Abstract

The background of this master thesis is the increased importance of improving vehicle fuel economy due to factors such as decreasing oil resources and growing fuel prices. Earlier performed tests have shown that real-world fuel economy is deviating significantly from fuel economy (FE) measured in simulated road driving. In this thesis the accuracy of the fuel economy measurement methods used in such measurements are investigated. It is done by examining the performance of different fuel economy measurement devices and by performing a test series with subsequently increased complexity. The test series consists both of chassis dynamometer and on road testing. All tests are performed with a Scania G450 long haulage truck which has been equipped with a portable fuel flow meter and a portable emissions measurement system (PEMS). Variables such as temperatures, engine mode and torques taken up by different auxiliary devices are analysed to improve the understanding about how the vehicle state is differing between different test drives. It is investigated if sensor fusion can be used to improve accuracy and repeatability in cases when multiple fuel consumption (FC) measurement devices are used. Obtained results show that the accuracy of the different fuel economy measurement methods investigated has an order of magnitude of 1 % for real-world on-road testing. The results do also show that a change of engine frictional losses are influencing the fuel economy significant in controlled environments. Finally it is concluded that the vehicle internal fuel economy estimation is reacting to changes in fuel economy in a similar way as the fuel flow meter estimation. The method based on exhaust gas analysis is deviating from this behaviour.
Sammanfattning

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1 — Introduction

This master thesis was carried out at the division YMDC at Scania CV AB in Södertälje, Sweden. The examiner of the master thesis was Associate Professor Jenny Jerrelind at the division of Vehicle Dynamics at the Royal Institute of Technology in Stockholm, Sweden. Supervisor at Scania was Tobias Lööf, Development Engineer at YDMC.

The background of this master thesis is the increased importance of improving vehicle fuel economy due to factors such as decreasing oil resources and growing fuel prices. To make it possible to improve fuel economy, accurate measurement methods are required. Today commonly used fuel economy measurement methods within vehicle validation are:

- real-world on-road testing
- chassis dynamometer testing

Earlier performed measurements have shown that fuel economy measured in chassis dynamometer is deviating significantly from the real-world fuel economy measured on-road. Due to the fact that the real-world fuel economy is proportional to the overall economy for haulage contractors, it is of course important to keep it low. A problem is that real-world testing has worse repeatability than other methods, which is due to the amount of parameters that may influence the fuel consumption randomly. Examples are weather, road and traffic conditions.

1.1 Aim

The aim of this master thesis is to improve the understanding of the existing real-world fuel economy measurement methods, to investigate with which accuracy fuel
economy measurements can be performed on-road and to investigate other opportunities to improve accuracy and repeatability of fuel economy measurements. This problem is attacked from three different angles:

- a theoretical investigation of accuracy and repeatability of different fuel consumption measurement methods
- a test series with stepwise increased complexity
- a data processing method based on sensor fusion is investigated to improve accuracy and repeatability

All tests are carried out with a 2013 4x2 Scania G450 long haulage truck with euro VI specification. However the experimental setup is chosen with universality in mind. I.e. it should be possible to apply the same setup on an arbitrary long haulage truck.
2 — Background

This chapter is intended to give background information within the field of this thesis work.

2.1 Fuel economy

The term fuel economy is used to state the amount of fuel consumed in litres per distance travelled or in distance travelled per litre. In Europe fuel economy is most commonly expressed in litres per 100 km travelled, this unit is used in this thesis work. The term fuel consumption is reserved for the amount of fuel consumed during a certain test drive.

For some vehicle categories it has been agreed upon certain test cycles that should be used when fuel economy is verified. Examples are the new European driving cycle (NEDC) for European cars and the standardised on-road test cycle (SORT) for buses. No such standard test cycle is available for heavy trucks. Thus how fuel economy should be verified is up to each manufacturer. This implies that test results from manufacturer independent tests, such as press tests, are of great relevance for both haulage contractors and truck manufacturers.

2.2 Fuel

Fuel quality is influencing fuel consumption and may also lead to different magnitudes of error in the fuel consumption measurement results depending on the measurement method used. In Sweden three different diesel environmental classes are existing; EC1, EC2 and EC3. The EC3 quality is equivalent to the European EN 590 diesel [1]. According to [2] European EN 590 diesel has a density of 820 - 860 kg/m$^3$ at 15
Fundamental parameters describing diesel fuel quality are cetan number, density, O/C and H/C atomicity ratios. These parameters may in turn be dependent of other parameters. Density is for example temperature and pressure dependent. The O/C and H/C atomicity ratios are referred to as carbon ratios.

2.3 Fuel system

The fuel system does broadly consist of fuel tank, fuel pump and common-rail assembly. The test vehicle is equipped with a special fuel tank with additional air bleeding pipes, see Figure 2.1. The purpose of these pipes is to minimise the probability for air pockets to occur in the tank. This makes it possible to estimate the fuel volume in the tank more accurately when using the fuel pump reading at a gas station.

The fuel system is described outgoing from the Scania XPI common-rail fuel injection system illustrated in Figure 2.2. The outlet fuel line from the tank is lead to the low pressure pump (1). The low pressure pump (1) is pumping the fuel through a pre-filter with water separator. After passing the main fuel filters the pressure is increased by the high-pressure fuel pump (4). The fuel is led to the accumulator rail (5) on which the injectors (9) are mounted. A pressure sensor (6) is also mounted on the accumulator rail. Fuel overflow is led back to the fuel tank via the return rail (8) [4].
2.4. REAL-WORLD ON-ROAD TESTING

Because the fuel system is influencing the combustion, which in turn is influencing exhaust gas parameters, the fuel system has to be controlled in order to keep the emissions within regulation limits. Fuel injection may for example be controlled to ensure correct temperature in certain parts of the exhaust gas system. To achieve this, the fuel system (and engine) runs in different modes depending on the state of the exhaust gas emission control system.

Figure 2.2: Scania XPI common-rail fuel injection [4].

2.4 Real-world on-road testing

A real-world on-road test is a test performed under the current road, weather, and traffic conditions. A well known fuel economy measurement method is to estimate the fuel consumption by filling the tank up to a certain mark, run the test route, fill the tank to the same mark again and note the fuel pump volume reading. In this thesis, this method is referred to as the standard method.

When performing on-road tests it is often preferable to use a reference truck. The reference truck makes it possible to filter out differences in fuel economy due to deviating ambient conditions from differences due to software or hardware modifications on the test object. It should be driven as similar to the test truck as possible, which implies that both trucks should be driven the same route simultaneously and as sim-
ilar as possible. Driver influence can be reduced by using cruise control. The fuel economy from the first test drive is normally set as reference. If the fuel economy is deviating from this reference in other tests, the relative change in fuel economy is calculated and used as correction factor. By assuming that the test object should be subject to the same change in fuel consumption due to the change in ambient conditions, the test objects fuel consumption can be corrected with the same factor. This makes the measurement results more comparable. Shifting strategies and different drive train components are examples of things that can be evaluated this way.

If different vehicles fuel economy is going to be compared, the trailers can be interchanged in between the trucks. This is in order to make the comparison as fair as possible, because the driving resistance of all trailers are most likely not exactly the same. When this is applied, the interchange should be performed to make sure that all trailers have been travelling the same route. An additional action to improve the test results is to use special test trailers which have been controlled in order to ensure correct rolling resistance.

2.5 Chassis dynamometer testing

A chassis dynamometer is an arrangement used to simulate on-road vehicle behaviour. There are different chassis dynamometer models available. A typical chassis dynamometer has two rollers, on which the propelling wheels of the test vehicle are standing. Depending on the test, different input parameters are needed to run the simulation. Examples are vehicle mass, axle loads and differential gear ratios. For some measurements a vehicle coast down is required to determine the speed dependent powertrain resistance [5].

In a vehicle coast down the speed dependent powertrain resistance is measured for a free turning powertrain. It can be performed on-road or on chassis dynamometer. When performing a coast down on chassis dynamometer the powertrain of the test vehicle is set into motion by the chassis dynamometer rollers. When a certain velocity is reached, the propelling torque is removed from the rollers and the powertrain starts to decelerate due to the frictional losses in the powertrain. Wheel angular velocity, time and measured force in the tyre-roller contact patch are logged until the powertrain has stopped turning [5].

In this work an axle shaft and a rear axle chassis dynamometer were used. In the axle shaft variant the drive shaft is directly connected to the chassis dynamometer output shaft. The main benefit is the possibility to eliminate influence from the rear
2.5. CHASSIS DYNAMOMETER TESTING

axis. In a rear axle chassis dynamometer the rear wheels of the truck are standing on rollers. This makes it possible to simulate the complete powertrain. In the rear axle chassis dynamometer used in this work the rollers are stiff connected to each other.

In chassis dynamometer testing it is possible to partly control the ambient conditions, which is decreasing complexity and increasing repeatability. Furthermore no driver is needed, which means that driver influence is eliminated, this does imply that more test drives can be driven in a row compared to on-road tests. It is also possible to simulate certain ambient conditions independent of time of year and location.

Schematically overviews of the axle shaft and rear axle chassis dynamometer available at Scania are presented in Figure 2.3 and Figure 2.4 respectively. In both of these it is possible to simulate certain road sections, examples are Södertälje-Jönköping-Södertälje in Sweden and Motril-Granada in Spain.

![Figure 2.3: Scania CD5 axle shaft dynamometer [6].](image1)

![Figure 2.4: Scania CD2 rear axle chassis dynamometer [7].](image2)
2.6 Fuel consumption measurement methods

To quantify fuel economy both fuel consumption and distance travelled have to be measured. The fuel consumption may be estimated either by volumetric or mass measurements. Examples of a volume measurements are the standard fuel economy measurement method and fuel flow metering. Depending on the method used the measurement result may be subject to different sources of error. In this section pros and cons are presented for different fuel consumption measurement methods treated. These are to be seen as a result of the literature study.

