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Examensarbete

Estimation of distance to empty for heavy vehicles

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan i Linköping
av

Nils Erikssson

LiTH-ISY-EX--10/4342--SE

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Estimering av återstående körsträcka för ett tungt fordon

Estimation of distance to empty for heavy vehicles

Författare
Author

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Sammanfattning
Abstract

The distance to empty (DTE) for a heavy vehicle is valuable information both for the driver and the hauler company. The DTE is estimated as the ratio between the current fuel level and a representative mean fuel consumption. This means the fuel consumption is a prediction of the most likely future mean fuel consumption based on earlier data. It is calculated by applying a forgetting filter on the signal of the momentary fuel consumption in the engine. The filter parameter control how many values that contributes to the output. This is a balance between desired robustness and adaptability of the estimate.

Initially, a pre-stored value is used as an estimate of the mean fuel consumption. By this, the driver gets a first hint of the DTE value and the estimation of the DTE gets a good starting point. Stored values will adapt continuously with an online algorithm using vehicle data from previous runs. An alternative to showing the DTE is to present the time to empty when the vehicle speed is close to zero.

The accuracy of the proposed algorithm depends on the quality of the input signals. With the current input signals, it is possible to get a DTE estimate that, over a longer time period, decrease in the same pace as the distance meter increase. This is considered as a good validation measurement. If altitude data for the current route would be used, a more accurate DTE estimate could be obtained. The sample distance for this altitude data could however be set to a 1000 meter without affecting the estimate significantly.

Nyckelord
Keywords

distance to empty, DTE, time to empty, TTE, Look-aHead, fuel consumption, adaptive map

Abstract

The distance to empty (DTE) for a heavy vehicle is valuable information both for the driver and the hauler company. The DTE is estimated as the ratio between the current fuel level and a representative mean fuel consumption. This means the fuel consumption is a prediction of the most likely future mean fuel consumption based on earlier data. It is calculated by applying a forgetting filter on the signal of the momentary fuel consumption in the engine. The filter parameter control how many values that contributes to the output. This is a balance between desired robustness and adaptability of the estimate.

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Sammanfattning

Sträckan till tom tank för ett tungt fordon är värdefull information, både för den enskilde föraren och åkeriet. Förkortad som DTE (Distance to empty) kan detta värde estimeras som kvoten av den nuvarande bränslenivån i tanken och en genomsnittlig bränsleförbrukning.

Denna genomsnittliga bränsleförbrukning är en prediktion av den troligaste framtida snittförbrukningen baserad på tidigare värden. Detta görs genom att ett glömskefilter appliceras på signalen för den aktuella bränsleförbrukningen i motorn. Filterparametern avgör hur snabbt gamla värden på insignalen ska klinga av och när den anpassas så måste önskad stabilitet vägas mot önskad känslighet hos skattningen.

Initialt så används förlagrade värden som skattning för den genomsnittliga bränsleförbrukningen. Detta gör att föraren får en första aning om hur långt fordonet kan köras samt ger DTE estimeringen en bra utgångspunkt. Dessa lagrade värden uppdateras under drift med information från det aktuella fordonet. För att hantera de problem som kan uppstå vid låga hastigheter eller tomgång kan istället tiden till tom tank visas.

Resultatet av DTE skattningen beror på kvalitén på insignalerna. Med de nuvarande insignalerna fås en DTE skattning som över en längre tidsperiod minskar sitt värde i samma takt som avståndsmätaren ökar sitt, vilket är ett önskvärt uppförande.

Om höjddata för en den aktuella rutten skulle användas skulle DTE estimeringen kunna göras mer noggrant. Det skulle dock räcka med att använda höjdinformation var 1000:e meter och ändå få en tillräckligt noggrann skattning.

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Nils Eriksson
Södertälje, April 2010

Contents

Chapter 1

Introduction

This Master's thesis project has been carried out at Scania CV AB in Södertälje at the Vehicle Management Controls group, REVM, from November 2009 to April 2010. In this first chapter the background to the studied problem will be given together with a problem definition, outline and contributions of this thesis.

1.1 Background

The information on how much further a vehicle can travel due to the fuel left in the tank, from now on referred to as the distance to empty (DTE), have both economic and environmental benefits. Especially within the long haulage transportation business the DTE information is of good use as the driver or hauler company easier should be able to more efficiently plan a route with combined rest, food and refuelling breaks. The fuel cost could also be reduced by planning the refuelling stops in countries with lower fuel price. The fuel tank of a heavy vehicle could contain several hundred liters. Fully filled the fuel ads a great amount of mass, thereby increasing the fuel consumption. With DTE knowledge a driver could wait longer before refuelling, thereby slightly reduce the vehicle weight and fuel consumption during that time.

1.2 Related research

The number of published papers on the subject is limited. However, there exist some patents on estimating the distance to empty and closely related subjects.

US 5301113 A Patent of Ford 1994. It describes a way of estimate the DTE for motorized (light) vehicle by taking the remaining fuel level divided by the mean fuel consumption in fuel amount per distance. Two different modes are used: one were the estimate only can decrease and one were both increase and decrease is possible.

US 6940401 B1 Patent of Daimler 2005. It is actually a warning system for a low fuel level, but the warning occur when there is a danger of not reaching a chosen destination. A DTE is calculated and compared to the distance remaining to the target. No further details in how the DTE is calculated is explained.

US 5790973 A Patent of Prince Corp. 1998. It describes a warning system, where the DTE is calculated and compared to the distances to different refuelling stations. The system is intended to be used on a highway with limited exit points and warn the driver at the last takeoff. The DTE information is assumed to be obtained through calculations of the vehicle sensor signals.

US 5734099 Patent of Yazaki Corp. 1998. It describes a way to determine the DTE of electric automobiles. The method is similar to those used in patents for conventional vehicles: the current battery capacity is divided by the consumption rate per unit travel distance.

US 6961656 B2 Patent of Hyundai 2005. It describes a way to estimate DTE when a refuelling has taken place. The system derives the mean fuel consumption as the ratio between the fuel consumed since last refuel and the distance travelled since then. A first DTE estimate is then done by using this mean fuel consumption together with fuel level in the tank when refuelled. A different DTE estimate use the same fuel level but a predetermined fixed fuel consumption. The final DTE estimate is created as the two estimates are weighted together. The weighting is done with a greater trust in the first estimate.

1.3 Problem definition

Here, the problems with estimating the DTE estimation are discussed. At a first look, the solution appears quite trivial. With the current fuel level and mean fuel consumption, the distance to empty is obtained by taking the ratio of those two. However, as one takes a closer look, several problems and special cases appear.

Predicting fuel consumption A main problem is to estimate a representative fuel consumption in the future, given that the coming route and driving behaviour of the driver is unknown. The fuel consumption therefore has to be based on earlier observations. It will be examined how this could be done and what methods that are available.

Handling low speed and idling At low speed or idling, the engine consumes fuel without the vehicle travelling any significant distance. This will result in the fuel consumption estimation in fuel per length unit to rise toward infinity which could lead to calculation difficulties.

Uncertainties in input signals One question that should be asked is: can we trust the input signals? It will be examined how an error in the input will propagate within the algorithm and how much better the output result would be with improvements in the input signals.

No or bad data to base the estimate on There are moments when the amount of data to base the estimate on is too small, e.g. when to engine is recently turned on. The data could also be bad due to a recent change in a condition affecting the fuel consumption, e.g. a when reloading the vehicle.

1.4 Outline and contribution

In this thesis report the problems from Section 1.3 will try to be solved in Chapter 2, Estimation of DTE. The model in that chapter is simulated and tested on real vehicle date. A brief description of the implementation along with the test result will be given in Chapter 3.

The use of information about the future road topography to estimate the DTE will be briefly touched in Chapter 4. There, a pre-study how the sample distance of the topography route data affect the DTE estimation, is done.

The work finishes with a summary and conclusions part and a notations part in Chapter 5.

This thesis work has contributed to a useful and memory efficient method to estimate the distance to empty for heavy vehicles. It has also shown that when estimating the fuel consumption for a route, it is sufficent enough to measure the altitude of that route every 1000 meter and still get an estimation error of only a few percent.

The thesis work has resulted in two possible patent applications. The first one regarding matters in Section 2.4.1, the second one from Section 2.5.5. Due to the long handling time for patents, the detailed information about the contribution of these patents can not be published in the report printed at Linköping University.

Chapter 2

Estimation of DTE

As mentioned in Section 1.3 the basic solution of how to estimate the distance to empty (DTE) appears quite trivial. With the fuel tank volume in liters V_f, and the fuel consumption $\bar{\gamma}_{l/km}$ in liters per kilometer, the DTE, denoted Γ_{DTE}, can be estimated as Equation (2.1).

$$\Gamma_{DTE} = \frac{V_f}{\bar{\gamma}_{l/km}} \; [km] \tag{2.1}$$

This is the foundation equation. But Section 1.3 also describes several difficulties and the purpose with this chapter is to overcome these problems.

2.1 Input signals

The estimation of the DTE is dependent on reliable input signals. The input signals used in this thesis will be discussed in this section. It is not within the limits of this thesis to manipulate and correct those input signal, for what ever reason, thought to be faulty. Instead, the thought is to merely point out where, when and how a false input signal could affect the estimate. The actual error propagation will be shown in Section 2.3, while this section merely will present the different inputs.

Throughout the vehicle runs a number of CAN-buses (Controller Area Network), connecting all the different ECUs (Electrical Control Units). The sensors on the vehicle are connected to the ECUs which uses the signals locally to perform their tasks. An implemented version of the system the will be derived in this master thesis project would probably be placed in an ECU denoted the Coordinator. One of its many tasks is that of a gateway function, connecting the different CAN-buses. If the information from one ECU is needed by the Coordinator, or any other ECU, the signal, defined by the CAN-protocol, is sent over the CAN-bus.

The CAN-bus has a limited bandwidth. Scania uses the SAE J1939/11 standard which transfers up to 250kbit/sec and signals can not always afford to be sent with the highest precision. This means any signal calculated in a different ECU will have an impaired precision, compared to a signal from the same ECU that don't need to be send over a CAN-bus.

2.1.1 Fuel consumed by the engine

The Engine Control Unit estimates the fuel flow in liters per hour $[l/h]$ into the engine cylinders. The fuel is injected directly into the cylinders under high pressure by the fuel injectors. This means the amount of fuel is basically controlled by the time between opening and closing of the injector, [4]. Other influencing factors are the geometry of the injector cam shape, the fact that diesel actually is an incompressible fluid and that its density varies with the temperature.

With these difficulties, the estimate has a slight variance. This variance is approximately $5 - 10\,\%$[1]. This signal is referred to as the *fuelRate*.

