. The list of supported vehicles can be provided. The accuracy of the method has to be tested against a laboratory emission test or a similar reference measurement.
42	The data logger solution implements a method to request the engine fuel rate (similar to SAE 1979, PID $5E) via a non-standard PID from the vehicle OBD system. The engine fuel rate shall indicate the amount of fuel consumed by the engine per unit of time. The data is available with a temporal resolution of at least 1 Hz. The list of supported vehicles can be provided. The accuracy of the method has to be tested against a laboratory emission test or a similar reference measurement.
43	The data logger solution implements a method to request the actual air-to-fuel ratio (similar to SAE 1979, PID $44) being commanded via a non-standard PID from the vehicle OBD system. The data is available with a temporal resolution of at least 1 Hz and the achievable accuracy is in the range of ten percent. The list of supported vehicles can be provided.
44	The data logger solution implements a method to get the operating state of electric power consumers of the vehicle as heating, air conditioning, light, radio via a non-standard PID from the vehicle OBD system. The data is available with a temporal resolution of at least 0.1 Hz. The list of supported vehicles can be provided. The accuracy of the method has to be tested against a laboratory emission test or a similar reference measurement.
45	The data logger solution implements a method to get the electrical load at the vehicle alternator via a non-standard PID from the vehicle OBD system. The data is available with a temporal resolution of at least 0.1 Hz. The list of supported vehicles can be provided. The accuracy of the method has to be tested against a laboratory emission test or a similar reference measurement.

46	The data logger solution implements a method to get the tires air pressure via a non-standard PID from the vehicle OBD system. The data is available with a temporal resolution of at least 0.1 Hz and the achievable accuracy is in the range of ten percent. The list of supported vehicles can be provided.
47	The data logger solution implements a method to get the fuel ethanol content via a non-standard PID from the vehicle OBD system. The data is available at least once after each engine start. The list of supported vehicles can be provided.

ID	Data Logger Safety & Security Measures
48	The data logger shall have a type approval for vehicle road use according to the regulations of the European union (e.g. ECE R10).

8 Summary

The pilot study dealt with different subjects that required a better understanding before carrying out the fuel economy field investigation across Europe. The main focus was to explore and evaluate the project feasibility and also to identify technical opportunities and challenges. This section summarizes the findings of different tasks and describes relevant next steps that should be investigated subsequently to this pilot study as preliminary tasks for the full-scale study. It also gives a first estimate of the costs for running the fuel economy field study.

8.1 Vehicle Sampling

The investigation of sampling methods showed that stratified sampling can be a proper approach for determining the vehicle sample size. The general stratification criteria have to be defined with regard to the objectives of the full-scale study. Related stratification parameters could be, for example, model year, vehicle model, engine type, fuel type, engine power, vehicle age, private or commercial vehicle use.

To gain a reasonable result, the stratification criteria and the sample size have to be determined in consideration of the representativeness of the sample. It has to be considered that the group of vehicles that is available for drawing the sample not necessarily represents the current fleet of registered vehicles appropriately. Not every vehicle provides the required OBD data for determining the fuel efficiency with the desired accuracy and, furthermore, the field study requires volunteer drivers. Thus, the sample has to be compiled by selecting suitable vehicles (with the required OBD data) from the pool of volunteers. This will assure the representativeness of the composed sample.

An exemplary sample size calculation has been performed based on certain assumptions. Depending on the main goals of the investigation, the resulting sample size can vary significantly. A smaller sample size in the range of 200 vehicles allows e.g. to analyze certain influences of the real vehicle fuel consumption for the vehicle fleet in general. A size in the range of 500 vehicles allows a more detailed analysis of the deviation of real fuel consumption from the type approval values, for example, to prove the model year curve created in the ICCT analysis based on the *Spritmonitor.de* data (cf. 3.3). A large sample size in the range of 1,000 vehicles or above might be suitable if a detailed investigation with analyzing the fuel economy for multiple specific vehicle models is intended.

Analyzing the available vehicle stock with regard to full-scale field study objectives in more detail allows to optimize the sample size and to make the results more representative. Information sources such as *Spritmonitor.de* can be analyzed in more detail for determining the variance of the research criteria. Available information on OBD systems and supported PIDs of different vehicles can be analyzed to preselect suitable vehicle models for the field investigation.