2.6.1 Standard method

According to the description in Section 2.4 this method is based on fuel pump readings at the gas station. Pros and cons are presented below.

Pros

• measured fuel volume is directly related to the fuel costs
• no additional measurement equipment is needed

Cons

• fuel quality is not taken into account
• a special fuel tank is needed to prevent air pockets
• fuel pump readings may not be exact enough
• road slope and banking at the gas station are influencing the fuel level

2.6.2 Fuel flow metering

The outlet fuel from the tank can be measured by using a fuel flow meter. For engines with return fuel to the tank, the return fuel does also need to be taken into account. This can be done by measuring the return flow or by modifying the fuel system. An example of a fuel flow meter based on the latter approach is the AIC 6004 Swissline uniflowmaster [8].
2.6. FUEL CONSUMPTION MEASUREMENT METHODS

AIC 6004 components and working principle

According to Figure 2.5 the fuel system is divided into two loops. One cooling fuel loop and one engine loop. These two loops are separated by a heat exchanger, fuel in the cooling loop is cooling down the fuel in the engine loop. In between the two loops the actual fuel flow sensor is positioned. To assure fuel circulation in the cooling loop, an additional fuel pump is mounted in the cooling loop. A check valve makes it possible for fuel to pass from the tank loop to the engine loop but not in the opposite direction. Due to the lack of return fuel to the tank, only one fuel flow measurement is needed. AIC Systems is calling this a direct fuel flow measurement [9].

The fuel flow metering is based on pulses from an hall element located in the flow meter sensor. An integrated rotor is set into motion by the fuel passing it, this is triggering electrical pulses. The flow meter is constructed to deliver a constant number of pulses for each litre fuel passing the sensor, independent of the fuel flow. The actual number may deviate between different flow meter individuals because it is a calibration parameter specified for each device. The sensor is creating 10 pulses per rotor revolution, but because the rotor is oval, each pulse does not correspond to the same amount of fuel. The fuel volume per pulse is varying between 0.2 and 0.8 ml. A mean value taken over the last 10 pulses results in 0.5 ml per mean pulse [10]. According to [10] it is preferable to count the number of pulses and approximate the fuel per pulse by 0.5 ml. This should according to [11] give an accuracy of ± 1 %

Figure 2.5: Schematically overview of the AIC-6000 series fuel flow meter [11].
CHAPTER 2. BACKGROUND

Pros

• fuel volume is measured which can be directly compared to measurements performed according to the standard method
• relatively simple setup
• the setup is not sensitive to dirt

Cons

• fuel quality is not taken into account
• electrical power is required for the fuel pump and flow sensor

2.6.3 Fuel weighting

The amount of fuel consumed can be estimated by weighting. One approach is to weight the fuel tank after and before a test route is driven while a more complex approach is to measure the tank weight continuously. The main issue with continuously weighting is the measurement noise due to waves and splashes in the tank. The noise can be reduced by putting a certain foam into the tank but signal filtering is likely going to be needed [9].

Pros

• fuel mass is proportional to the heat value of the fuel
• if the fuel structure is known the amount of molecules is also known

Cons

• the fuel tank has to be demounted, which in turn may require the test route to be modified in on-road tests
• signal filtering may be needed
• the result must be transferred to a volume in order to be compared with the standard method
2.6.4 In-vehicle fuel consumption estimation

The in-vehicle fuel consumption estimation is performed by the EMS and is normally based on injector characteristics. Injectors are typically specified to deliver a certain fuel flow at a certain fuel pressure. Thus, with a known fuel rail pressure the injector opening time can be adjusted to inject a desired amount of fuel \( m_{inj} \) in mg. Outgoing from this, the fuel volume in each time step \( i \) can be calculated according to Equation 2.1 for a six cylinder engine. The factor 6 in Equation 2.1 is the number of cylinders, the factor \( 1/2 \) is a correction factor because it is a four-stroke engine, the factor \( 1/10^6 \) is to convert from mg to kg, \( n_{engine} \) is the engine speed in revolutions per minute \( 1/60 \) is a conversion factor from revolutions per minute to revolutions per second and \( \rho_{fuel} \) the fuel density. The fuel consumption is calculated by summation according to Equation 2.2, \( n \) is the number of time steps and \( T_s \) the sampling time.

\[
\Delta V_{L,i} = \frac{m_{inj,i} \cdot 6 \cdot 1/2 \cdot \frac{1}{10^6} \cdot n_{engine,i} \cdot \frac{1}{60}}{\rho_{fuel}} \tag{2.1}
\]

\[
FC_L = \sum_{i=1}^{n} \Delta V_{L,i} \cdot T_s \tag{2.2}
\]

Error sources

Injector characteristics may change differently depending on the circumstances under which the engine has been run. The cause for a change may i.e. be aging or an earlier engine malfunction. The accuracy of this fuel consumption measurement method is not clearly stated and depends on the fuel system, engine developers at Scania have estimated the momentarily error of \( \Delta V_L \) to be around \( \pm 10 \% \) [12].

Pros

- no extra measurement equipment is needed
- no extra costs
- is not dirt sensitive
Cons

- unknown accuracy
- accuracy may be vehicle dependent

2.6.5 Exhaust gas analysis

Fuel consumption can be measured by exhaust gas analysis. For on-road testing a portable emissions measurement system is needed. The calculations are based on measurements of the exhaust gas components containing carbon together with the exhaust gas flow. The underlying theory is that the amount of carbon entering the engine must be the same as the amount of carbon leaving the engine in form of exhaust gases. Fuel is the only carbon-containing component injected to the engine, therefore it is possible to estimate the amount of fuel injected by estimating the amount of carbon in the exhaust gas. In order to do this, the fuel and exhaust gas composition need to be known. The fuel composition is given by the fuel carbon ratios and the exhaust gas composition by the exhaust gas H/C-ratio.

The carbon-containing components of the exhaust gas can be separated into carbon monoxide (CO), carbon dioxide (CO$_2$) and total hydrocarbon (THC). Concentration measurements of these components together with an exhaust gas flow measurement equipment makes it possible to calculate the mass flow of each component. An example of a system that is using this principle is the Horiba OBS 2200 [13]. Equations 2.3-2.6 are the calculations performed in the Horiba OBS 2200 in order to calculate the fuel consumption. $HC_{Mass}(t)$, $CO_{Mass}(t)$ and $CO_{2,Mass}(t)$ are mass flows calculated from the exhaust gas concentrations. The constants $\alpha$ and $\beta$ are the fuel H/C- and O/C-ratios respectively. $\alpha_{Ex}$ is the exhaust gas H/C-ratio. $M_C$, $M_O$, $M_H$, $M_{CO}$ and $M_{CO_2}$ are the molar mass of carbon, oxygen, hydrogen, carbon monoxide and carbon dioxide respectively [14].

\[
FC = \sum_{t_1}^{t_2} Fuel_{CB}(t) \cdot T_s \tag{2.3}
\]

\[
Fuel_{CB}(t) = \frac{R_{CWFC} \cdot HC_{Mass}(t) + \frac{M_C}{M_{CO}} \cdot CO_{Mass}(t) + \frac{M_C}{M_{CO_2}} \cdot CO_{2,Mass}(t)}{R_{CWFC}} \tag{2.4}
\]
\[ R_{CWF} = \frac{M_C}{\alpha \cdot M_H + \beta \cdot M_O + M_C} \] (2.5)

\[ R_{CWFHC} = \frac{M_C}{\alpha_{Ex} \cdot M_H + M_C} \] (2.6)

Error sources

Faulty values of the fuel carbon ratios is leading to errors in the fuel consumption estimation. Furthermore EGR-rate and blow-byes may influence accuracy and real-time performance. The power consumption of the measurement equipment may influence the actual fuel consumption of the vehicle.

Pros

- real-time capability
- both exhaust gas analysis and fuel consumption can be measured with the same equipment
- fuel quality is taken into account

Cons

- more complexity is added to the measurement by performing the measurement after the engine
- the carbon ratios have to be known
- electrical power from the vehicle is needed in on-road tests
- the installation is relatively complex
- the main unit can not withstand dirt
- depending on the measurement equipment, drift checks may be needed
2.7 Distance measurement methods

The distance measurement methods treated in this work are based on satellite navigation and vehicle odometry.

2.7.1 Satellite navigation

A satellite navigation system is measuring position with respect to an external reference system. Examples of existing satellite navigation systems are NAVSTAR global positioning system (GPS) and GLONASS. Distance travelled is calculated out from the measured positions. In satellite navigation systems atmospheric effects, sky blockage and receiver quality are influencing the accuracy. According to [15] the accuracy for position measurements is equal or less than 7.8 m with a 95 % confidence level during normal operations over all age of data.

Pros

- each distance measurement is independent from the other, thus reduced systematic error
- vehicle condition does not influence the accuracy

Cons

- only applicable when satellite contact can be established
- not suited for short distance measurements

2.7.2 Odometry

Vehicle odometry can be used to estimate the distance travelled. These estimations are based on data from the wheel sensors, measuring the turning rate of the wheels. In an ideal situation when driving straight ahead with no wheel slip, the distance travelled can be calculated according to Equation 2.7.

\[ d = \sum_{i=1}^{n} 2\pi \cdot r_{dyn,i} \cdot \omega_{wheel,i} \cdot T_s \]  

(2.7)
\( \omega_{\text{wheel}} \) is the turning rate of one wheel, \( r_{\text{dyn}} \) is the dynamic tyre radius, \( T_s \) is the sample time and \( n \) the number of time steps. This means that a correct estimated dynamic tyre radius is crucial in this estimation. Examples of parameters influencing the dynamic tyre radius are vehicle speed, tyre pressure and wear. Hence, a tyre model is needed for this estimation to be accurate.