2.1.2 Fuel level in tank

The estimation of the fuel level in the tank is done by merging the fuelRate from Section 2.1.1 and the signal from a level measuring device, placed in the fuel tank, [12]. The merging is done using a kalman filter. The estimate is performed in the Coordinator Unit which means that signals could be obtained without lost bandwidth as it would if transferred over the CAN-bus. This signal is referred to as the *fuelLevel* and is denoted V_f.

2.1.3 Vehicle speed

The vehicle speed in kilometers per hour $[km/h]$ is estimated using a tachograph and sent over the CAN-bus. This signal is denoted v.

2.1.4 Vehicle gross train weight

The gross weight of a vehicle combination is estimated by evaluating several sensor signals, such as engine torque, vehicle acceleration, air suspension load information, transmission state of operation and vehicle combination configuration. A large number of estimates are gathered and stored to supply a basis for statistically determining the actual gross combination weight to be used by other functions. The estimation starts immediately when the ignition is turned on and is updated continuously as the vehicle manoeuvres and changes its load or configuration[2]. This signal will be denoted m.

[1] According NME, Emissions and performance group, Scania CV
[2] According to REVM, Vehicle Management Control, Scania CV

Table 2.1. Denotations for different types of fuel consumption.

Denotation	Description
$\gamma_{l/h}$	Raw input signal. Momentary fuel consumption in liters per hour
$\bar{\gamma}_{[unit]}$	A bar above denotes a filtered fuel consumption signal. The unit is either liters per hour *[l/h]* or liters per kilometer *[l/km]*.
$\bar{\gamma}_{mean}$	Mean of raw input signal, in liters per hour, see Equation (2.3).
$\bar{\gamma}_{MA}$	Raw input signal filtered with a moving average, see Equation (2.4).
$\bar{\gamma}_{\lambda}$	Raw signal filtered with a forgetting filter, see Equation (2.6).

2.2 Estimation of fuel consumption

One of the first problems to solve is how to best estimate a representative fuel consumption. For the DTE estimation seen in Equation (2.1), the output signal should be in the unit liter per kilometer as it then, together with a signal of the remaining fuel in liters, easy provides the distance to empty in kilometer.

The different notations for fuel consumption in this chapter are clarified in Table 2.1.

2.2.1 Choice of fuel input signal

The first step in the estimation of the fuel consumption, is to choose an appropriate raw input signal. There are two interesting candidates available: fuelRate described in Section 2.1.1 and fuelLevel described in Section 2.1.2. These two signals have different advantages and disadvantages.

The fuelRate signal would be the logical choice since it is already in the right unit. The fuelLevel is in liters which means that to get the momentary fuel consumption it has to processed as

$$\gamma_{l/h}[k] = 3600 f_s \; (V_f[k-1] - V_f[k]) \tag{2.2}$$

where f_s is the sample time in Hz. There is no guarantee that this signal will be non-negative [12], and since the fuelLevel change at quite low frequency, it could remain negative for some time.

The benefits using the fuelLevel signal is the fact that it is estimated on both the fuelRate signal and the fuel level sensor signal. Thus, for a longer time period, the decrease of the fuelLevel should be considered as a better estimate of the total amount of consumed fuel than the integrated fuelRate signal alone. However, the purpose and thereby the character of the signal differs from that required for this algorithm. Mainly because the level sensor that the fuelLevel signal relies on has discrete steps. For the fuelLevel signal presented to the driver this is sufficient enough, but this algorithm needs a more precise estimate of the momentary consumption to follow the possible changes in the driving behaviour. One disadvantage of not using the fuelLevel signal is the loss of the possibility to take the use of external connected fuel users into account, e.g. external cab heaters which can add up to $1-2\%$ on the fuel consumption[3].

Despite the latter issue, the fuelRate signal will be used as an input to the fuel consumption estimation. For a further discussion of a mix of the two signals, see Section 5.2.

2.2.2 Filtering fuel signal

With the conclusions made in Section 2.2.1, the fuelRate signal will from now on by denoted $\gamma_{l/h}$. As seen in Figure 2.1, the fuelRate signal varies heavily as it alternates between zero and about 100 liter/hour. The goal is to estimate the characteristic fuel consumption, which is not captured in one single momentary value. It is therefore necessary to include fuel consumption values over a longer time period and treat them with some sort of filter. This leads to two questions: how many values should be included and what sort of filter should be used?

A simple alternative would be to include all values by taking the mean of the entire signal. A problem with this method is that, as the number of samples increases, the outputs sensitivity to react to new input data decreases, as seen in Equation (2.3). This result in a more and more steady signal, but also add the risk of missing a distinct change in the pattern of the input signal.

$$\bar{\gamma}_{mean}[k] = \frac{1}{k}\sum_{i=1}^{k}\gamma_{l/h}[i] = \frac{1}{k}\sum_{i=1}^{k-1}\gamma_{l/h}[i] + \underbrace{\frac{\gamma_{l/h}[k]}{k}}_{\to 0 \text{ as } k\to\infty} \tag{2.3}$$

A better choice of method would be to use a moving average filter (MA), taking the mean over a limited horizon looking backwards. The number of sample points or more common in literature, the width W of this time window is crucial; a wider window will give a smoother estimation and a steadier output signal, whilst a smaller window enables the filter to better perceive pattern change in the signal, e.g. when reaching a hillier area. The mathematical expression for the moving average filter, denoted $\mathbf{H}_{MA}$ is given by Equation (2.4), where q is the delay operator defined in [7] and $\bar{\gamma}_{MA}$ is the filtered fuel consumption defined in Table 2.1.

$$\bar{\gamma}_{MA}[k] = \mathbf{H}_{MA}(q)\gamma_{l/h}[k] = \frac{1}{W}\sum_{i=0}^{W-1} q^{-i}\gamma_{l/h}[k] \tag{2.4}$$

[3]Scania System Description - ATA & WTA #1511032

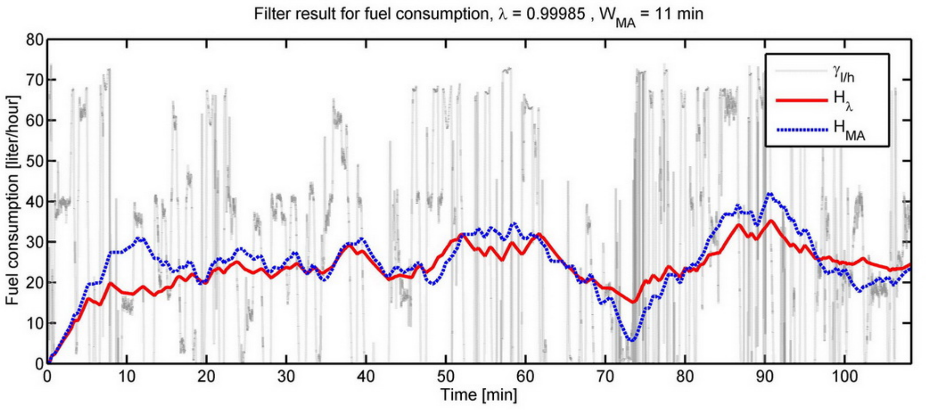

Figure 2.1. Filtering the raw fuel consumption signal, $\gamma_{l/h}$. The usage of a forgetting filter $\mathbf{H}_\lambda$ gives a similar result as using a moving average $\mathbf{H}_{MA}$, but requires substantially less stored data. In this example the window with W_{MA} is set to 11 min which, according to Equation (2.7), corresponds a forgetting parameter $\lambda = 0.99985$.

The problem with a MA filter is the large amount of memory it consumes, which cause a problem for online algorithms. As every value within the time window has to be stored, a window size of $W = 20$ min and a sample frequency of 100 Hz would require 120 000 stored values, each with a high precision. By instead using a so-called forgetting filter, the number of stored values vastly decreases, down to two. This filter can be defined by the recursion

$$\bar{\gamma}_\lambda[k] = \lambda\bar{\gamma}_\lambda[k-1] + (1-\lambda)\gamma_{l/h}[k]\ , \quad 0 \le \lambda \le 1\ . \tag{2.5}$$

Where $\bar{\gamma}_\lambda$ is the filtered value defined in Table 2.1. Letting $\mathbf{H}_\lambda$ denote the filter, Equation (2.5) can also be written as,

$$\bar{\gamma}_\lambda[k] = \mathbf{H}_\lambda(q)\gamma_{l/h}[k] = \frac{(1-\lambda)q}{q-\lambda}\,\gamma_{l/h}[k] \tag{2.6}$$

A forgetting filter can approximate a MA filter and the number of samples included, i.e. the width of the forgetting filter, is by a role of thumb a function of λ according to [6].

$$W_\lambda \approx \frac{1}{1-\lambda} \tag{2.7}$$

The result of the filtering can be seen in Figure 2.1. As a result of the conclusions done in this section, $\bar{\gamma}_{l/h}$ and $\bar{\gamma}_{l/km}$ will from now be notations of signals filtered with the forgetting filter $\mathbf{H}_\lambda$.

2.2.3 Converting to liter per kilometer

To convert the fuel consumption from liters per hour to liters per kilometer, information about the vehicle speed, v, needs to be added. This is done by,

$$\bar{\gamma}_{l/km} = \frac{\bar{\gamma}_{l/h}}{\bar{v}} \ . \tag{2.8}$$

where $\bar{v}$ is the filtered vehicle speed.

If $\bar{\gamma}_{l/h}$ would be filtered with a MA filter with a certain window size W, the logic way would be to apply the same filter to v. This would have been interpreted as, taking the ratio between the mean fuel consumption and mean vehicle speed over the (same) interval W.

The same logic has been applied when using a forgetting filter for $\bar{\gamma}_{l/h}$ as that filter is an approximation to the MA filter. The same forgetting parameter λ is therefore used for $\bar{v}$.

The reason to not use the raw signal values of the inputs in Equation (2.8) and filter the result is that the ratio sometimes, e.g. during idle, would be infinite. This is a problem as the forgetting filter in Equation (2.6) can't recover from an infinite input signal.