8.2 Vehicle Driver Recruiting

A survey with customers of different TÜV stations showed that more than 50 % of the questioned people have the impression that the fuel consumption of their vehicle is higher than specified in the manufacturer's data sheet. Around 25 % of the people who filled out the questionnaire showed interest in participating in the fuel economy data collection study. Nine out of ten volunteers are interested in receiving a report on their driving data and the majority of these persons would prefer receiving digital data via e-mail or a website. Every third volunteer desires a further incentive for their participation worth € 80 to € 100 (e.g. a tankful of fuel or a general vehicle inspection). Increasing the individual incentives up to € 250 would presumably increase the participation rate and also facilitate the recruiting process. An additional task-based incentive could motivate participants to remain in the program over the whole runtime and also to perform particular activities.

The survey also showed the opportunity to recruit participants and support vehicle drivers with the installation of data loggers via TÜV stations.

In search of further opportunities to recruit volunteers for the data collection project, several commercial companies and organizations that have a large base of vehicle drivers were contacted. Vehicle clubs showed big interest in the results of the fuel economy field study. For recruiting vehicle drivers in Europe, it would be generally possible to contact the members of different clubs. During the project it was found that the Fédération Internationale de l'Automobile (FIA) could be a potential field study partner, acting as the global contact for different vehicle clubs. As the share of commercial vehicles is increasing in the new vehicle business, it seems meaningful to consider them in the sample, too. Vehicle leasing suppliers that were contacted showed no interest in participating in the study because of market policy reasons. Discussions with companies from other sectors showed that it is generally possible to include commercial vehicles from companies that operate large vehicle fleets or use vehicle fleets that are already equipped with data loggers. If this option were considered, cost and legal aspects would have to be clarified in the next steps.

8.3 Determining the vehicle fuel consumption via OBD data

The OBD standard specifies a large set of parameter identifiers to request sensor data and further information from the vehicle ECUs that are connected to the diagnosis system. The investigation showed that common vehicles support only a small set of the functionality specified in the OBD standard.

Within the pilot study, three Otto engine vehicles and three Diesel vehicles were equipped with OBD data loggers and tested with defined driving cycles on a chassis dynamometer test stand. With the logged data, determining vehicle fuel consumption based on the stoichiometric air-to-fuel ratio was investigated. As vehicle OBD systems support the MAF and/or MAP sensor data, this data could be taken as a basis for calculating the vehicle fuel consumption. It turned out that, depending on the supported PIDs and also the engine and fuel type, the achievable accuracy varies strongly.

MAF based FC estimation with Gasoline Vehicles

The experiments showed that estimating the fuel consumption for the tested Otto engine vehicle that supports the MAF sensor data via the OBD system leads to a result that is very close to the calculated fuel consumption based on the dynamometer emission measurement. For the tested vehicle and driving cycle, the total deviation is less than 2 %, but it should be noted that the deviation is not constant during runtime. With regard to the full-scale fuel economy field study, the minor inaccuracy can be neglected.

MAF based FC estimation with Diesel Vehicles

The vehicle test showed that the value of the determined fuel consumption for the tested Diesel vehicles using only the MAF sensor data is much higher than the real fuel consumption. This is because diesel vehicles always operate lean and the air-to-fuel ratio is never held constant.

Further experiments showed that the accuracy of the FC estimation can be improved significantly when additional OBD parameters are considered that are related to the current air-to-fuel ratio, commanded by the fuel management system. Thus, if the vehicle OBD system supports such parameters as the calculated load value and the equivalence ratio, then the accuracy of the FC estimation can be improved significantly. Without available OBD air-to-fuel ratio correcting parameters, the observed accuracy is not sufficient for the intended purpose of the full-scale study.

MAP based FC estimation

The estimation based on the MAP sensor does not lead to sufficient results for both vehicle types, Diesel and Otto engine vehicles. Estimating the air flow based on the MAP sensor data requires consideration of further OBD parameters such as the engine speed and the intake air temperature and also knowledge on the engine’s volumetric efficiency. The volumetric efficiency is usually unknown for a specific vehicle engine and varies for one engine in different operation conditions. Specific vehicle tests could be designed to determine the volumetric efficiency of a vehicle, but the high costs probably makes it unfeasible for all vehicles of the sample.

Based on the experienced acquired from the vehicles experiments, it is recommended to use only vehicles in the sample, that support the MAF sensor data and for Diesels also the calculated load value and the equivalence ratio or oxygen sensor data. Referring to this, the percentage of vehicles has to be determined, that support the required OBD data for an accurate estimation of the fuel consumption. If the majority of vehicles does not support the required OBD data, non standard vehicle PIDs would be required.