**Pros**

- well suited for short distances
- independent of external measurement equipment

**Cons**

- systematically errors is likely going to be vacant if no correction is made

### 2.8 Sensor fusion

Sensor fusion makes it possible to increase accuracy of a system state estimation by combining information from different sources describing some system parameter. Information sources may be sensors or mathematical models.

One approach is to introduce a variance-weighted mean value. This method is based on the fact that different measurement equipment and different models are describing reality differently and do have different error characteristics. This implies that if different estimations of the same quantity are combined in a sensible manner, the overall accuracy of the joint estimation can be increased. One way of combining different estimations is to use an arithmetic mean value, which is an unbiased point estimation of the expected value \( \mu \) [16].

Another approach is to calculate a variance-weighted mean value according to Equation 2.8. \( \sigma_{z1} \) and \( \sigma_{z2} \) is the to the estimations \( z_1 \) and \( z_2 \) corresponding standard deviations. Assumed that the to the estimations related noise is white and gaussian, this estimation is equal to the maximum likelihood and the least squares estimate [17]. The corresponding variance is given by Equation 2.9, it should be noted that the variance is less than or equal to the variance of each individual estimation. In general, the variance-weighted mean value can be shown to be the linear estimate giving the smallest variance [17].
\[ \mu = \frac{\sigma_{z_1}^2}{\sigma_{z_1}^2 + \sigma_{z_2}^2} z_1 + \frac{\sigma_{z_1}^2}{\sigma_{z_1}^2 + \sigma_{z_2}^2} z_2 \quad (2.8) \]

\[ \sigma^2 = \left( \frac{1}{\sigma_{z_1}^2} + \frac{1}{\sigma_{z_2}^2} \right)^{-1} \quad (2.9) \]

Gaussian and white noise

As mentioned in Section 2.8 the variance-weighted mean value is best applicable when white gaussian noise is at hand. Gaussian noise implies that the noise is normally distributed and thus can be modelled if its standard deviation and mean value are known. White noise implies that the noise has equal power at all frequencies and that it is not correlated in time.
3 — Method description

It is obvious that many vehicle components and parameters are influencing fuel economy. This leads to difficulties in performing a complete state estimation of the vehicle, which is relevant in order to understand the measurement results. The vehicle state is dependent of both the state of its electronic subsystems as well as physical parameters such as tyre pressure and gearbox temperature. To simplify the vehicle state estimation it was decided to do a test series in which complexity is increased subsequently.

3.1 Testing

A test series consisting of three test sets was performed. The first set on the CD5 drive shaft chassis dynamometer, the second on the CD2 rear axis chassis dynamometer and the third on-road. The reason for this test layout is to be able to investigate how the accuracy and repeatability is changing when more complexity is added but also to see how much the measured fuel economy is differing in between the different testing environments.

To make results comparable, the test route must be possible to drive in reality as well as on chassis dynamometer. It should be long enough to give reasonable fuel economy results, but not too long because of limited testing time to get a sufficient statistical basis. The Södertälje-Norrköping-Södertälje test route which has a duration of slightly three hours was chosen. The aim was to run 20 test drives in both CD5 and CD2 and to run three on-road tests. To achieve this, unmanned test drives were run nightly in the chassis dynamometers. The measurements are intended to show how repeatability and accuracy of the measurements are changing when complexity is increased.
3.2 Vehicle setup

In all test drives the vehicle was set up with the following portable fuel consumption measurement devices:

- Horiba OBS-2200 exhaust gas analyser
- AIC 6004 SWISSLINE uniflowmaster fuel flow meter
- Vehicle-internal fuel consumption estimation

To fulfil certain accuracy requirements a drift check should be performed at least once per hour for the Horiba OBS 2200 exhaust gas analyser. This reduces the risk for the measurements values from drifting. The drift check takes 150 seconds, which implies that 150 seconds of fuel consumption measurement data is lost once per hour. Therefore it was chosen to manually run a drift check before each manned test run. When multiple test drives were run unmanned, one drift check per hour was run.

In the tests performed on chassis dynamometer, fuel consumption was also measured with the in the test cells integrated coriolis fuel flow meter. In the on-road tests fuel consumption was also measured according to the standard method. These measurements are intended to be reference values for the portable fuel consumption measurement devices. As additional reference for the Horiba OBS 2200, exhaust gas concentrations were measured with a stationary Horiba MEXA 7500-DEGR exhaust gas analyser in the chassis dynamometer test drives. Apart from this, fuel tank weighting was tested in the manned test drives in CD2.

Because the vehicle internal distance estimation is the only distance estimator available in all testing environments, this estimation was used in order to be able to use the same setup in all tests.

Apart from fuel consumption and distance other parameters were logged. Estimated engine crankshaft torque losses due to the following axillary combustion engine devices were logged:

- Alternator
- High pressure fuel pump
- Air condition compressor
- Air compressor
- Radiator fan
- Exhaust brake

Indicated crankshaft torque and crankshaft torque losses due to engine frictional losses were logged. Road gradient and vehicle speed were logged in all tests to make
3.3. DATA LOGGING AND CUTTING

it possible to compare driving conditions and driver influence between different test environments and to investigate chassis dynamometer repeatability. Engine mode versus time was analysed for the different test drives as well as the share of engine work done in each engine mode.

Beyond these, gearbox, ambient and fuel temperature were logged. The fuel temperature thermocouple was mounted on the fuel inlet pipe to the fuel flow meter in order to measure the temperature of the fuel passing the fuel flow sensor. The purpose of the gearbox oil temperature sensor is to be able to do an as similar warm-run before each test as possible. This should improve repeatability and thus comparability in between different test drives.

Data is logged from different computers, to make it possible to synchronise different sets of measurement data, engine speed was added to all logs. Parameters logged are summarised in Table B.1 in Appendix B.

3.3 Data logging and cutting

Data was mainly logged from the vehicle EMS, but also from the chassis dynamometer computer, the computer belonging to the portable emissions measurement system and the added sensors. To be able to run multiple unmanned test drives, the logging time was set to be large. This means that one log-file may contain more than one test drive which implies that it need to be cut in between each test drive.

The data cutting is vital to get accurate results. If data is not cut accurate enough, fuel consumption contributions from the end of one test drive will contribute to the beginning of the next test drive. This is leading to an increased uncertainty in the fuel consumption and distance estimations.

The log files were cut outgoing from the end-time of each test drive, available from additional chassis dynamometer log files. Because the chassis dynamometer computer is simulating the actual test, this time should be the end-time of the actual test drive. The time vector for each parameter logged was searched for the to the actual test corresponding end-time to find out at which list index that test drive ends for the actual parameter. Both time and data vector were cut at this index. Furthermore the time vectors had to be adjusted to start from zero in all test drives.

The Horiba OBS 2200 log files were assembled and cut manually in MS Excel. The same end times from the chassis dynamometer log files were used. In the tests performed on-road, the logs were started and stopped simultaneously, no other data-
cutting was done.

3.4 Data analysis

The main goal with the data analysis is to achieve better understanding about parameters influencing fuel economy and to investigate if it is possible to ensure a certain accuracy of the fuel economy measurements. The data analysis is performed in the same way for the different sets of test drives.

3.4.1 Fuel economy

The fuel economy estimations from each test drive are plotted in one bar graph for each test environment. This is in order to get an overview of how the fuel economy is varying in between different test drives and fuel consumption measurement devices. By comparing the graphs one can get an overview of how added complexity is influencing the fuel economy measurements.

The time dependent behaviour of each fuel consumption measurement device is evaluated by plotting fuel consumption versus time for an arbitrary test drive and all measurement devices in one graph. The repeatability of the fuel consumption measurement devices is evaluated by plotting the time dependent fuel consumption versus time for all test drives in separate graphs for each fuel consumption measurement device.

The measurement repeatability is evaluated by plotting gearbox oil temperature, fuel temperature and ambient temperature in separate graphs for each test drive. Engine frictional losses and auxiliary device torques are plotted the get an estimation of the vehicle state.

Fuel economy repeatability is quantified by calculating the standard deviation of the fuel economy estimated in each environment. The worst case error is calculated for each fuel consumption measurement device by obtaining the largest difference in fuel economy observed and dividing by the lowest fuel economy observed.

3.4.2 Fuel carbon ratios

An investigation of how faulty values of the fuel carbon ratios are influencing a fuel economy estimation based on exhaust gas analysis was carried out. The fuel
carbon ratios are contained Equation 2.5, which is used in order to calculate the fuel consumption. A worst case analysis is carried out in order to get an indication of how the measured fuel consumption is influenced by these constants.

Carbon ratios used in the tests performed are $\alpha_{test} = 1.86$ and $\beta_{test} = 0.006$. The error in real-time fuel flow is calculated for the $CO_{Mass}(t)$, $CO_{2,Mass}(t)$ and $THC_{Mass}(t)$ measured in the first test drive performed in CD5 for the $\Delta\beta$-values in Table 3.1 as function of $\Delta\alpha$.