2.3 Error propagation

To evaluate the quality of the DTE estimate, given the quality of the input signal, the error propagation in Equation (2.1) will be derived. Even if the exact variance and offset of an input signal is unknown, this will show which signals that will affect the output the most. If combining Equation (2.1) and (2.8), the following expression of the DTE estimate occur,

$$\Gamma_{DTE} = \frac{\bar{v}}{\bar{\gamma}_{l/h}} V_f \tag{2.9}$$

If both $\bar{\gamma}_{l/h}$ and $\bar{v}$ are filtered over a large number of samples ($\lambda \approx 1$), they could be assumed to be unbiased if $\gamma_{l/h}$ and v are unbiased. Any bias will propagate through unscaled. The common error propagation function is defined in [3], for a function f as

$$\Delta f \approx \sum_{j=1}^{n} \frac{\partial f}{\partial x_j} \Delta x_j \ . \tag{2.10}$$

With the set $x \in \{V_f, \bar{v}, \bar{\gamma}_{l/h}\}$, the partial derivatives of Equation (2.10) becomes,

$$\frac{\partial f}{\partial x} = \begin{pmatrix} \frac{\bar{v}}{\bar{\gamma}_{l/h}} \\ \frac{V_f}{\bar{\gamma}_{l/h}} \\ -\frac{V_f \cdot \bar{v}}{\bar{\gamma}_{l/h}^2} \end{pmatrix} \tag{2.11}$$

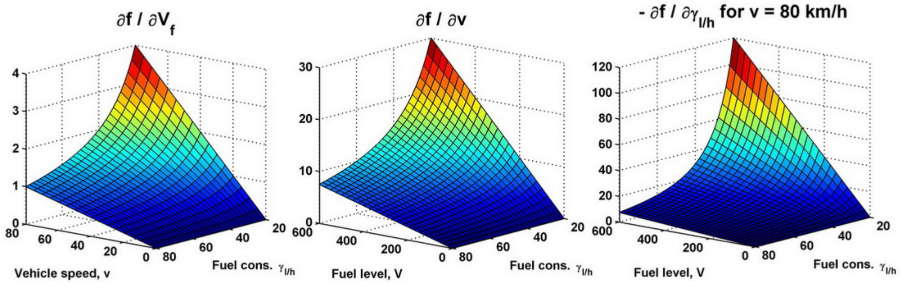

Figure 2.2. The figure shows the partial derivative of the input signals of the DTE estimate, in the order left to right: V_f, $\bar{v}$ and $\bar{\gamma}_{l/h}$. The Z-axis shows how much an input error of one unit step affect the DTE. In the last sub plot the vehicle speed has been locked on 80 km/h.

These partial derivatives are plotted in Figure 2.2 for different ranges of x. Note that the last sub plot, $\partial f/\partial\bar{\gamma}_{l/h}$, is plotted without the negative sign and with a fixed vehicle speed, v = 80 km/h. The Z-axis shows the contribution to the error of Γ_{DTE} for one unit of the error of that specific input signal, as seen in Equation (2.10). Although the effect of V_f seems negligible, it can still have som effect on Γ_{DTE} as the absolute error of V_f probably is larger than that of $\bar{\gamma}_{l/h}$ and $\bar{v}$. A set of numeric examples from Equation (2.11) is shown in Table 2.2. These examples are calculated from Equation (2.11). They show, as can be seen

Table 2.2. The table shows in three different examples how much an input error of one unit step affect the DTE. For each input signal, the other two input signals are assumed to have correct value.

Ex.nr.	ΔV_f	$\Delta\bar{v}$	$\Delta\bar{\gamma}_{l/h}$	Γ_{DTE}
#1	± 3.2 km	± 16 km	± 51.2 km	1280 km
#2	± 2.8 km	± 27.5 km	± 75.6 km	1500 km
#3	± 3.4 km	± 4 km	± 13.6 km	340 km

#1	$V_f = 400\ l,\ \bar{v} = 80\ km/h,\ \bar{\gamma}_{l/h} = 25\ l/h$
#2	$V_f = 550\ l,\ \bar{v} = 55\ km/h,\ \bar{\gamma}_{l/h} = 20\ l/h$
#3	$V_f = 100\ l,\ \bar{v} = 85\ km/h,\ \bar{\gamma}_{l/h} = 25\ l/h$

in Figure 2.2, that Γ_{DTE} is quite sensitive to errors in the input signals but that the sensitivity variates with the value of them.

Another option is to study at the relative error, defined in [3] as,

$$\frac{\Delta\Gamma_{DTE}}{\Gamma_{DTE}} \leq \left|\frac{\Delta V_f}{V_f}\right| + \left|\frac{\Delta\bar{v}}{\bar{v}}\right| + \left|\frac{\Delta\bar{\gamma}_{l/h}}{\bar{\gamma}_{l/h}}\right| . \tag{2.12}$$

This usually gives a pessimistic estimation of the relative error. No data of the relative errors of the signals in set x is presented here. But Equation (2.12) however states that the relative error of the DTE never can exceed the sum of the relative errors of the input signals. This is important as it gives an upper limit of the relative error.

2.4 TTE: Handling low velocities and idling

The distance to empty (DTE) signal estimates the remaining distance based on a characteristic fuel consumption [l/km] and the current fuel level V_f. Problem occurs when the vehicle speed is close to zero. A low or zero vehicle speed while the engine is running, thus consuming fuel, results in a high or infinitive fuel consumption, if given in liter per kilometer.

One solution would be to use the mean or freeze the latest filtered fuel consumption, as soon as the speed drops below a certain level, and use that value together with the current fuel level to estimate the DTE. This holds, if the idle or low speed period is short (a few minutes) but for heavy vehicles it is common to operate for long times in this condition. Therefore, if not handled, the estimated DTE would be misleading. In these cases, a better solution would be to estimate and present the *time to empty (TTE)* rather than the DTE.

The TTE mode will in this thesis work be treated as a complement to the DTE, which always will be considered as the prime mode. There is however other alternatives available.

1. Constant use of the DTE mode.
2. Constant use of the TTE mode.
3. Use of both modes: Switch controlled by online algorithm.
4. Use of both modes: Switch controlled by driver.

With 3 as the standard choice alternative, 1 and 2 could be done by changing the settings at a service hall or by the driver. Alternative 4 could seem handy, but add another task to all the things a driver needs to keep under control. As mentioned, this thesis work will treat alternative 3. The switch between DTE and TTE modes will be controlled by an online algorithm and never be under the direct influence of the driver.

2.4.1 Mode switch algorithm

The description of the algorithm for this switch between DTE and TTE is left out in this thesis version as it is currently part of a possible patent application. For the full text version, please contact REVM, Scania.

2.4.2 TTE estimation

The TTE is calculated in similar way to the DTE in Equation (2.1). The main difference is that it is based on the fuel consumption in liter per hour instead of liter per kilometer. The equation for calculating the TTE, denoted Γ_{TTE} is,

$$\Gamma_{TTE} = \frac{V_f}{\bar{\gamma}_{l/h}} \text{ [h]} . \tag{2.13}$$

2.5 Mapped fuel consumption

Sometimes, there isn't enough valid information to base the estimate of the characteristic fuel consumption for the trip on. To compensate for this, a pre-stored fuel consumption map is used. This will be used mainly during the first minutes of the trip, but also when a greater change in the conditions has occurred, e.g. reloading.

As the fuel consumption while driving and idling differs substantially, the fuel consumption map needs to separate the DTE and the TTE cases. The difference between these maps will be pointed out below.

2.5.1 Map input

To store a map or model that accounts for every input that could possible affect the fuel consumption would be taking it to the extreme. The focus should instead be on one or maybe a few parameters, that affect the fuel consumption the most.

One such parameter is the vehicle weight. The total weight, or train weight, of a vehicle can vary significantly from unloaded up to 60 ton for long haul transports. To evaluate the affects of a load change, data from several test runs with different weights are collected. The tests are run in a test hall where a real trucks driveline are disconnected from the wheels and mounted to a brakesystem. The truck is then driven against a pre-stored drivecycle. The effect of different loads can be seen in Figure 2.3.

Another parameter that affects the fuel consumption is the temperature. A cold vehicle consumes more fuel than a heated one[4]. Moreover, cold tires increase the rolling resistance for some time before they by friction reach a steady state temperature. However, these increases in fuel consumption are only visible in the beginning of a route and since no information about how long the driver intend to

[4]According to NMGF, Scania CV

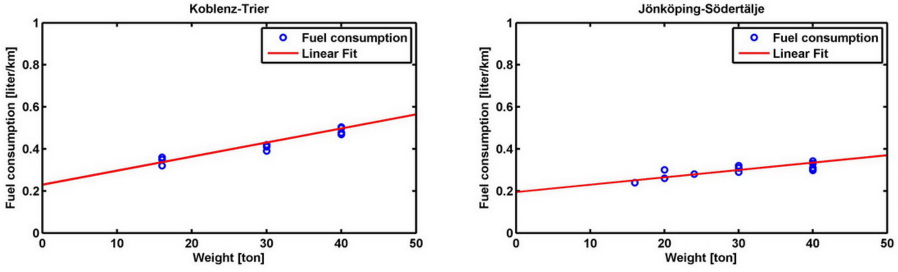

Figure 2.3. Mean fuel consumption for two different routes: Koblenz-Trier and Jönköping-Södertälje. As seen, different vehicle weights has a clear impact on the fuel consumption. However, to describe the relationship, a linear approximation seems to be sufficient. Koblenz-Trier is a hillier route which is seen by the higher overall fuel consumption.

drive exist, we can not adjust for them. The effects of a cold vehicle will therefore be neglected.

The air pressure in the tires will also affect the fuel consumption. In this thesis it is however assumed that the driver or haulier company is well aware of this and keep a good tire pressure. Therefore, the map will only have one single input parameter: the vehicle train weight.

The DTE and TTE maps will have the same input signal. Although the vehicle weight effect on the idle fuel consumption probably is limited, the TTE is also operational at low speed.

2.5.2 Storage of the map

Preferably, the map would have a high grid resolution. Though, as the storage space is limited, a better way would be to model the fuel consumption as a function of the weight, $\gamma_{map} = f(m)$. This way a continuous function is achieved, with a limited number of parameters. When studying Figure 2.3, it is clear that a linear fitting is sufficient. Thereby, the storage requirement is only two parameters, $c = [c_1\ c_2]$.

$$\gamma_{map} = c_1 \cdot m + c_2 \tag{2.14}$$

Two separate parameters will be used to represent the TTE map.

2.5.3 Control of map mode

To control when the stored map will be used, an algorithm based on DTE/TTE switch algorithm from section 2.4, is applied. As the algorithm in that section has been censored, a simplified version of the map control algorithm will be shown here.

There are two different maps to control, one for DTE and one for TTE. They will be used in those moments the information about the fuel consumption in the respective mode is insufficient. When the map becomes active, a timer will be initiated. As long as this timer stays below a threshold value T_{MAP}, the map will be active.

The reset condition seen in Figure 2.4 could be triggered by any action controlled by the algorithm but will from now on be linked with a weight change detection. If the conditions of $M = 1$ are fulfilled when the map already is active, e.g. due to a weight change detection, the timer will be reset. The logic scheme for the whole algorithm is seen in Figure 2.4.