Non-standard PIDs are not offered for purchase in the European public domain. Several data logger manufacturers perform intensive reverse engineering activities with existing vehicles for improving their product functionality by providing access to manufacturer specific PIDs. In further project preparations, the discussion and information exchange with selected data logger manufacturers could be deepened. Incorporating vehicle specific information that may be available via non-standard PIDs can improve the accuracy of the FC estimation. It can be assumed that reading the engine fuel rate as defined in SAE J1979 via $5E leads to an accurate result. The accuracy of the PID $5E should be studied against laboratory grade instruments within the next steps preparing the field study.

For an investigation of additional power consumption by air conditioning, tire air pressure variation or additional vehicle loading, an analysis of non-standard PID data availability would be necessary. AC systems are one of the most significant factors of variability in fuel economy. However, standard PID data do not provide any information useful for AC activity determination. If a further study of non-standard PIDs also cannot provide useful AC activity data, then a special data collection method should be designed for a subset of the sample.

Vehicle Speed

For estimating the total fuel consumption over a distance, the accuracy of the vehicle speed has to be considered. The performed vehicle tests showed that the inaccuracy of the OBD vehicle speed value increases in particular at higher vehicle speeds. Further vehicle test could be performed at higher speeds and investigate the influences in more detail.

The vehicle tests showed that the influence of different OBD parameters on the estimated FC value also depends on the vehicle and engine type, the used technologies and the manufacturer dependent design. To derive more general statements on the applicability and accuracy of the FC determination based on the stoichiometric A/F ratio, additional tests with further vehicles and different engine types would be necessary.

8.4 Evaluation of OBD Data Loggers

A large amount of different OBD data loggers is available on the market. Depending on the intended purpose, these devices differ in functionality, quality and costs. The pilot study evaluated different selected devices and showed that common loggers as used for fleet management applications are generally suitable to fulfill some of the requirements of the data collection project. Nevertheless, the evaluation pointed out some limitations of the devices, e.g., in runtime behavior, configurability and device handling.

Based on the experiences of the different work packages, the study describes the necessity of implementing project specific functionality into the data logger software. Within the scope of the study, a list of data logger requirements was created that can be used for designing a suitable data logger application. Furthermore, these requirements can be used for discussing the opportunities of different products with manufacturers in more detail and also to negotiate detailed price conditions.

The communication between a vehicle OBD system and an external scan tool might be implemented using different bus systems. Theoretical analysis of the OBD standard and experiments with different data loggers and different vehicles showed that the available bandwidth of K-Line based vehicle OBD systems is not sufficient to collect the intended number of parameters with a frequency of 2 Hz. As a consequence, for stable and reliable data collection with the required number of parameters and the desired data collection frequency, **it is recommended to use only vehicles that support CAN-based OBD systems**.

Experiments within the scope of the study also showed variations of the communication behavior, reaction times and supported PIDs of different vehicle OBD systems and also of different data loggers. Due to this fact and the ambiguity of determining accurate fuel consumption for different vehicles, it is highly recommended to select a data logger that allows implementation of project specific data collection mechanisms. In other words, the data logger should allow model-specific configurations, and preferably, an over-the-air update. To ensure a trouble-free data collection and facilitate an optimized FC calculation, the data collection mechanism could initially check the PIDs supported by the vehicle and the data exchange timing and configure the data collection process related to the technical facts of the vehicle. This may be handled by an automated data initialization procedure running on the data logger. In general, the logger must detect general OBD information such as supported PIDs, VIN and vehicle specific scaling factors for sensor data like MAF and equivalence ratio that is used for the FC estimation. The initialization process of the data logger must determine the vehicle specific communication requests with consideration of the communication timing between the vehicle and the OBD logger.

If manufacture dependent PIDs are available for particular vehicles, the data collection procedure should also consider these parameters. Depending on the data logger functionality, a conceivable solution for handling manufacture dependent PIDs would be a vehicle specific pre-configuration or an over-the-air update of the device.

8.5 Cost Estimation

The following table shows an exemplary cost estimation for performing the data collection field study. As the desired sample size depends on the main goals of the field investigation, the knowledge about the vehicle population and the sampling method, the costs were estimated for different sample sizes of 200, 500 and 1,000 vehicles (cf. sections 3.3 and 8.1) and assuming a one year operation. It should be noted that cost reduction can be achieved by extending the operation along several years and reducing the number of required data loggers. The cost estimation also draws a comparison between different data logger prices, using a device with a unit price of approximately € 120 as often used in common M2M fleet management applications (cf. section 7.2) and using a more expensive device of € 500 per unit. Furthermore, the cost estimation is based on the following assumptions:

- Several automobile clubs collaborate in the field study and perform vehicle recruitment and driver support without any charge.
- Each participant receives € 100 as an incentive and gets an automatically generated monthly driver report via e-mail.
- The data logging solution provides a mobile connection to a data collection server. The data traffic is additional € 60 for each data logger during the one-year project runtime.