Table 3.1: Assumed $\Delta\beta$-values

<table>
<thead>
<tr>
<th>$\Delta\beta$:</th>
<th>-0.003</th>
<th>-0.002</th>
<th>-0.001</th>
<th>0.000</th>
<th>0.001</th>
<th>0.002</th>
<th>0.003</th>
</tr>
</thead>
</table>

The error is calculated by subtracting the fuel consumption assumed to be correct from the error-associated real-time fuel flow according to Equation 3.1. The total error in litres fuel for this test drive was calculated by summing all contributions according to Equation 3.2 and the fuel economy by dividing $\Delta FC$ by the distance travelled.

$$\Delta Fuel_{CB}(t) = Fuel_{CB}(\alpha, \beta, t) - Fuel_{CB}(\alpha_{test}, \beta_{test}, t)$$ \hspace{1cm} \text{(3.1)}$$

$$\Delta FC = \sum_{t_1}^{t_2} \frac{\Delta Fuel_{CB}(t)}{\rho_{fuel}}$$ \hspace{1cm} \text{(3.2)}$$

3.4.3 Sensor fusion

To be able to apply a variance-weighted mean value, the measurement noise need to be white and gaussian. The gaussian property is investigated by calculating the relative frequencies of the fuel economies observed by the different fuel consumption measurement devices in CD5.

3.5 Calculations

The fuel economy is calculated by dividing the fuel consumption by the distance travelled. Distance as function of test time was logged from the EMS ECU. Time
dependent fuel consumptions were calculated for the different measurement devices. The total fuel consumption is then easily obtain by taking the last fuel consumption value of each test drive. All fuel consumptions were calculated in both litres and kg. Conversions were performed with an assumed constant diesel density of 832 kg/m$^3$.

The AIC fuel consumption is given in ml by a counter with a maximum value of 32768 ml. When the count reaches this value, the counter starts over from zero again. The time dependent fuel consumption was calculated by obtaining the fuel volume difference in each time step and summarising according to $\sum [V_{fuel}(t = i + 1) - V_{fuel}(t = i)]$.

The stationary fuel flow meter in the CD2 and CD5 test cells gives fuel consumption values in kg. The time dependent fuel consumption was calculated in the same manner as for the AIC fuel flow meter, by calculating the difference in fuel consumption in between each time step.

The time dependent EMS fuel consumption was calculated according to Equation 2.1 and Equation 2.2.

Fuel flow in g/h is available in the Horiba OBS 2200 log. The time dependent fuel consumption was calculated as $m_{fuel}(t) = \sum_{i=0}^{t/T_s} \dot{m}_{i,fuel} \cdot T_s$, where $\dot{m}_{i,fuel}$ is fuel mass flow at the discrete time step $i$ and $T_s$ the sampling time. Time dependent fuel consumption is calculated by obtaining the accumulated fuel consumption value corresponding to each time step. The drift checks performed in the unmanned test drives are limiting accuracy. The fact that different road sections are deleted in different test drives do also make the fuel consumptions less comparable. To improve accuracy, lost measurement data was replaced by a mean PEMS test drive. The mean PEMS test drive was obtained by calculating the mean fuel flow in each time interval for all test drives in the actual environment. This was done for the unmanned test drives in CD2 and CD5.

The to the auxiliary device torque losses corresponding energy loss was calculated according to Equation 3.3. The loss in fuel economy due to this loss of energy was calculated according to Equation 3.4. $T_{i,Nm,device}$ is the torque loss for the actual device and $n_{i,rpm}$ is the engine speed logged in the tests. $T_s$ is the sampling time and $d$ the distance travelled in hundreds of km. The heat value $H_{diesel}$ of diesel is assumed to be 44 MJ/kg and the engine efficiency $\eta_{engine}$ to be constant 40 %. $\pi/30$ is an conversion factor from engine speed in revolutions per minute to angular velocity in radians per second.
3.5. **CALCULATIONS**

\[ E_{loss} = \frac{\pi}{30} \sum_i T_{i,Nm,device} \cdot n_{i,rpm} \cdot T_s \]  

(3.3)

\[ FE_{loss} = \frac{E}{H_{diesel} \cdot \eta_{engine} \cdot d} \]  

(3.4)

The work done by the engine in each engine mode relative to the total work performed was calculated according to Equation 3.5 for each engine mode. \( T_{i,ind} \) and \( n_{i,Engine} \) are engine indicated torque and speed at time \( i \). The index \( i \) goes over all discrete time steps, \( T_s \) is the sampling time. The numerator sum is summing all \( (T_{i,ind} \cdot n_{i,Engine}) \)-values when the engine is running in engine mode \( k \). \( t_2 \) is the end time of the test and the factor 100 a conversion constant to percentage.

\[
\text{Engine work in mode } k = \frac{\sum_{i=0}^{t_2/T_s} T_{i,ind} \cdot n_{i,Engine})_k}{\sum_{i=0}^{t_2/T_s} T_{i,ind} \cdot n_{i,Engine}} \cdot 100
\]  

(3.5)
4 — Experimental setup

All tests were carried out with a 2013 4x2 Scania G450 long haulage truck with euro VI specification. This implies that it has Scania XPI common-rail fuel injection together with exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). For this vehicle, the most fuel efficient engine mode is mode D, a rule of thumb is that lower engine modes implies a significantly higher fuel consumption.

The trailer used in the on-road tests is a 2007 Schmitz SKO 24 three axis semi-trailer. The axes have been realigned to make sure that the rolling resistance corresponds to the rolling resistance of a trailer in good condition. The fuel used in the tests is Swedish EC3 diesel with an assumed density of 832 kg/m$^3$.

4.1 Sensoric

The Horiba MEXA and coriolis fuel flow meter available in the chassis dynamometer test cells are broadcasting its data to the chassis dynamometer computer. Which in turn is forwarding selected data to a PC with the logging program ATI Vision via CAN-bus. The Horiba OBS 2200 has a certain logging computer which does not allow data to be forwarded. All data were logged with a sample rate of 10 Hz. The AIC 6004 requires an additional module to count electrical pulses and the temperature thermocouples need a module to convert the analog temperature signals into digital signals.

4.1.1 AIC 6004 fuel flow meter

The AIC 6004 swissline flow master fuel flow meter is mounted on the outer side of the left side member according to Figure 4.1. The pulse counter chosen is an
IPEtronik SIM-CNT. The electrical wiring was done according to the description in [9].

![Image](image1.png)

Figure 4.1: AIC fuel flow meter mounted on the left side member.

### 4.1.2 Temperature sensors

Thermocouple sensors are used for the gearbox and fuel temperature measurements. The gearbox thermocouple is attached to the gearbox filter housing and the fuel thermocouple to the AIC 6004 fuel inlet pipe, see Figure 4.2. An IPEtronik SIM TH-16 thermo module was used for the temperature sensors.

![Image](image2.png)

Figure 4.2: Fuel and gearbox thermocouple.
4.1.3 IPEtronik CAN-bus

An CAN bus of the IPEtronik SIM-CNT and SIM-TH-16 was created. The modules are compatible with different sensors, which implies that a CAN database (dbc) file is needed for each setup. The dbc-file is later imported to ATI Vision. The dbc-file was created in the computer program IPEmotion with settings summarised in Figure B.2 in Appendix B.

4.1.4 Stationary coriolis fuel flow meter

The stationary coriolis fuel flow meter available in the chassis dynamometer test cells has its own fuel inlet from a central fuel depot. The vehicle fuel hoses were simply connected to fuel pipes entering the test cells. This fuel is passing the coriolis fuel flow meter, which allows fuel to be measured in either volume or mass. This fuel flow meter is taking the vehicle return fuel into account. According to the pros and cons presented in Section 2.6.3, fuel mass is closer related to the energy content of the fuel, therefore it was set up to measure mass.

4.1.5 Exhaust gas analysers

The Horiba OBS 2200 and MEXA 7500 DEGR exhaust gas analyser require apart from exhaust gas components also the exhaust gas flow to be measured. Exhaust gas samples are taken from a tailpipe attachment. In the tests performed with both Horiba OBS 2200 and MEXA 7500 two tailpipe attachments were mounted after each other with the OBS 2200 attachment next to the exhaust silencer. In the OBS 2200 the exhaust gas samples are led through a heated line to the main unit, where the sample is distributed to different internal analysers. This principle applies for both the OBS 2200 and MEXA 7500. An overview of the OBS 2200 system can be seen in Figure 4.3. Not shown in the figure are GPS sensor and weather station. The weather station is required to be able to do weather-dependent corrections. The OBS 2200 was also connected to the vehicle CAN bus to be able to log the engine speed required for data synchronisation.
In tests performed on chassis dynamometer the PEMS analyser and its power supply were positioned on the floor outside the truck. In on-road tests the main unit was mounted in the cabin with sample pipes lead in through the right hand side storage room according to Figure 4.4.

4.1.6 Pallet lifter

An extra fuel tank was positioned on a pallet lifter with weighting function beside the truck to be able to try the fuel tank weighting method. The fuel hoses were extended by approximately 1.5 metres to reach the external tank. A camera was directed towards the display of the pallet lifter to make it possible to display the weight on one of the screens in the chassis dynamometer manoeuvre room.
4.2 Vehicle setup

All tests were performed with regular cruise control i.e. without active prediction and adaptive cruise control. Cruise speed was set to 80 km/h and downhill cruise to 85 km/h. The chassis dynamometer tests were performed with an ambient temperature of 20 °C. Axle loads and gross train weight were set as shown in Table 4.1.

Table 4.1: Axle loads for the chassis dynamometer tests.

<table>
<thead>
<tr>
<th>Position</th>
<th>Weight [tons]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck front axle</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Truck rear axle</td>
<td>11</td>
<td>27.5</td>
</tr>
<tr>
<td>Trailer front axle</td>
<td>7</td>
<td>17.5</td>
</tr>
<tr>
<td>Trailer middle axle</td>
<td>7</td>
<td>17.5</td>
</tr>
<tr>
<td>Trailer rear axle</td>
<td>7</td>
<td>17.5</td>
</tr>
<tr>
<td>GTW</td>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>

In the on-road tests the trailer was loaded with concrete loads which resulted in the GTW and axle loads presented in Table 4.2. The scale available at Scania does not allow each trailer axle to be weighed separately, therefore the front and middle trailer axle were weighted together. The front axle load was subtracted from the total load to get the middle axle load.