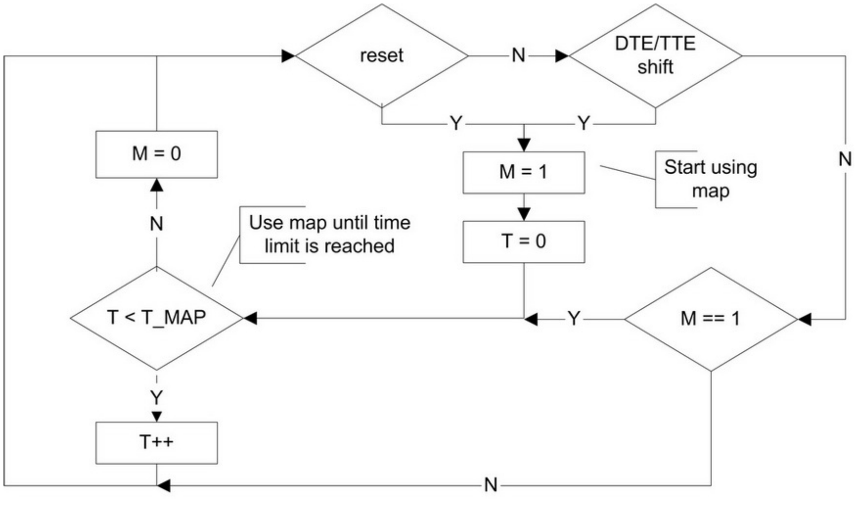

Figure 2.4. The logic scheme for control signal M. M is set to TRUE (1) at a reset or a when a switch between DTE and TTE occurs. When this is done, a timer (T) is reset, and M will stay TRUE until $T > T_{MAP}$. The algorithm is initiated with the reset condition set TRUE.

2.5.4 Faster filters at map use

As mentioned above, the reason for the existence of the map is to give the fuel consumption estimate time to adapt. By using a faster filter parameter λ during the time the map is active, the mapping time can be reduced. The method is simple: when the mapping mode is activated a timer is initiated. As long as the timer has not reached its maximum value, the faster filter will be used.

2.5.5 Adaptive map

As the fuel consumption vary with a lot of different parameters, e.g. vehicle weight, engine type, route, it would be unrealistic to make a general map that covers all different cases. Instead, the idea is to make the map good enough to fit the average vehicle and average route, and then online, letting the algorithm slowly adapt the map parameters with the current weight and the mean fuel consumption for the particular vehicle.

The method to make this adaptation is not shown here as it is part of a possible patent application.

2.6 Final adjustments of the output

The calculated signals Γ_{DTE} and Γ_{TTE} in Equation (2.1) and (2.13) undergoes some adjustments before being presented to the driver. These changes can be divided into different parts:

- Low fuel uncertainty compensation
- Smoothing of the signal
- Applying hysteresis effect

Note that most operations in this section are more practical than theoretical. A great amount of time should be spent to fine tune the parameters before a customer release. In the examples below, there is no guarantee that the optimal parameter choice has been made, but the methodology is still of interest.

2.6.1 Low fuel compensation

When the fuel level in the vehicle approaches a critical level, the zero level of the DTE/TTE estimation will risk being within the margin error of the output. This results in a problem as the vehicle could run out of fuel before the estimation predicts it. A situation with low fuel level is shown in Figure 2.5.

As seen in the Figures 2.5 and 2.2, the largest uncertainty factor here is the variation in the fuel level, as the possible error in fuelRate diminish when the fuel level approaches zero. In Figure 2.5 the fuelLevel signal (V_f) is compared to a linear approximation of it, V_f^{linear}. The difference between these two signals mainly stays within 2 liters. This is sufficient, but more interesting when the fuel level approaches a critical level is the relative error,

$$e_{rel} = \left| \frac{V_f - V_f^{linear}}{V_f} \right| \tag{2.15}$$

which increases significantly as the fuelLevel approaches zero. This is bad since the relative error of XTE also will increase. Near this critical level the driver will probably be planning a stop on available refueling stations and a precise estimation is of great value. It must by all cost be avoided to show a positive value of Γ while out of fuel.

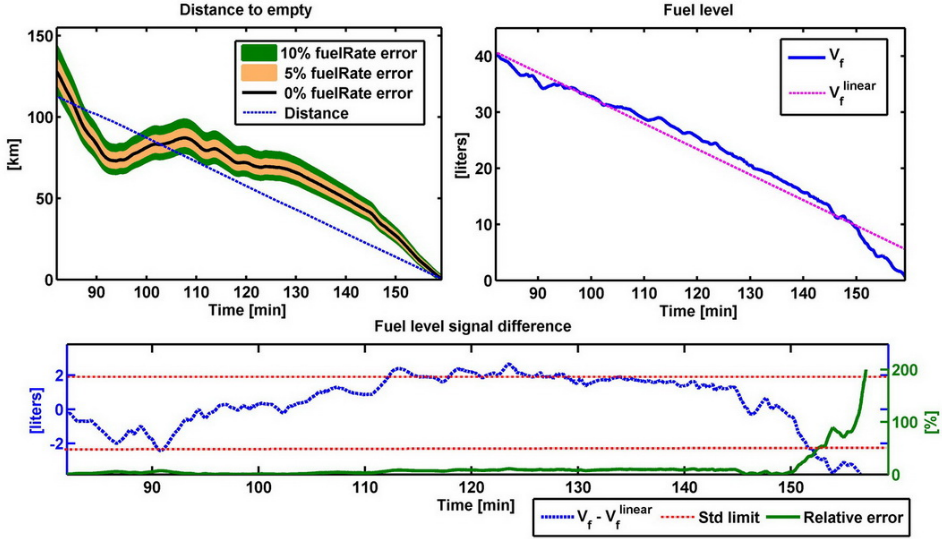

Figure 2.5. The upper left figure shows the DTE estimation together with its margin error. The dashed blue line is the accumulated distance withdrawn from a chosen start point. The upper right figure shows the fuelLevel and how it differs from a linear approximation. In the bottom figure that difference is analyzed. It shows the difference, the standard deviation and the relative error.

To compensate for the smaller margins in this situation, a pessimistic adjustment will be made to the estimated DTE/TTE output by lowering it.

Two design parameters are present here; the *lowFuelLimit* in liter or percent and the *pessimisticAdjustmentSize* in percent. The lowFuelLimit is the trigger level for the algorithm. It reacts when the fuel tank level drops below the threshold. This level needs to be set as small as possible to avoid unnecessary compensation. But still, large enough to avoid the margin error from reaching a zero level. The pessimisticAdjustmentSize determines how much of the DTE/TTE signal that should be kept.

In Figure 2.6, a simulation where this method is implemented is shown. Here the lowFuelLimit is set to 6% and the pessimisticAdjustmentSize to 60%. In the 99th minute, the fuel level reaches the 6% of its max level and the raw DTE signal instantly drop 60%.

2.6.2 Smoothing of the signal

The result presented to the driver should not vary too heavily. As mentioned in Section 1.3, this could lead to a mistrust of the output. It would therefore be logical to smooth the signal.

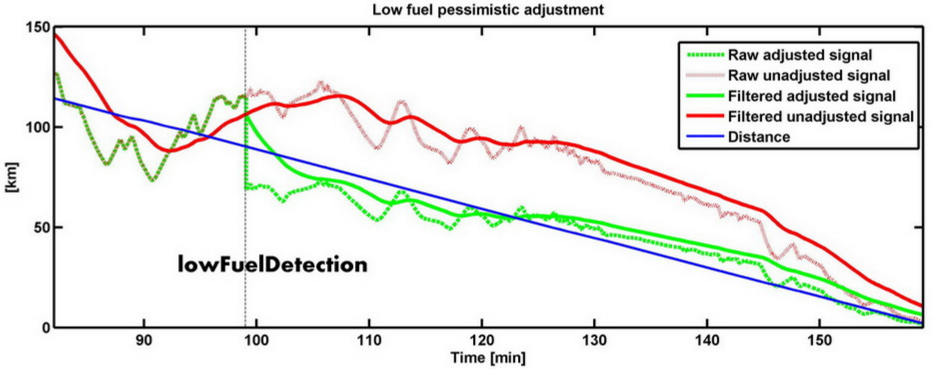

Figure 2.6. Figure showing the same case as in Figure 2.5, but here an uncertainty adjustment is done when the fuel level in the 99th minute reaches 6% of its max level. The raw DTE signal is then reduced to 60% of its value, whilst the filtered signal adapting more smoothly.

The smoothing is done by applying a forgetting filter,

$$\bar{\Gamma}[k] = \lambda \cdot \Gamma[k-1] + (1-\lambda) \cdot \Gamma[k] \ . \tag{2.16}$$

The result of this could be seen in Figure 2.6. The filter parameter λ should be tuned so that it follows the distinct changes in Γ but ignores the smaller, faster oscillations. The filter is especially important to get a smooth transition from the mapped to the estimated fuel consumption value when switching from mapping mode.

When a switch between the DTE and TTE mode occurs, the filter is bypassed one sample to quickly adjust to the new mode.

2.6.3 Applying hysteresis effect

By displaying the output $\bar{\Gamma}$ in Equation (2.16) in discrete steps, the driver obtain the insight that the displayed value is rounded and that the true value can differ slightly. The step size is set to 10 km since estimates below that limit are too uncertain.

A hysteresis effect is applied to the signal, so that a discrete step is taken only when it is certain that the signal tend to that value. An example of this can be seen in Figure 2.7.

2.7 Weight change detection

As seen in Section 2.5.1, the weight of the vehicle has a major effect upon the fuel consumption. Therefore, it would be desirable to be able to detect a larger weight

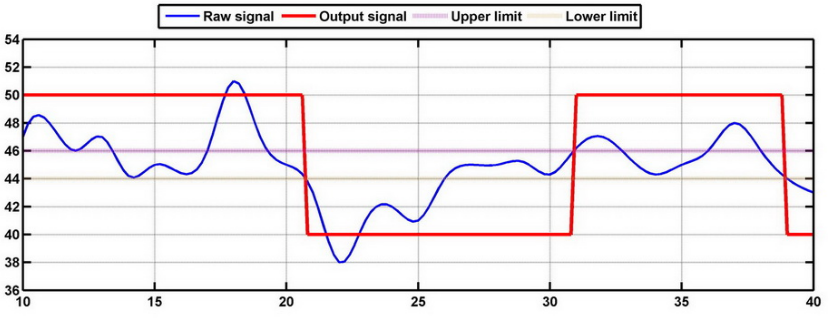

Figure 2.7. Figure showing how the output is presented in discrete steps of 10 km. The hysteresis effect ensures that the step up occurs when above 60% of the step size and the step down occurs when below 40% of the step size.

change. The input signal is the grossTrainWeight signal described in section 2.1.4. The signal during a test run is seen in Figure 2.8 where three weight changes occur: one reloading and one unloading.

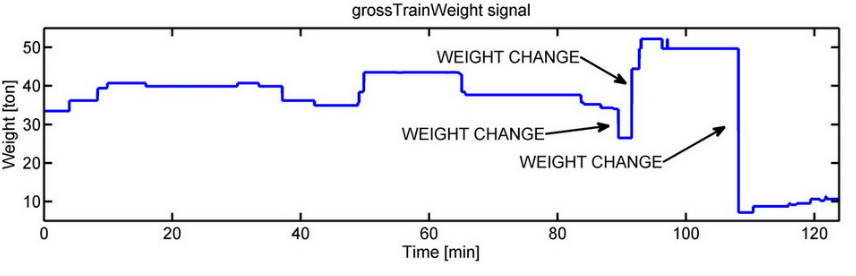

Figure 2.8. The grossTrainWeight signal from a two hour data sample. The vehicle starts with a lighter load, switches to a heavier and then unload it all.