- The cost estimation in table 8-2 considers fix costs for purchasing non-standard PIDs. It should be noted, that the costs can vary depending on the required amount of PIDs for different vehicle models.

Project Step	Subject	Data Logger Unit Price	€ 120			€ 500		
		Vehicle Sample Size	200	500	1000	200	500	1000
Vehicle Sampling	Definition of the sample criteria and sample size, compilation of the vehicle sample based on the voluntary drivers		€ 30,000					
	Driver Incentives (assuming € 100 per vehicle)		€ 20,000	€ 50,000	€ 100,000	€ 20,000	€ 50,000	€ 100,000
Driver Maintenance	Development of data logger installation guide, shipment of devices, driver support over the one-year project runtime		€ 15,000	€ 20,000	€ 25,000	€ 15,000	€ 20,000	€ 25,000
Data Logging Solution	Data logger hardware, including data traffic		€ 36,000	€ 90,000	€ 180,000	€ 112,000	€ 280,000	€ 560,000
	Development of a customized application including required tools and data collection server		€ 75,000					
	Estimated costs for purchasing non-standard PIDs		€ 50,000	€ 90,000	€ 130,000	€ 50,000	€ 90,000	€ 130,000
Data Evaluation	Development of evaluation framework for the collected data including report generation for the participants		€ 75,000					
	Analysis of collected data and documentation of the project results		€ 20,000	€ 25,000	€ 30,000	€ 20,000	€ 25,000	€ 30,000
Total Sum [€]			**€ 321,000**	**€ 455,000**	**€ 645,000**	**€ 397,000**	**€ 645,000**	**€ 1,025,000**

Table 8-2: Cost Estimation for running the data collection field study during one year

8.6 Outlook and Next Steps

As also mentioned in the summary of this document, several issues should be investigated subsequently to the pilot study.

Additional vehicle tests

Deriving generally valid conclusions from the measured vehicle data is of particular relevance for achieving the project goals. Executing additional tests with different vehicle models, engine and fuel types would enable to improve the methods for estimating the fuel consumption. The study showed that different calculation methods are required for different vehicles types and/or different sets of supported OBD parameters. Suitable methods should be available for estimating the vehicle fuel efficiency for a wide range of vehicles. Therefore, further vehicle tests should be executed in preparation of the full-scale field study. These could pursue the following targets:

- Improvement of the achievable accuracy of estimation methods for different engine and vehicle types.
- Confirmation of the accuracy of the MAF based calculation method for Otto vehicles by further vehicle tests.
- Identification and evaluation of additional OBD parameters to improve MAF based FC estimation for Otto and especially for Diesel vehicles.
- Improvement of the calculation methods for vehicles that do not support the MAF sensor.
- Identification of Diesel vehicles that provide fueling rates as standard and non-standard PIDs
- Evaluation of non-standard PIDs fueling rates against laboratory-grade equipment.
- Evaluation of the accuracy of calculation methods in different drive situations and at higher vehicle speed.

Vehicle population

Based on the specific aims of the project founders, the vehicle sample has to be compiled by determining the investigation and stratification criteria as well as the sample size. A deeper analysis of existing data on the vehicle population and real world vehicle fuel consumption would allow deriving more precise assumptions that may lead to a smaller and more representative sample.

Mapping of Fleet PID availability

Available databases on supported OBD PIDs of available vehicles may be investigated to gain useful information for defining the vehicle sample and also for developing the data collection application.

Data Logger

Based on the experiences gained by the evaluation of different OBD data loggers and the data logger requirements delineated within section 7.3, a number of generally suitable devices could be selected for executing the field study. Within the next steps the applicability of these products has to be discussed with the manufacturers in detail. This would also allow receiving additional information on costs and on the availability of non standard PIDs. Further evaluation of the selected data loggers can be performed with additional vehicle tests on the chassis dynamometer test stand, on the road and also by execution of the OBD data logger laboratory test developed by TÜV NORD.

9 References

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[ISO 15765]	ISO 15765-2:2011 Road vehicles - Diagnostic communication over Controller Area Network (DoCAN) - Part 2: Transport protocol and network layer services
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