Table 4.2: Axle loads for the on-road tests.

<table>
<thead>
<tr>
<th>Position</th>
<th>Weight [tons]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck front axle</td>
<td>7.08</td>
<td>18.0</td>
</tr>
<tr>
<td>Truck rear axle</td>
<td>9.30</td>
<td>23.6</td>
</tr>
<tr>
<td>Trailer front axle</td>
<td>7.81</td>
<td>19.9</td>
</tr>
<tr>
<td>Trailer middle axle</td>
<td>7.56</td>
<td>19.2</td>
</tr>
<tr>
<td>Trailer rear axle</td>
<td>7.59</td>
<td>19.3</td>
</tr>
<tr>
<td>GTW</td>
<td>39.34</td>
<td>100</td>
</tr>
</tbody>
</table>
5 — Results

The results are separated into one section for each set of test drives. In sections 5 and 6 the following abbreviations are used for the different fuel consumption measurement devices; AIC for the portable fuel flow meter, COR for the stationary coriolis fuel flow meter, PEMS for the Horiba OBS 2200 exhaust gas analyser, SCALE for fuel consumption estimations based on fuel tank weighting and PUMP for fuel consumption estimations performed according to the standard method.

5.1 CD5 testing

Due to problems with the Horiba MEXA 7500, it was decided to exclude these measurement results from this investigation. Because of an engine malfunction the differential pressure sensor on the exhaust gas silencer was exchanged between test drive 6 and 7. During the last unmanned set of test drives the Horiba OBS 2200 logging computer lost contact with the exhaust gas analyser, due to this PEMS measurement results are missing from test drives 16-19. Drift checks were performed once per hour in test drives 2-19.

Fuel economy for each test drive are presented in Figure 5.1, the corresponding numerical values are available in Table C.3 in Appendix C. Mean, median, standard deviation and worst case error of the estimated fuel economies are presented in Table 5.1.

In Figure 5.2 fuel consumption versus time estimated by the AIC fuel flow meter, the EMS and the Horiba OBS 2200 PEMS are plotted in the same graph for the first 1200 seconds of test drive 1. In Figure 5.3 the fuel consumptions are plotted for the time interval 8400-9200 seconds for all test drives.

Gearbox, fuel and ambient temperature for each test drive in CD5 are presented in
Figure 5.4. It can be seen that fuel and ambient temperature are approximately constant 22 °C and 20.5 °C respectively. The gearbox reaches its maximum temperature of around 88 °C after approximately 5500 seconds in all test drives. The gearbox operating temperature, i.e. the temperature when driving at constant speed on horizontal ground is around 81 °C. Test drive 13 was started with a lower gearbox temperature than the other test drives, which is the blue line.

Engine frictional losses for each test drive are presented in Figure 5.5 and auxiliary device torques are plotted in Figure 5.6. The engine frictional losses are separated in two groups, the upper group consists of test drives 1-12 and the lower of test drives 13-19. The difference in frictional losses in between test drive 12 and 13 corresponds to an increase in fuel economy of around 1.2 l/100 km with the assumptions described in Equation 3.3 and 3.4.

The amount of engine work performed in each engine mode is presented in Table 5.2. It can be seen that the engine performs less work in mode D and more in mode C in test drive 12 than in test drive 13. Engine mode as function of time is presented for test drive 12 and 13 in Figure 5.7.

The result from the investigation of how much certain deviations of the H/C and O/C carbon ratios are influencing the PEMS fuel consumption estimation is presented in Figure 5.8.

The relative frequencies for the different fuel economy estimations in test drive 1-19 are presented in Figure 5.9. Because the fuel economies are separated in two distinct groups, an additional relative frequency plot was created for test drive 1-12 in order to investigate the distribution within each group. The relative frequencies for test drives 1-12 are presented in Figure 5.10.

Table 5.1: Mean value, median and standard deviation for the fuel economies measured in CD5 in l/100 km. Worst case error in %.

<table>
<thead>
<tr>
<th></th>
<th>AIC</th>
<th>COR</th>
<th>EMS</th>
<th>PEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE mean</td>
<td>32.37</td>
<td>32.51</td>
<td>33.43</td>
<td>32.74</td>
</tr>
<tr>
<td>FE median</td>
<td>32.33</td>
<td>32.49</td>
<td>33.44</td>
<td>32.68</td>
</tr>
<tr>
<td>FE stddev</td>
<td>0.07</td>
<td>0.08</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td>Worst case</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>
5.1. **CD5 TESTING**

![Fuel economy](image1)

**Figure 5.1:** Estimated fuel economy in each test drive in CD5.

![Fuel consumption](image2)

**Figure 5.2:** Fuel consumption versus time in test drive 1 for AIC fuel flow meter, Horiba OBS 2200 PEMS and EMS.
CHAPTER 5. RESULTS

Figure 5.3: Fuel consumption versus time measured by the AIC fuel flow meter, the Horiba OBS 2200 exhaust gas analyser and the EMS.

Figure 5.4: Gearbox, fuel and ambient temperature for each test drive in CD5.
5.1. CD5 TESTING

Figure 5.5: Engine frictional losses for each test drive in CD5.

Figure 5.6: Crankshaft torque losses due to engine auxiliary devices for each test drive in CD5.
Table 5.2: Share of the total engine work performed in each engine mode (m.) in %.

<table>
<thead>
<tr>
<th>Test</th>
<th>m. A</th>
<th>m. B</th>
<th>m. C</th>
<th>m. D</th>
<th>m. F</th>
<th>m. G</th>
<th>m. H</th>
<th>m. I</th>
<th>m. J</th>
<th>m. K</th>
</tr>
</thead>
<tbody>
<tr>
<td>test 1</td>
<td>3.5</td>
<td>7.1</td>
<td>13.9</td>
<td>68.5</td>
<td>5.1</td>
<td>0.6</td>
<td>1.3</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 2</td>
<td>3.5</td>
<td>7.4</td>
<td>15.2</td>
<td>66.7</td>
<td>5.1</td>
<td>0.6</td>
<td>1.4</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 3</td>
<td>3.4</td>
<td>6.9</td>
<td>14.9</td>
<td>68</td>
<td>4.9</td>
<td>0.6</td>
<td>1.1</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 4</td>
<td>4.1</td>
<td>6.3</td>
<td>14.3</td>
<td>68.4</td>
<td>4.9</td>
<td>0.7</td>
<td>1.2</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 5</td>
<td>2</td>
<td>6</td>
<td>12.2</td>
<td>73.2</td>
<td>4.9</td>
<td>0.7</td>
<td>0.9</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 6</td>
<td>1.7</td>
<td>6.1</td>
<td>11.6</td>
<td>73.7</td>
<td>4.7</td>
<td>0.7</td>
<td>1.2</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 7</td>
<td>1.1</td>
<td>4.5</td>
<td>11.8</td>
<td>75.7</td>
<td>4.8</td>
<td>0.7</td>
<td>1.1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 8</td>
<td>1.1</td>
<td>4.4</td>
<td>10</td>
<td>77.7</td>
<td>4.7</td>
<td>0.7</td>
<td>1.1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 9</td>
<td>1</td>
<td>4.3</td>
<td>11.1</td>
<td>76.9</td>
<td>4.8</td>
<td>0.6</td>
<td>1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 10</td>
<td>1</td>
<td>3.7</td>
<td>8.9</td>
<td>79.7</td>
<td>4.6</td>
<td>0.7</td>
<td>1.1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 11</td>
<td>1.7</td>
<td>4.6</td>
<td>12.5</td>
<td>74.4</td>
<td>4.8</td>
<td>0.6</td>
<td>1</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 12</td>
<td>1.1</td>
<td>4.3</td>
<td>10.1</td>
<td>78</td>
<td>4.7</td>
<td>0.6</td>
<td>0.9</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>test 13</td>
<td>1</td>
<td>2.5</td>
<td>7.8</td>
<td>81.9</td>
<td>4.6</td>
<td>0.7</td>
<td>1.3</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 14</td>
<td>0.9</td>
<td>2.6</td>
<td>7.2</td>
<td>82.8</td>
<td>4.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 15</td>
<td>1</td>
<td>3.2</td>
<td>8.3</td>
<td>80.7</td>
<td>4.6</td>
<td>0.7</td>
<td>1.4</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 16</td>
<td>1.3</td>
<td>3.3</td>
<td>9.8</td>
<td>79</td>
<td>4.8</td>
<td>0.7</td>
<td>0.8</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 17</td>
<td>1.6</td>
<td>4.1</td>
<td>11.8</td>
<td>76.1</td>
<td>4.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 18</td>
<td>1.5</td>
<td>4.7</td>
<td>13.2</td>
<td>74.1</td>
<td>4.5</td>
<td>0.7</td>
<td>1</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>test 19</td>
<td>1.6</td>
<td>4.5</td>
<td>12.3</td>
<td>75.2</td>
<td>4.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 5.7: Engine mode as function of time for test drive 12 and 13 in CD5.
5.1. CD5 TESTING

Figure 5.8: Error in fuel economy as function of the error in $\alpha$ for different errors in $\beta$.

Figure 5.9: Relative frequencies for the fuel economies measured in test drives 1-19.
5.2 CD2 testing

Test 1, 6, 7, 13 and 14 were performed with the external fuel tank, this means that the stationary coriolis fuel flow meter was disconnected in these tests. In test 13 the truck run out of fuel. Unmanned test sets were run, but unfortunately the ATI Vision log settings were set to short, which implied that measurement data logged in ATI Vision was lost for test drives 3-5 and 9-12. Because the distance measurements are contained in this log, the PEMS fuel economy could not be calculated. During the testing it was noticed that the chassis dynamometer ambient temperature sensor was mounted unusually far away from the front of the truck.