2.7.1 Detection algorithm

To detect a change, a simple model of the measurements is considered.

$$y = \theta + e \tag{2.17}$$

In the measurement, y, an error is added to the true weight, θ. The error, e, may be dependent on several different parameters, e.g. vehicle speed or road slope. A more theoretically analysis is left out here and it is just considered to be an unknown error.

Since there are two possible outcomes, where either a change has occurred or has not, a hypothesis test is constructed, see [5]. The two hypotheses states

$$\begin{array}{ll} H^0: & \text{No change in } \theta \\ H^1: & \text{A change in } \theta \end{array} \tag{2.18}$$

By finding a test quantity, $T(y)$, and comparing it to a threshold value, J, a decision whether to reject H^0 or not can be made. The procedure is to reject H^0 only if the test quantity exceeds the threshold value, all according to

$$\begin{array}{lll} T(y) \leq J & H^0 \text{ is accepted} & \\ T(y) > J & H^0 \text{ is rejected} & \Rightarrow H^1 \text{ is accepted} \end{array} \tag{2.19}$$

The test quantity should be sensitive to distinct, low frequency changes but without reacting to measurement error of higher frequencies. When studying Figure 2.8 one can see that the signal can vary quite a lot, though the real weight does not change. By taking the mean value of the signal the true value is estimated. The test quantity $T(y)$ is then computed by taking the difference between that mean value and a smoothing of the current measurement signal, eq. (2.20). By smoothing it with a forgetting filter, $\mathbf{H}_\lambda$, defined in Equation (2.6), $T(y)$ is prevented from reacting to high frequent measurement errors.

$$T(y)[k] = \left| \frac{1}{k} \sum_{i=1}^{k} y[i] - \mathbf{H}_\lambda(q) y[k] \right| \tag{2.20}$$

The size of the threshold is determined by studying experiments and manually tune the parameter. As noticed in Section 2.5, a small weight change doesn't affect the fuel consumption enough to make a recalculation necessary. Hence, a larger threshold can be chosen.

An important step is to reset the test quantity calculation and consider a new hypothesis test as soon as a weight change has been confirmed. By doing so the detection signal stays high only during one sample interval.

2.7.2 Result

In Figure 2.9 the algorithm is applied on the gross train weight signal in Figure 2.8. As seen the mean value changes instantly as soon as a detection is confirmed. Only the last two weight changes are detected, but as the first one together with the second one is part of a reloading, that is accepted. With several weight changes occurring close in time, there is no need to detect any but the last. But as seen in Figure 2.9, the unloading at the 90th minute would have been detected within a few minutes if no reloading had been done.

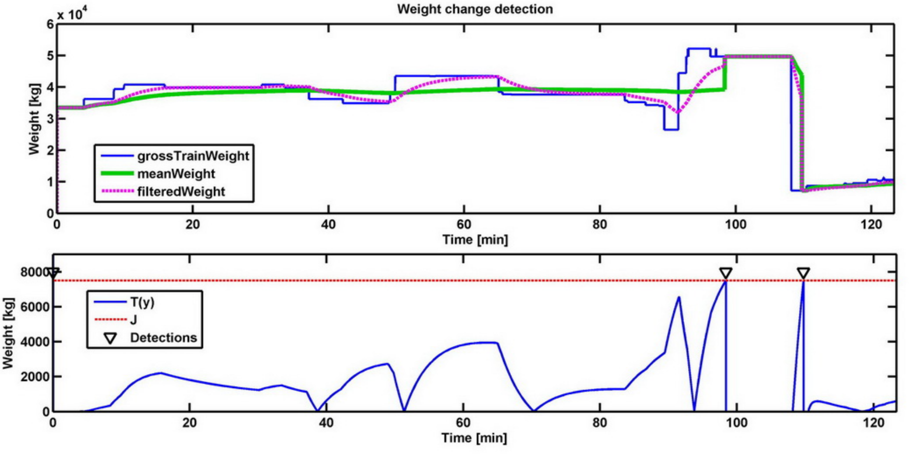

Figure 2.9. Figure showing the weight detection algorithm. The top figure shows the grossTrainWeight signal together with the two components in the test quantity. At a detection alarm these signals reset to the original signal values. The figure below shows the test quantity and the threshold limit. A detection is registered at 98.4 min and again at 109.7 min, the initial detection is just part of an initial reset.

Chapter 3

Result

To test the method described in Chapter 2, the algorithm will be simulated with real vehicle data. The data is logged from test drives of different routes in Sweden and Europe. The simulations are done by implementing the model in SIMULINK and using the logged data as input signals.

One large issue in this thesis work is the validation of the method. The DTE estimate is actually a prediction and can never be anything but just a guess, based on information of the past. But as the number of important parameters, such as topography of route ahead, driving behaviour and future surrounding traffic events, at this time is unknown, the prediction can turn out to be very bad.

Therefore, before judging the result it must be determined if the conditions have changed too much to expect the initial estimation to be in line with the final result. If the conditions are consistent, a useful measurement would be to compare the decrease of the DTE to the increase of distance. But as it is easier to compare two signals changing in the same direction, a measurement where the accumulated distance is withdrawn from a chosen initial level will be used instead. This measurement, D, is defined by,

$$D(t) = D_0 - \int_0^t v(x)dx \tag{3.1}$$

where D_0 is the initial level and v the vehicle speed. D_0 should be chosen so that the gradienst of $\bar{\Gamma}_{DTE}$ and D are easy to compare.

Below a number of different test routes are presented. They all have different difficulties which need to be compensated for.

3.1 Route: Södertälje - Vagnhärad

The first route to test is that from Södertälje to Vagnhärad and back again, a total distance of 56 km. The route can be divided into different parts, both seen in Figure 3.1 and described below:

1. Start-up phase. Driving from Scania in Södertälje
2. Highway. 26 km on the E4 highway south to Vagnhärad.
3. Turing around by driving 4 km through Vagnhärad industrial area.
4. Highway. Return journey to Södertälje
5. Cool-down phase. Back at Scania, Södertälje.

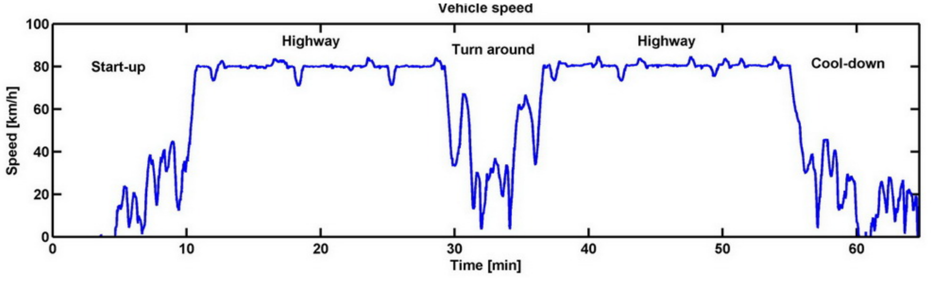

Figure 3.1. The character of the test route: Södertälje–Vagnhärad. The figure shows the vehicle speed together with a description of the different parts of the route.

The estimated fuel consumption for this route can be seen in Figure 3.2. It shows the fuel consumption estimate in liters per hour, $\bar{\gamma}_{l/h}$, the equivalent filtering of the vehicle speed, $\bar{v}$, and the ratio of those two, $\bar{\gamma}_{l/km}$. Initially, the faster filter described in Section 2.5.4, is applied, shown by a coloured area in the last sub plot. After 10 minutes the faster filter is applied again as the map is used once more. As seen in the coloured areas, both $\bar{\gamma}_{l/h}$ and $\bar{v}$ are more sensitive to changes in the raw signal. When the steady filter is used during the 6th to 10th minute and from the 16th minute and forward, the output is smoother and less sensitive to changes in the raw signal.

The result of a steadier filter is seen as there is no immediate effects in $\bar{\gamma}_{l/km}$ by the shorter turn around period between 35 and 40 minutes. When $\bar{v}$ drops, so does $\bar{\gamma}_{l/h}$, thereby preserving the ratio $\bar{\gamma}_{l/km}$. The fuel consumption $\bar{\gamma}_{l/h}$ during the return journey is slightly lower, probably as a result of the road topography. This results in a lower $\bar{\gamma}_{l/km}$. Also seen in that figure is the mean fuel consumption calculated over the whole horizon at that time, see Equation (2.3). Comparing this signal to $\bar{\gamma}_{l/km}$ shows that the latter is a good approximation to the mean value during the period of consistent driving conditions (10–30 min and 35–55 min). But it will still have the advantage of being sensitive to larger changes in the raw signal.

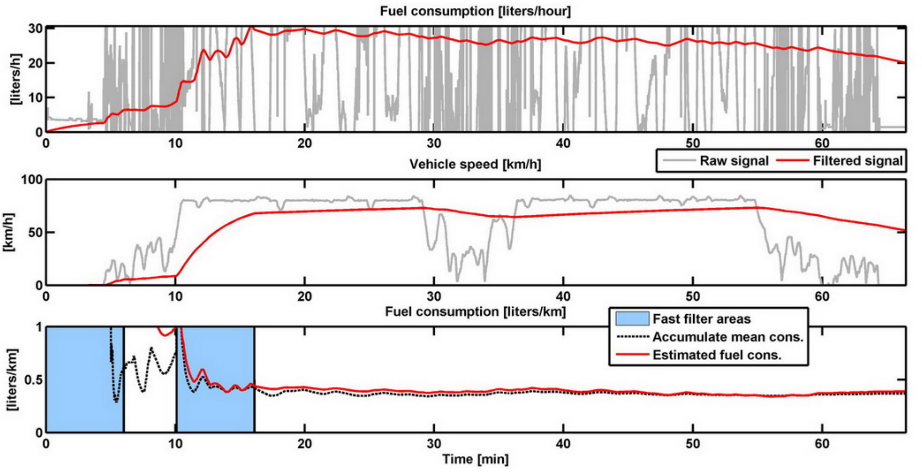

Figure 3.2. The filter result from the raw signals $[\bar{\gamma}_{l/h}, \bar{v}]$ and the estimation of $\bar{\gamma}_{l/km}$ on route Södertälje–Vagnhärad. The coloured areas in the last subfigure (0–6 and 10–16 min) indicates that a faster filter parameter is used. The dashed line in the last sub plot is the mean value described in Equation (2.3).

The final result, that is the displayed DTE or TTE output, is seen in Figure 3.3. The DTE and TTE are presented in the same axis, so the unit should be read as either a distance [km] or a time [h].

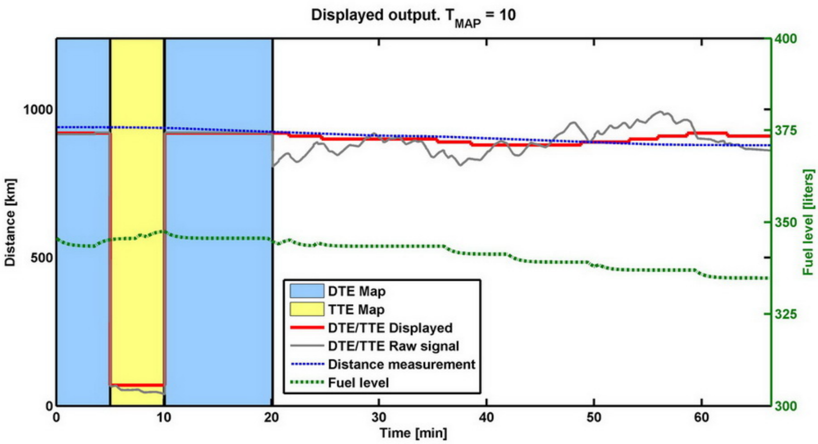

Figure 3.3. Figure showing the estimated raw value of the DTE/TTE together with the smoothened, displayed version. The coloured areas indicate the usage of DTE map (0–5 and 10–20 min) and TTE map (5–10 min). When TTE is active the unit of the output is switched to hours. The dashed line is the inverted distance in Equation (3.1).

By default, the DTE map is used to produce an initial estimate of the mean fuel consumption for the first 5 minutes. But since the vehicle remains still for a longer period, a switch is made to the TTE mode. As before, a map value is used initially. At the 10th minute, when the vehicle has gained speed, the algorithm switches back to DTE mode and reset the timer of the DTE map. At the 20th minute the timer exceed T_{MAP} and the raw DTE value from Equation (2.1) will be used instead of the map value.

As a result of the lower $\bar{\gamma}_{l/km}$ during the return journey, the DTE estimate will actually increase during the route. The dashed line in the Figure 3.3 is the measurement signal, D, described by Equation (3.1). The output deacrease in the same pace D from the 20th to the 50th minute but then raises to a level slightly above due to the lower fuel consumption on the return route.

3.2 Route: Södertälje-Vagnhärad, country road

The second route also stretches out to Vagnhärad. The return however, is a smaller country road up to Hölö before it rejoins with the E4 highway, a total distance of 60 km. It also contains an idle period and a longer cool-down phase to illustrate the idling behaviour. Last, a reload is done. The route can be divided into different parts, both seen in Figure 3.4 and described below:

1. Start-up phase. Driving from Scania in Södertälje
2. Highway. Going 26 km on the E4 highway south to Vagnhärad.
3. Country road. Driving 22 km on country road to Hölö.
4. Stop. Stops in Hölö on idle for 5 minutes.
5. Highway. Going back 12 km on E4 highway to Södertälje.
6. Cool-down-phase. Idle and low speed driving inside Scania area, Södertälje.
7. Reload. A major weight change of the load.

The estimated fuel consumption for this route can be seen in Figure 3.5. It shows the fuel consumption estimate in liters per hour, $\bar{\gamma}_{l/h}$, the equivalent filtering of the vehicle speed, $\bar{v}$, and the ratio of those two, $\bar{\gamma}_{l/km}$.

The faster filter is used in the coloured areas (0–10 min, 76–86 min and from 99 min). As it is switched off, the more steady filter is applied, giving a smoother but less sensitive filter result. This is seen in the short break in Hölö, where 5 minutes isn't enough to affect the output. As both $\bar{\gamma}_{l/h}$ and $\bar{v}$ decrease at about the same rate, the ratio between stays rather steady. Only a slight increase is seen on $\bar{\gamma}_{l/km}$ shortly after the brake.

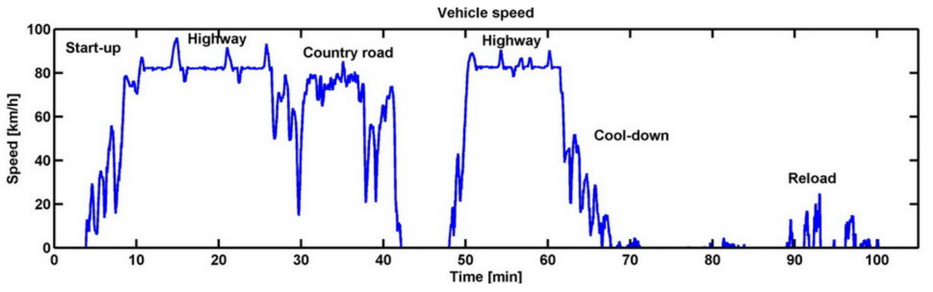

Figure 3.4. The character of the test route: Södertälje–Vagnhärad, Country road. The figure shows the vehicle speed together with a description of the different parts of the route.

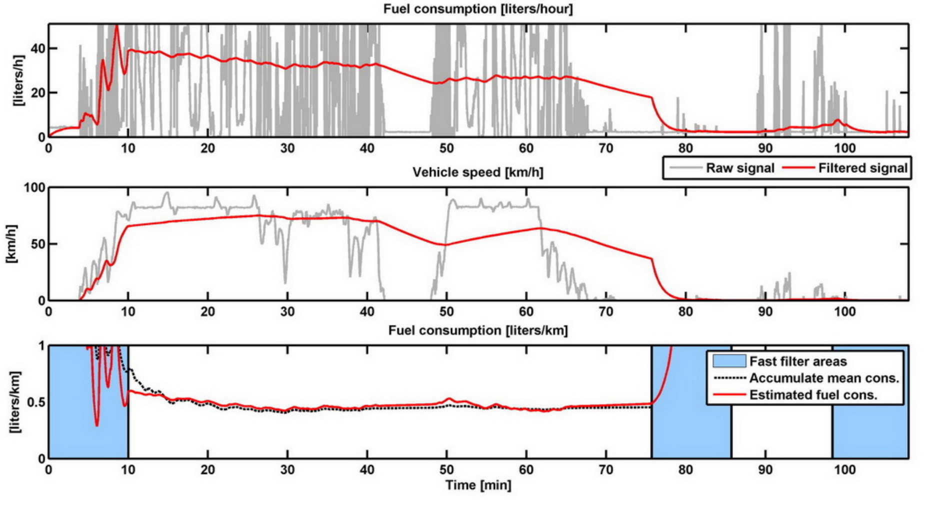

Figure 3.5. The filter result from the raw signals $[\bar{\gamma}_{l/h}, \bar{v}]$ and the estimation of $\bar{\gamma}_{l/km}$ on route Södertälje–Vagnhärad, country road. The coloured areas in the last subfigure (0–10, 76–86 and from 99 min) indicates that a faster filter parameter is used. The dashed line in the last sub plot is the mean value described in Equation (2.3).

The DTE/TTE output is seen in Figure 3.6. Initially, the DTE map is used to estimate the mean fuel consumption. Here, the vehicle gain speed quick enough to stop a switch to the TTE mode as done in Figure 3.3. After 10 minutes, the map is switched off and the raw DTE value from Equation (2.1) is used as an input to the smoothing filter. When reaching Södertälje both the raw signals decrease quickly to finally end up in idle mode. In the 76th minute the TTE mode is initiated. This means the faster filter is used again, quickly increasing $\bar{\gamma}_{l/km}$ as $\bar{\gamma}_{l/h}$ goes toward idle consumption but $\bar{v}$ goes toward zero. A weight change is detected in 99th minute which result in a use of a mapped fuel consumption for a few minutes.

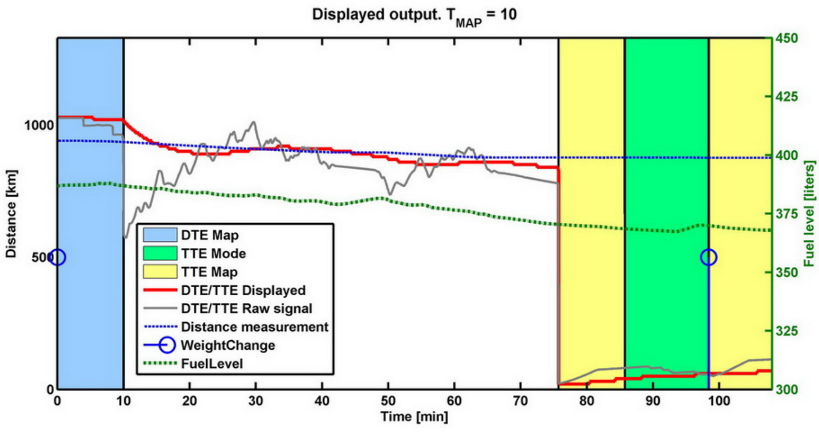

Figure 3.6. Figure showing the estimated raw value of the DTE/TTE together with the smoothened, displayed version. The coloured areas indicate the usage of DTE map (0–10 min), TTE map (76–86 and from 99 min) and TTE mode (86–99 min). When TTE is active the unit of the output is switched to hours. The dashed line is the inverted distance in Equation (3.1).

The dashed line in the figure is the distance measurement signal, D, described by Equation (3.1). The output decrease in about the same pace as D, though the initial DTE map estimate is a bit high.

3.3 Route: European highway

The third test route is based on data logged during a summer logging session done in Europe 2008. It consists of mainly highway driving on Autobahn, with occasional exceptions. The route is seen in Figure 3.7 and described below:

1. Highway. 104 km.
2. Short brake. Stops for 1 min.
3. Highway. 142 km.
4. Low speed area. Pulling of the highway for 20 minutes.
5. Highway. 33 km.

The estimated fuel consumption for this route can be seen in Figure 3.8. It shows the fuel consumption estimate in liters per hour, $\bar{\gamma}_{l/h}$, the equivalent filtering of the vehicle speed, $\bar{v}$, and the ratio of those two, $\bar{\gamma}_{l/km}$.

In this test, as the vehicle initially has a high speed, it can be seen as if a reset was done to the algorithm. Again, the faster filter is used initially. The shorter brake at the 73rd minute pass without any major change in $\bar{\gamma}_{l/km}$. At the low

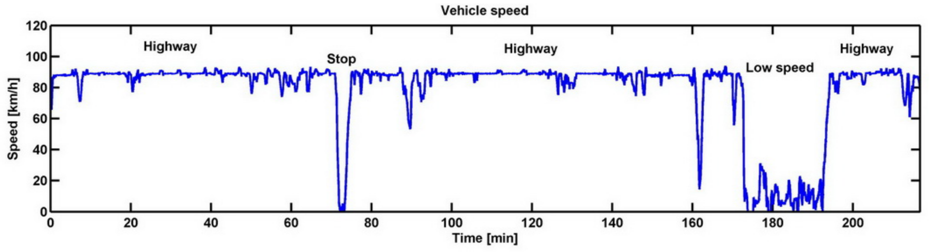

Figure 3.7. The character of the test route: European autobahn. The figure shows the vehicle speed together with a description of the different parts of the route.