Fuel economy for each test drive are presented in Figure 5.11, the corresponding numerical values are available in Table C.1 in Appendix C. It can be seen that the AIC fuel flow meter agrees well with the COR fuel flow meter measurement results. It does also agree well with SCALE values in some of the test drives. Mean, median, standard deviation and worst case error of the estimated fuel economies are presented in Table 5.3.

In Figure 5.12 fuel consumption versus time estimated by the AIC fuel flow meter,
5.2. CD2 TESTING

Horiba OBS 2200 PEMS, EMS and stationary coriolis fuel flow meter are plotted in the same graph for the first 1200 seconds of test drive 1 in CD2. In Figure 5.13 the fuel consumptions are plotted for the time interval 8400-9200s for all test drives.

Gearbox, fuel and ambient temperature for each test drive in CD2 are presented in Figure 5.14. The ambient temperature is varying frequently between around 30 °C and 60 °C. The maximum ambient temperature is reached in the time interval 5000-6000 seconds. The gearbox reaches its maximum temperature of around 100 °C after approximately 5500 seconds in all test drives. The operating temperature is approximately 90 °C. The fuel temperature is at different levels in different test drives, it can also be seen that it is increasing as time evolves in all test drives but test drive 2 and 8.

Engine frictional losses are presented in Figure 5.15 and auxiliary device torques in Figure 5.16. The engine frictional losses are separated in different levels but they seem to follow the same pattern. The magnitude of the frictional losses in test drives 1, 6, 13 and 14 are comparable. The exhaust brake goes in at three different time intervals in the time interval plotted.

Share of the total amount of engine work performed in each engine mode is presented in Table 5.4 for each test drive.

![Figure 5.11: Estimated fuel economy in each test drive in CD2.](image)
Table 5.3: Mean value, median and standard deviation for the fuel economies measured in CD2 in 1/100 km. Worst case error in %.

<table>
<thead>
<tr>
<th></th>
<th>AIC</th>
<th>COR</th>
<th>EMS</th>
<th>PEMS</th>
<th>SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE mean</td>
<td>34.11</td>
<td>34.04</td>
<td>35.08</td>
<td>33.29</td>
<td>34.60</td>
</tr>
<tr>
<td>FE median</td>
<td>34.14</td>
<td>34.04</td>
<td>35.12</td>
<td>33.33</td>
<td>34.60</td>
</tr>
<tr>
<td>FE stddev</td>
<td>0.27</td>
<td>0.39</td>
<td>0.25</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Worst case</td>
<td>2.5</td>
<td>1.6</td>
<td>2.2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 5.12: Fuel consumption versus time measured with the AIC fuel flow meter, PEMS exhaust gas analyser, EMS and stationary coriolis fuel flow meter.
5.2. CD2 TESTING

Figure 5.13: Fuel consumption versus time measured with the AIC fuel flow meter, PEMS exhaust gas analyser and EMS.

Figure 5.14: Gearbox, fuel and ambient temperature for each test drive in CD2.
CHAPTER 5. RESULTS

Figure 5.15: Engine frictional losses for all test drives in CD2.

Figure 5.16: Torque losses in auxiliary engine devices for all test drives in CD2.
5.3 On-road testing

Due to the traffic situation other vehicles had to be overtaken. In the first test drive three over takings had to be done, in the second one overtaking was done and in the third no overtaking was done. In the second test drive it was noticeable more windy and unfortunately the log was of some reason stopped after around 70 minutes. Approximately one minute of logged data was lost due to this. This does not imply that the SIM CNT counter loses its count, but a time dislocation is to be expected in the time dependent fuel consumption measurement. Because the EMS is summing the contributions in each time step, this will contribute to an to low EMS fuel consumption estimation. Total distance and Horiba OBS 2200 PEMS fuel consumption estimations are not influenced. The AIC fuel economy estimation agrees well with the fuel economies measured according to the standard method in test drive 1 and 2. Calculated fuel economies are presented in Figure 5.17, the corresponding mean, median standard deviation and worst case error in fuel consumption are presented in Table 5.5.

In Figure 5.18 fuel consumption versus time estimated by the AIC, PEMS and EMS are plotted in the same graph for the first 1200 seconds of third on-road test drive. In Figure 5.19 fuel consumptions are plotted for the time interval 8400 to 9200 seconds for all test drives and each fuel consumption measurement device separately.

Gearbox, fuel and ambient temperature for each on-road test drive are presented in Figure 5.20. The ambient temperature is approximately constant in all test drives. The difference in between the warmest and coldest ambient temperature observed is around 9 °C. The gearbox reaches its maximum temperature of around 85 °C in test drive 1 and 2 and 88 °C in test drive 3 after approximately 5500 seconds.

### Table 5.4: Share of the total engine work performed in each engine mode (m.) in %.

<table>
<thead>
<tr>
<th></th>
<th>m. A</th>
<th>m. B</th>
<th>m. C</th>
<th>m. D</th>
<th>m. F</th>
<th>m. G</th>
<th>m. H</th>
<th>m. I</th>
<th>m. J</th>
<th>m. K</th>
<th>m. L</th>
</tr>
</thead>
<tbody>
<tr>
<td>test 1</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>95</td>
<td>3.6</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>test 2</td>
<td>0</td>
<td>2.5</td>
<td>5.7</td>
<td>86.3</td>
<td>3.3</td>
<td>0.4</td>
<td>1.3</td>
<td>0</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>test 6</td>
<td>0</td>
<td>3.6</td>
<td>8.8</td>
<td>81.1</td>
<td>4.2</td>
<td>0.8</td>
<td>1.1</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>test 7</td>
<td>0</td>
<td>8.3</td>
<td>15.1</td>
<td>70.5</td>
<td>3.4</td>
<td>0.7</td>
<td>1.3</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>test 8</td>
<td>1.5</td>
<td>3.5</td>
<td>9.3</td>
<td>79.2</td>
<td>3.5</td>
<td>0.9</td>
<td>1.3</td>
<td>0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>test 13</td>
<td>0</td>
<td>3.7</td>
<td>12.2</td>
<td>77.7</td>
<td>4.1</td>
<td>0.7</td>
<td>0.9</td>
<td>0</td>
<td>0.6</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>test 14</td>
<td>0</td>
<td>3.5</td>
<td>9.3</td>
<td>80.3</td>
<td>4.4</td>
<td>0.9</td>
<td>1.1</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The operating temperature is approximately 77 °C for these tests. Test drive 2 was started with a lower gearbox temperature. The fuel temperature starts in the interval 10-15 °C and reaches temperatures in between 20 and 27 °C in the end of the tests.

Engine frictional losses are presented in Figure 5.21 and auxiliary device torques in Figure 5.22. The engine frictional losses are of approximately the same order of magnitude and are following the same pattern in all test drives. The frictional losses are slightly bigger in test drive 1. If the AC compressor torques are studied, it can be concluded that the AC runs equally in test drive 1 and 2. In test drive 3 the torque is increased in short intervals, this implies a change in fuel economy of less than 1 cl/100 km. The exhaust brake was not actuated in the plotted interval.

Engine modes for all test drives are presented in Table 5.6. The engine runs significantly less in mode D in test drive 1 than in test drive 2 and 3.

**Fuel economy**

![Fuel economy graph](image)

*Figure 5.17: Estimated fuel economy in each on-road test drive.*
Table 5.5: Mean value, median and standard deviation for the fuel economies measured in CD2 in l/100 km. Worst case error in %.

<table>
<thead>
<tr>
<th></th>
<th>AIC</th>
<th>EMS</th>
<th>PEMS</th>
<th>PUMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE mean</td>
<td>30.87</td>
<td>31.75</td>
<td>30.02</td>
<td>30.98</td>
</tr>
<tr>
<td>FE median</td>
<td>30.75</td>
<td>31.82</td>
<td>29.93</td>
<td>30.77</td>
</tr>
<tr>
<td>FE stddev</td>
<td>0.43</td>
<td>0.55</td>
<td>0.28</td>
<td>0.68</td>
</tr>
<tr>
<td>Worst case</td>
<td>2.7</td>
<td>3.5</td>
<td>1.8</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Figure 5.18: Fuel consumption versus time in test drive 3 for the AIC fuel flow meter, Horiba OBS 2200 PEMS and EMS.
CHAPTER 5. RESULTS

Figure 5.19: Fuel consumption measured by the AIC fuel flow meter, the Horiba OBS 2200 PEMS and EMS versus time.

Figure 5.20: Gearbox, fuel and ambient temperature for each on-road test drive.
5.3. ON-ROAD TESTING

Figure 5.21: Engine frictional losses for each on-road test drive.

Figure 5.22: Engine crankshaft torque losses due to losses in auxiliary engine devices for each on-road test drive.
Table 5.6: Share of the total engine work performed in each engine mode (m.) in %.