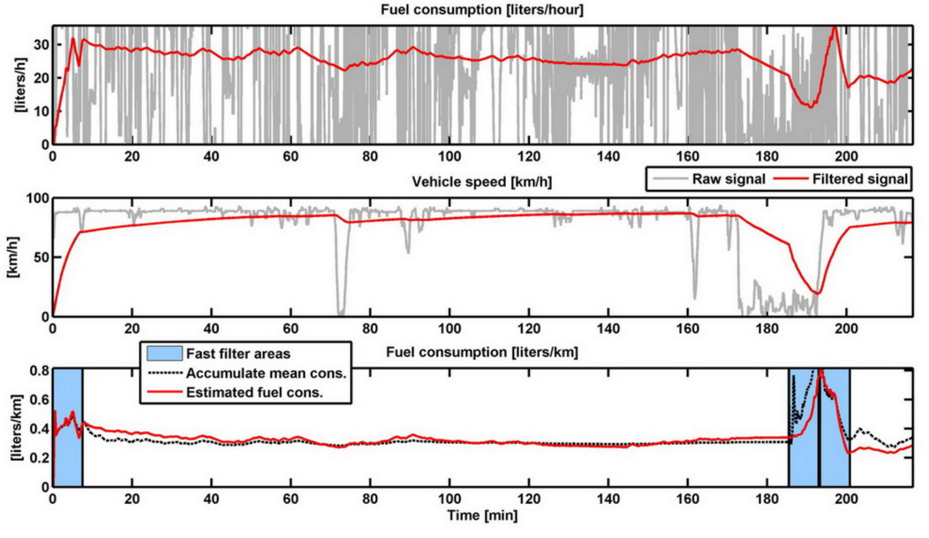

Figure 3.8. The filter result from the raw signals $[\bar{\gamma}_{l/h}, \bar{v}]$ and the estimation of $\bar{\gamma}_{l/km}$ on route European highway. The coloured areas in the last subfigure (0–6 and 186–200 min) indicates that a faster filter parameter is used. The dashed line in the last sub plot is the mean value described in Equation (2.3).

speed area, $\bar{\gamma}_{l/km}$ increase slightly, indicating a higher mean consumption in liters per kilometer for these driving pattern.

Figure 3.9 shows the DTE/TTE signal. The decrease pace of the displayed output should be compared to the measurement signal D, defined in Equation (3.1). At the low speed area the TTE mode is soon triggerd, but a switch is made back to DTE mode shortly after, as the vehicle gain speed again. This result both in a use of the DTE map as well as a faster filter, seen at the 95th minute in Figure 3.8.

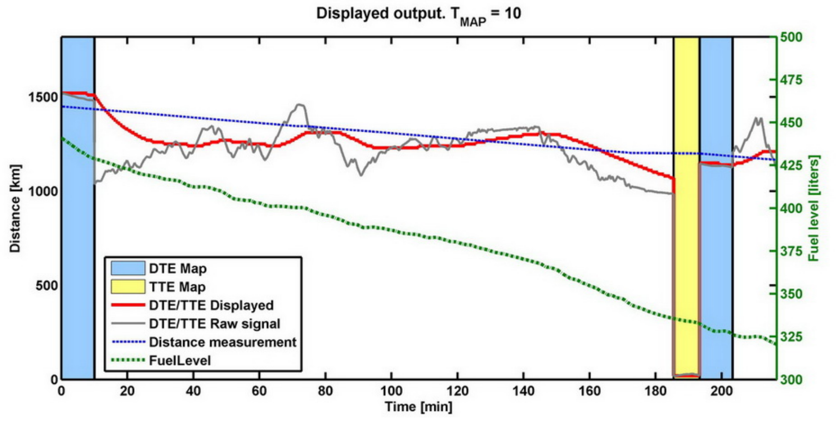

Figure 3.9. Figure showing the estimated raw value of the DTE/TTE together with the smoothened, displayed version. The coloured areas indicate the usage of DTE map (0–10 min and 195–205 min) and TTE map (186–195 min). When TTE is active the unit of the output is switched to hours. The dashed line is the inverted distance in Equation (3.1).

3.4 Route: European highway 2

The final test route is, as the previous, based on data logged during a summer logging session in Europe 2008. It consists of mainly highway driving on a European highway, but the route ends with a longer part of mixed speed driving. The route is seen in both Figure 3.10 and described below:

1. Start-up phase. Start from rest.
2. Highway. 185 km.
3. Short brake. Stops for about 5 min.
4. Mixed speed. 100 km

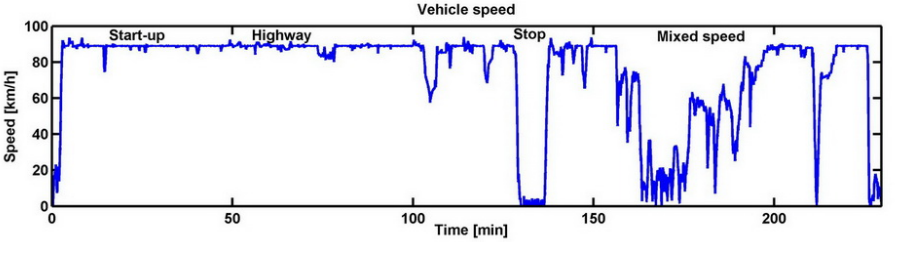

Figure 3.10. The character of the test route: European highway 2. The figure shows the vehicle speed together with a description of the different parts of the route.

The estimated fuel consumption for this route can be seen in Figure 3.11. It shows the fuel consumption estimate in liters per hour, $\bar{\gamma}_{l/h}$, the equivalent filtering of the vehicle speed, $\bar{v}$, and the ratio of those two, $\bar{\gamma}_{l/km}$.

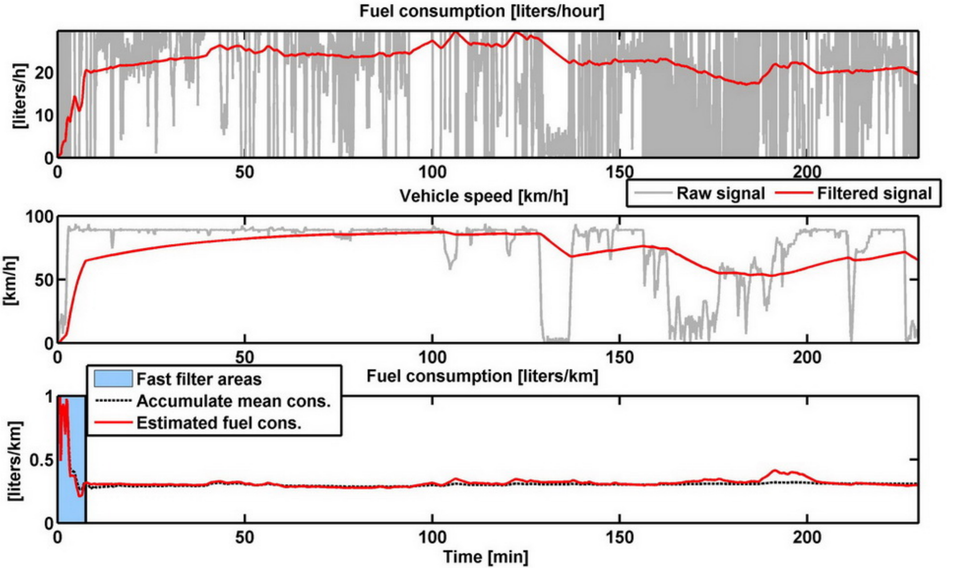

Figure 3.11. The filter result from the raw signals $[\bar{\gamma}_{l/h}, \bar{v}]$ and the estimation of $\bar{\gamma}_{l/km}$ on route European highway. The coloured area in the last subfigure (0-6 min) indicates that a faster filter parameter is used. The dashed line in the last sub plot is the mean value described in Equation (2.3).

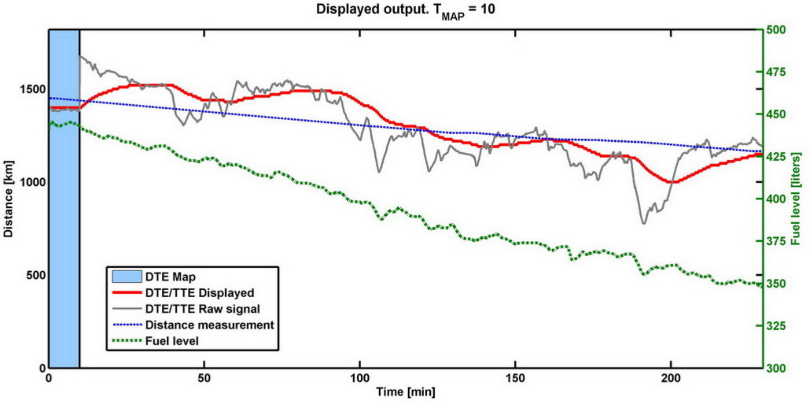

Figure 3.12. Figure showing the estimated raw value of the DTE/TTE together with the smoothed, displayed version. The coloured areas indicate the usage of DTE and TTE map and TTE mode. When TTE mode is active the unit of the output is switched to hours. The dashed line (D) from Equation (3.1) show that the average decreasing pace of the DTE is close to that of D, altough the output signal oscillates quite much.

The result is similar to that of Figure 3.8, the difference is seen at the end of the route. Again, the shorter stop at the 130th minute doesn't affect $\bar{\gamma}_{l/km}$ significantly. But in the mixed speed area, there is a clear change in $\bar{\gamma}_{l/km}$ as a result of that the fuel consumption hasn't decreased as much as the vehicle speed.

The effect of this is propagated to the DTE estimate and can be seen after 180 minutes in Figure 3.12. In this figure, the clear relationship between Γ_{DTE} and the fuel level, V_f, can be seen. With a steady $\bar{\gamma}_{l/km}$ signal, Γ_{DTE} follows the decreasing of V_f. Even smaller, more high frequent changes are seen (e.g. at the 110th minute).

Chapter 4

A first look ahead

The estimation of the distance to empty (DTE) for a heavy vehicle has a large uncertainty in knowing nothing about the route the driver is planning to take. With known topography of the road ahead, a vehicle model could estimate the fuel consumption for that specific route and thereby significantly improve the DTE estimate.

Combined with a navigation system where the driver selects a destination, an improved DTE-algorithm could estimate the total fuel needed to reach that place. If the current fuel level isn't enough, a warning could be presented along with a list of appropriate refuelling stations along the way.