<table>
<thead>
<tr>
<th></th>
<th>m. A</th>
<th>m. B</th>
<th>m. C</th>
<th>m. D</th>
<th>m. E</th>
<th>m. F</th>
<th>m. G</th>
<th>m. H</th>
<th>m. I</th>
<th>m. J</th>
<th>m. K</th>
</tr>
</thead>
<tbody>
<tr>
<td>test 1</td>
<td>1.6</td>
<td>4.2</td>
<td>12.6</td>
<td>76.5</td>
<td>2.9</td>
<td>0.7</td>
<td>0.1</td>
<td>1.4</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>test 2</td>
<td>2.7</td>
<td>2.9</td>
<td>5.2</td>
<td>87.5</td>
<td>0</td>
<td>0.5</td>
<td>0.2</td>
<td>0.8</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>test 3</td>
<td>0.9</td>
<td>2.7</td>
<td>4.9</td>
<td>89.9</td>
<td>0</td>
<td>0.6</td>
<td>0.1</td>
<td>0.7</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>
6 — Discussion

Firstly measurement results from the CD5 drive shaft chassis dynamometer test drives are discussed. It is found out that significantly better accuracy and repeatability can be achieved in this test environment compared to the CD2 and real-world environments. Because of this, the CD5 results are used as reference for the CD2 and on-road results presented afterwards.

6.1 Drive shaft chassis dynamometer

The CD5 fuel economy results presented in Figure 5.1 indicates that the fuel economy estimation done by the EMS, COR and AIC are reacting in approximately the same manner to changes in fuel economy. In test 13 all measurement devices are registering an increase of fuel economy compared to test 12. According to the fuel economy values in Table C.3 in Appendix C it can be seen that the increase in fuel economy registered by AIC, COR and EMS is approximately 0.2 l/100 km but the same number for the PEMS is approximately 0.6 l/100 km. This indicates that different parameters are influencing the different fuel consumption measurement devices differently. The AIC, COR and EMS do however seem to react similar, a possible reason for the deviating behaviour of the PEMS estimation is that something went wrong with the PEMS during the last set of test drives (test drives 13-19). The fact that the PEMS computer lost contact with the analyser in test 16 indicates that something was not correct.

The standard deviations stated in Table 5.1 indicates that fuel economy estimated by the EMS is varying least and the PEMS most. The worst case error observed is smaller for the AIC than the EMS, for the standard deviation it is the other way around. This indicates that most of the EMS measurements are gathered relatively close to the mean fuel economy but the worst outliers are further away from the mean
than for the AIC results than the EMS results. Support for the standard deviations and worst case errors can also be found in Figure 5.3 where it is obvious that the PEMS fuel consumption is deviating more in between each test drive. Because the lower fuel consumptions are corresponding to test drives 1-12, it can be concluded that the difference in fuel economy in between test drive 12 and 13 is mainly due to a change in fuel consumption and not a difference in the distance estimation.

In Figure 5.2 it can be seen that the difference in the fuel consumption estimations between the AIC, EMS and PEMS is increasing as time evolves. This is indicating that systematical errors are at hand. A possible contribution to the systematical error is a false value of the fuel density. After the fuel economy calculations were done it was realised that an fuel density estimation is performed by the stationary coriolis fuel flow meter system, fortunately this parameter was logged, which gave an estimated fuel density of 840 kg/m$^3$ in CD5. Using this value instead of the earlier value of 832 kg/m$^3$ is decreasing the difference between all fuel consumption estimations.

It seems to be likely that the change of engine frictional losses (see Figure 5.5) is the reason for the increase in fuel economy in between test drive 12 and 13. The calculated change in fuel economy due to the frictional losses is however significant bigger than the changes noted. Because of this it seems like other parameters have influenced fuel economy in the other direction as well. It can for example be seen that the engine have performed more work in energy efficient modes in test drive 13 than 12. This should counteract the increase in fuel economy due to the frictional losses. The reason to why the engine frictional losses did change was not fully investigated, but it was found out that a difference in exhaust and ambient pressure also occurred in between test drive 12 and 13.

The auxiliary device torques in Figure 5.6 show that alternator and AC compressor are running at constant load. The radiator fan, diesel pump and exhaust brake torques seem to follow the same behavior in all tests, which indicates that the test is repeatable. It is difficult to distinguish the different test drives in the air compressor torque plot, thus it would be better to calculate the amount of work performed by the air compressor in each test drive instead of studying its behavior graphically.

From Table 5.2 it can be concluded that the engine did perform more work in mode D in test drive 13 than test drive 12. Because mode D is the most fuel efficient engine mode, a decrease in fuel economy is to be expected in test drive 13 due to this. The fact that the time dependent engine modes does not follow exactly the same pattern in Figure 5.7 implies that the test is not fully repeatable.
The investigation of how much faulty carbon ratios are influencing the PEMS fuel economy estimation shows that the fuel economy may deviate maximum 22.5 cl/100 km with the assumed deviations of $\alpha$ and $\beta$. These deviations are however big compared to the standard values used in the measurements. It may be more realistic assume deviations depending on the significant figures of the standard values. This implies $\Delta \beta = 0.0005$ and $\Delta \alpha = 0.005$ which gives an worst case error in fuel economy of around 2.5 cl/100 km. It should be noted that different signs of the $\alpha$- and $\beta$-deviations implies that the error is partly or fully cancelled out.

If the fuel economy relative frequencies are normally distributed, a variance-weighted mean value may be introduced to be able to decrease the fuel economy measurement uncertainty according to Equation 2.9. Because the fuel economies are separated in two different groups, it is obvious that this set of data is not normally distributed. If Figure 5.10 is studied, it can also be concluded that the measurement data is not normally distributed within each group of fuel economies either. This implies that the benefits a variance-weighted mean value would have given if white gaussian measurement noise were at hand will not apply. The variance-weighting do still imply that the measured values are weighted depending on how much they are deviating from their mean values, which is a measure of the sensor precision. Thus, the sensor values are still weighted depending on the sensor precision, which sounds sensible. In this case, big differences in between the measurement results from the different fuel consumption measurement devices are at hand (large compared to the standard deviations obtained). This implies that a fuel economy estimation based on a mean value of multiple measurement devices may result in a fuel economy which has actually never been measured. Thus, a mean value estimation may be a better choice if the difference in between the different fuel economies estimated are of the same order of magnitude as the fuel economy measurement precision.

6.2 Rear axis chassis dynamometer

Fuel economy results from CD2 show that the fuel economies measured by AIC, EMS and COR are deviating significantly more in between each test drive compared to CD5. The fuel economies measured with PEMS are on the other hand deviating less than in CD5. Two possible reasons for this have been found. The first is the fact that the wind speed in CD5 was much higher than the wind speed in CD2. The PEMS analyser components need to operate within a certain temperature rang, the fact that it was positioned outside the cabin may have influenced the measurements...
negatively. However no malfunction message was displayed during the testing. The other reason is the fact that analyser drift checks were run in all measurements but the first. Because lost measurement data was replaced by calculated mean PEMS fuel flows, a random error may have been introduced if the mean PEMS fuel flows did not match the lost fuel flows good enough.

The standard deviation for the AIC, COR and EMS are increasing by approximately a factor 5 each, but the PEMS standard deviation did not increase significantly compared to in CD5. The worst case errors observed increases to 2.5 % for the AIC, 1.6 % for the coriolis fuel flow meter, 2.2 % for the EMS and 1.5 % for the PEMS. Because all worst case errors are increasing compared to CD5, the reason is most likely due to worse measurement repeatability.

The ambient and fuel temperature are varying more than in CD5. A likely reason for the strange ambient temperature behavior is the fact that the chassis dynamometer ambient temperature sensor was mounted to far away from the truck. Which may imply a too small cooling capacity to ensure constant temperature at the truck front. The reason for the different fuel temperatures is that the external fuel tank was used in some test drives. This means that the fuel circulating in the tank loop is getting warmer as time evolves, which is not the case when fuel is taken from the central fuel depot. Fuel density is temperature dependent, this means that corrections for these temperature variations have to be introduced in order to ensure a correct estimated fuel consumption.

The gearbox temperature reaches its peak value at approximately the same time in all testing environments, but the operating and maximum temperatures are higher in CD2 than in CD5 and on-road tests. The operating gearbox temperature measured in CD5 is slightly less than the operating temperature measured on-road.

In Figure 5.16 it can be seen that the exhaust brake has been attached multiple times in the same time interval as it was only attached once in CD5. It is also possible to see that it has been attached at different times in different test drives. This is indicating that the test drives are less repeatable in CD2 than in CD5.

### 6.3 On-road

The worst case errors obtained from the on-road tests are 2.7 %, 3.5 %, 1.8 % and 4.3 % for the AIC, EMS, PEMS and standard method respectively. These values are of the same order of magnitude as the worst case errors obtained from
The obtained standard deviations are 0.43 l/100 km, 0.55 l/100 km, 0.28 l/100 km and 0.68 l/100 km for the AIC, EMS, PEMS and standard method respectively. The standard method has the largest standard deviation and worst case error observed, thus one may question that as reference value. Figure 5.22 shows that the air condition pump did only operate in the third test drive. This could motivate the higher fuel economy compared to test drive 1 and 2, but the calculations show that the influence on the fuel economy is negligible. The exhaust brake was not actuated during the first 1000 seconds, which it did in the other tests, this means that the tests are not identical in the different environments. The engine frictional losses are approximately similar in all on-road test drives. The behaviour is similar to the behaviour of the frictional losses logged in CD5 but the magnitude suits some of the CD2 test drives better.

The on-road fuel economy measurements resulted in the mean fuel economies 30.9 l/100 km, 31.7 l/100 km, 30.0 l/100 km and 31.0 l/100 km for the AIC, EMS, PEMS and standard method respectively. These values are much lower than the mean fuel economies measured in CD2 and significantly lower than the CD5 mean fuel economy results. The reason for these differences is most probably due to the fact that the chassis dynamometer simulations are not exactly the same. Differences found in between the CD2 and CD5 tests are different gearbox, fuel and ambient temperatures. The exhaust brake did not operate similarly which is indicating that the vehicle was not run equal in these environments. Engine frictional losses was also shown to be different. Furthermore wheel slip is to be expected in the rear axle chassis dynamometer but not in the drive shaft chassis dynamometer. Differences in between the on-road and chassis dynamometer tests are firstly that deviations from the planned test had to be done because of the traffic situation. Driving resistance simulated in chassis dynamometer is based on tyre models. Because tyre dimensions are the only tyre specific input parameters for the simulations, the rolling resistance estimation is most likely going to deviate from the rolling resistance when driving on-road. The input axle loads in the chassis dynamometer tests did according to Tables 4.1 and 4.2 not correspond to the axle loads in the on-road tests. This implies that the rolling resistance simulations are based on faulty axle loads.
7 Conclusion

Fuel economy standard deviation and worst case error are increasing when complexity is increased to a fuel economy measurement. If standard deviation is used as measure of repeatability, it can be concluded that the repeatability for on-road testing is almost 10 times as bad as for testing in a drive shaft chassis dynamometer.

The worst case errors observed for on-road tests are 2.7 % for fuel consumption measurements performed with the portable AIC fuel flow meter, 3.5 % for vehicle internal fuel economy estimations, 1.8 % for measurements performed with an Horiba OBS 2200 portable exhaust gas analyser and 4.3 % for measurements based on fuel pump readings at the gas station. These values are comparable to values obtained in measurements performed on a rear axle chassis dynamometer but significantly higher than values obtained in a drive shaft chassis dynamometer.

The fuel economy estimations performed with the AIC fuel flow meter agrees well with the coriolis fuel flow meter and measurements performed according to the standard method. In all measurements performed, the EMS fuel economy estimation is the highest.

Results show that the fuel consumption measurements are equipped with systematically measurement errors. A possible reason to this is that more parameters need to be taken into account, e.g. parameters influencing fuel density. The systematic measurement errors is limiting the possibilities in using sensor fusion (variance-weighted mean value). It could be concluded that the fuel consumption measurements are changing in discrete steps in controlled environments. It may be sensible to take this into account when ambient condition changes are quantified by using a reference truck.
The results show that systematical errors are at hand in the fuel consumption estimations. It would be good to do an more detailed investigation of each fuel consumption measurement method in order to identify the sources of these systematically errors. Minimising the difference between each measurement device to a level comparable to the corresponding standard deviations, would make a variance-weighted mean value better applicable.

The aim in this work was put on fuel the consumption estimations, it may also be interesting to investigate the accuracy of the distance estimation more into detail.

Because the data cutting is getting a vital part to get accurate measurement results, it would be good to introduce automatic triggering for logging start and stop. This would be profitable in both chassis dynamometer and on-road testing. To reduce the data post processing effort it is better to log all data with only one computer.

Another problem is that fuel density may deviate depending on the ambient conditions in different seasons, because it is expensive to send fuel samples for analysis, it would be interesting to investigate if it is possible to do an accurate estimate of fuel density by using one fuel mass and one fuel volume measurement device.
Bibliography


Appendices
A — Specifications

In Tables A.1 and A.2 specifications of the AIC 6004 fuel flow meter and the Horiba OBS 2200 are presented.

AIC-6004/6008 SWISSLINE - UNIFLOWMASTER

Table A.1: Specifications for the AIC-6004 swissline uniflowmaster [11].

<table>
<thead>
<tr>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Return line backpressure:</td>
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</tr>
<tr>
<td>Viscosity Max:</td>
<td>100 mPa s</td>
</tr>
<tr>
<td>Accuracy:</td>
<td>±1 %</td>
</tr>
<tr>
<td>Repeatability:</td>
<td>±0.2 %</td>
</tr>
<tr>
<td>Pressure range:</td>
<td>-1-6 bar</td>
</tr>
<tr>
<td>Temperature range:</td>
<td>-30 - 90 °C</td>
</tr>
<tr>
<td>Protection:</td>
<td>IP 65</td>
</tr>
<tr>
<td>Power supply:</td>
<td>24 VDC</td>
</tr>
</tbody>
</table>

Horiba OBS-2200

Table A.2: Specifications for the Horiba PEMS 2200 [13].

<table>
<thead>
<tr>
<th>Specification</th>
<th>CO, CO₂, THC &amp; NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy:</td>
<td>Zero, Span: within ± 0.3 % of full scale</td>
</tr>
<tr>
<td>Noise:</td>
<td>Zero, Span: less than 0.4 % of full scale or 2.0 % of readings</td>
</tr>
<tr>
<td>Repeatability:</td>
<td>Zero, Span: within ±1.0 % of full scale</td>
</tr>
<tr>
<td>Temperature range:</td>
<td>0-40 °C</td>
</tr>
</tbody>
</table>
B — Logging

The parameters presented in Table B.1 were logged with two different computer programs; ATI Vision and the Horiba OBS 2200 logging program. In ATI Vision it is possible to set the log length. The length of each test drive is however going to vary, therefore a log length much longer than the test length was set. When multiple test drives were run, the log length was set to make one log file contain all test drives. The output format of the data was chosen to be in MATLAB format. Data is outputted in structures, each logged parameter has an own structure which is containing one vector with parameter values and one vector with the corresponding sample times. Each parameter has its own time vector, i.e. all variables are not sampled synchronised.

The Horiba OBS 2200 system creates one log file per hour. This means that log files have to be assembled to get complete tests. In this system logged data is given in csv-files.

In ATI Vision data was logged from the chassis dynamometer (only in chassis dynamometer tests), the IPEtronik CAN bus, the EMS and the Coordinator (only in on-road tests). Additional to this, PEMS data was logged with the PEMS computer. Thus data from three different CAN-buses was needed to be logged simultaneously time in ATI Vision. To be able to do this, two Kvaser USBcan professional HS/HS VCIs were used. The setup in vision does basically consist of two parts, device setup and screen construction. The device setup is made in the device manager. It may be possible to do the same setup in more than one way but in this case it was done as follows. An USB port was added under which four Kvaser channels were added. CAN Monitors were added for the IPEtronik and chassis dynamometer forwarding CAN buses. The corresponding dbc-files were imported to the CAN Monitors. CAN calibration protocol- (CCP-) Devices were added for EMS and Coordinator. To these devices corresponding strategy files were added. The setup can be seen in Figure B.1. The dbc-files needed for the external sensor setup was created in the
computer program IPEmotion. The IPEmotion-settings are presented in Figure B.2. In the screen manager different logging tools are available. In this case a stripchart recorder was chosen. Apart from the recording function, this recorder makes it possible to display variables in real-time. This allows errors to be discovered directly instead of later in the post processing.

Figure B.1: Device structure in ATI Vision.

Figure B.2: Settings for the SIM-CNT and SIM-TH-16 in IPEmotion.
Table B.1: Logged parameters and its origin. Coordinator (COO), chassis dynamometer (CHDYN) and external CAN bus (CANEX).

<table>
<thead>
<tr>
<th>Parameter</th>
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</tr>
<tr>
<td>engine speed</td>
<td>EMS</td>
</tr>
<tr>
<td>engine speed</td>
<td>EMS</td>
</tr>
<tr>
<td>distance</td>
<td>EMS</td>
</tr>
<tr>
<td>ambient temperature</td>
<td>EMS</td>
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<td>vehicle speed</td>
<td>EMS</td>
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<tr>
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<td>est. air compressor torque</td>
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</tr>
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</tr>
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<tr>
<td>est. road slope</td>
<td>COO</td>
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<td>fuel consumption</td>
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<tr>
<td>actual engine torque</td>
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<tr>
<td>vehicle speed</td>
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<tr>
<td>road slope</td>
<td>CHDYN</td>
</tr>
<tr>
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<td>Horiba MEXA NOₓ</td>
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<tr>
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<td>gearbox temperature</td>
<td>CANEX</td>
</tr>
<tr>
<td>fuel temperature</td>
<td>CANEX</td>
</tr>
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</table>
In tables C.1, C.2 and C.3 the fuel economies for the test drives performed in CD2, on-road and in CD5 respectively are presented in numerical form.

Table C.1: Calculated fuel economies for the test drives performed in CD2.

<table>
<thead>
<tr>
<th></th>
<th>FE AIC [L/100 km]</th>
<th>FE COR [L/100 km]</th>
<th>FE EMS [L/100 km]</th>
<th>FE PEMS [L/100 km]</th>
<th>FE PALL [L/100 km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>test 1</td>
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<td>35.17</td>
<td>33.01</td>
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<td>33.08</td>
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<td>35.14</td>
<td>33.42</td>
<td>34.87</td>
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</tr>
<tr>
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<td>34.48</td>
<td>35.39</td>
<td>33.52</td>
<td>34.87</td>
<td></td>
</tr>
<tr>
<td>test 8</td>
<td>34.12</td>
<td>34.32</td>
<td>35.1</td>
<td>33.46</td>
<td></td>
</tr>
<tr>
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<td>34.54</td>
<td>32.83</td>
<td>38.09</td>
<td></td>
</tr>
<tr>
<td>test 14</td>
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<td>35.04</td>
<td>33.25</td>
<td>34.34</td>
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</table>

Table C.2: Calculated fuel economies for the test drives performed on-road.

<table>
<thead>
<tr>
<th></th>
<th>FE AIC [L/100 km]</th>
<th>FE EMS [L/100 km]</th>
<th>FE PEMS [L/100 km]</th>
<th>FE STD [L/100 km]</th>
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</table>
APPENDIX C. FUEL ECONOMY DATA

Table C.3: Calculated fuel economies for the test drives performed in CD5.

<table>
<thead>
<tr>
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<th>FE AIC [L/100 km]</th>
<th>FE COR [L/100 km]</th>
<th>FE EMS [L/100 km]</th>
<th>FE PEMS [L/100 km]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>33.43</td>
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<tr>
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