4.1 Problem definition

When driving over a hill on an otherwise flat road, a first thought would be that the potential energy gained when driving uphill could be used when rolling downhill, thereby eliminating the effect of the hill. This utopian dream is however crushed for two reasons:

Increased air resistance As will be seen below the air resistance varies with the square of the vehicle speed (v^2), thereby quickly gaining more losses as the speed increases. In a scenario where the vehicle speed drops a specific amount, δv, below a desired speed v_d during the uphill phase and then rise the same amount δv above v_d during the downhill phase, making the average speed exactly v_d, the losses would still be greater than it would be if driving the same distance on a flat road in constant speed, [10].

Vehicle forced to brake The effects of the hill are larger for a heavy vehicle than for passenger cars. With a multiple greater mass, a heavy vehicle gain a huge amount of potential energy when driving uphill. When this is released in a downhill the vehicle quickly accelerates to a speed above the legal limit, forcing the driver to brake and waste that energy to heat friction in the brakes. For the effect of the mass in downhill, see Figure 4.4.

The last effect could be overcome by installing a short-term storage system, thus making the vehicle a hybrid vehicle. With regenerative brakes, the energy usually lost to heat could be temporarily stored and used to propel the vehicle after the downhill. The energy could be stored in different ways, eg. electrostatic (super capacitor), kinetic (flywheel) or hydraulic (hydraulic accumulator) [8]. However, since there today is no Scania vehicle using regenerative brakes on the market, this feature will not be included in the simulation.

Road altitude data describing these hills could be received by the vehicle from an offboard database or by an onboard navigation system. In both cases, huge amounts of data would have to be handled by the DTE Look Ahead algorithm if each elevation and hollow of the road was to be included. The length of the required horizon is significantly larger then that of look-ahead functions intended for cruise controls and fuel optimization. Such a function has a typical horizon of about 1.5 km [9], whilst a DTE look-ahead horizon would have to cover the entire possible route, i.e. hundreds of kilometers.

Reducing the topographic resolution by taking longer steps between each sample point would result in a lot less data needed to be treated, thereby saving resources. But how much data could be lost without significantly reducing to accuracy of the DTE estimation? The purpose with this pre-study is to investigate the result on the DTE estimate when decimating road altitude data. This is done by estimating the total fuel consumed on a given route with a given resolution. Worth mentioning is that in this chapter V_f denotes the estimated total amount of fuel consumed on a route, and not the amount of fuel in the tank.

In Section 4.2 the handling of the raw data will be discussed. In Section 4.3, a vehicle model will be derived. This will be used in a simulation described in Section 4.4. Finally the results are presented in Section 4.5.

4.2 Simulation routes

This study will use four different routes selected from a set of standard routes used by Scania: Jönköping-Södertälje (SWE), Oslo-Haugesund (NOR), Koblenz-Trier (DEU) and Zwolle-Apeldoor (NDL), all seen in Figure 4.1. The specific four drive cycles were selected on the bases that they all differs in length and hilliness and should hopefully cover the most common road types. The different length of the routes could be a problem since a comparison of the total fuel consumption estimate should be performed on routes of equal length. This will be solved by simulating the vehicle to turn around when reaching an end station and continue driving until the distance of the longest route is achieved.

4.2.1 Segmentation of routes

A route's resolution is classified by the distance between the altitude sample points. Each such part of the route is called a segment, denoted ΔS. The smallest segment

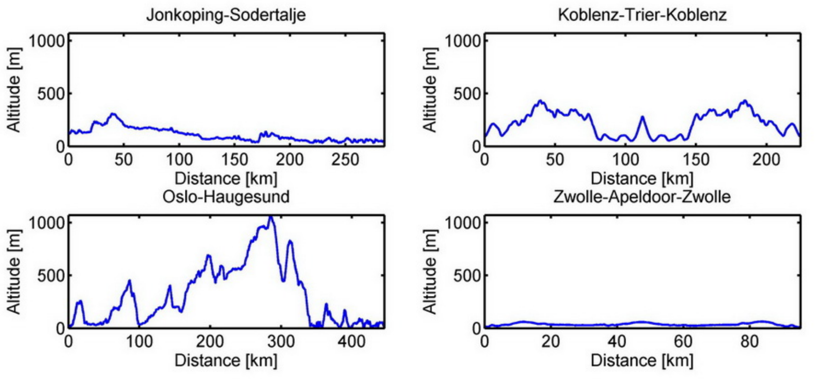

Figure 4.1. Altitude for the four different routes used in this study. They all differ in altitude and length and should cover the most usual type of roads. Note that two of them, in the raw data includes the return journey, that is Koblenz-Trier and Zwolle-Apeldoor.

size and thereby the highest resolution, denoted ΔS_0, is 50 meter. The largest segment is created by taking the whole route as one segment. As ΔS increases, so does the risk of missing important altitude variations. In Figure 4.2, the effect of different ΔS can be seen on a part of the Jönköping-Södertälje route. Although it's obvious that a larger ΔS result in a loss of information, it isn't clear how important that lost information is.

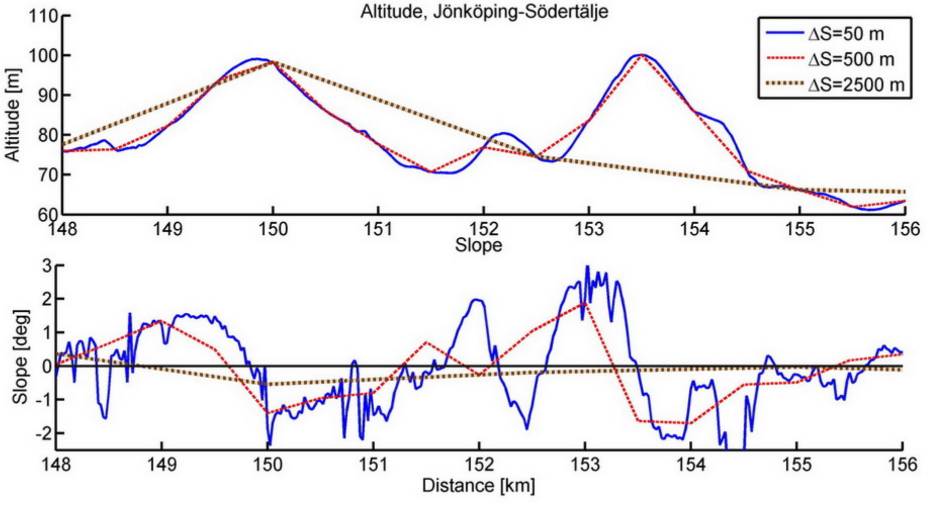

Figure 4.2. The effect of different segment sizes. The figure shows the altitude and the slope over a part of the Jönköping-Södertälje route

When simulating the fuel consumption, the problem will be described as a discrete process. The simulation step size will be independent and the same for all ΔS. It is merely the altitude sampling that should be considered to be of limited resolution.

The true interesting information is the road slope, rather then the altitude. The slope over the segment j is denoted α_j and is given by,

$$\alpha_j = \arctan\left(\frac{h_{j+1} - h_j}{\Delta S}\right) \tag{4.1}$$

where h_j is the altitude in the beginning of segment k. This tends to smooth the slopes as ΔS increases. The slopes that correspond to the altitudes can be seen in Figure 4.2.

4.2.2 Dispersion of the route altitude

As seen in Figure 4.1, the routes differ in hilliness. It isn't too hard to see that a DTE estimate on a hillier route is more likely to be affected by a large ΔS. Therefore, different choices of segment size could be made for different routes, depending on the hilliness of them. This will be measured using the variance (σ^2) of the altitude. It is here defined according to [2] as,

$$\sigma_h^2 = \frac{1}{N-1}\sum_{k=1}^{N}\left(h_k - \bar{h}\right)^2 \tag{4.2}$$

where $\bar{h}$ is the mean altitude and N the number of measurement points.

4.3 Vehicle model

The model of the vehicle is divided into two parts: the forces acting upon the vehicle from the outside and the dynamics in the powertrain. The model is based on the vehicle models described in [4], [8] and [9].

4.3.1 Longitudinal motion

The energy stored in the vehicle can be divided into two forms: kinetic and potential energy. The kinetic energy varies with the vehicle speed and the potential energy with the height over a reference point.

The approach is that the propulsion system produces mechanical energy that is assumed to be momentarily stored in the vehicle. The driving resistance is assumed to drain energy from this reservoir, [8]. The driving resistance consist of the aerodynamic friction losses, the rolling resistance and the energy dissipated in the brakes. To that is also the gravitational effect when driving uphill or downhill which could either drain or supply energy to the vehicle.

By using Newton's second law, an equation that describes the longitudinal dynamics is derived,

$$m\frac{d}{dt}v = F_t - (\underbrace{F_a + F_r + F_g + F_d}_{F_w}) \tag{4.3}$$

where m denotes the vehicle mass in kilograms and v the vehicle speed in meter per seconds. F_t is the force produced by the propulsion system minus the internal losses in the driveline. The force F_w is the combination of all external, opposing forces (F_a, F_r, F_g and F_d), see Figure 4.3. The first three forces will be described in the following sections, the last one, F_d, summarize all non specified forces, e.g. the wind. This force is assumed to be zero in this study.

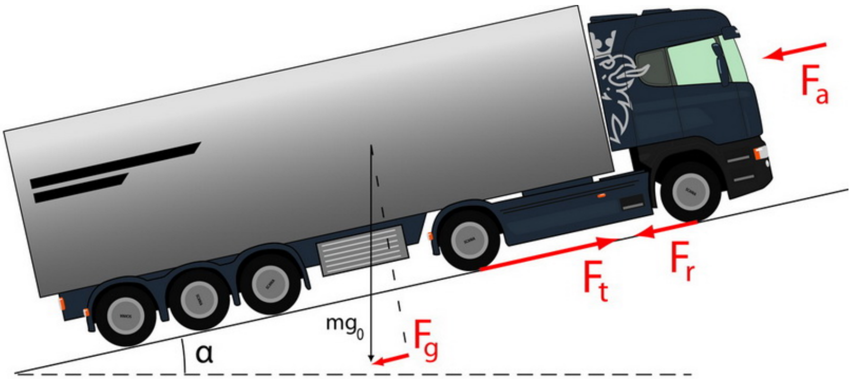

Figure 4.3. The forces acting upon the vehicle. F_a is the aerodynamic resistance, F_r the rolling friction losses and F_g the force due to the gravitation. Finally there is the traction force, F_t, generated by the prime mover.

Aerodynamic friction losses

The force F_a denotes for the air resistance acting on the vehicle. It is commonly modelled as Equation (4.4) according to [4] and [8].

$$F_a = \frac{1}{2} \cdot c_d \cdot \rho_a A_f v^2 \tag{4.4}$$

Here, ρ_a denotes the air density and v the vehicle speed. A_f is the frontal area of the prismatic body the vehicle is simplified to. The force is scaled by the aerodynamic drag coefficient c_d. This parameter is sometimes modelled as a function of v, but when driving a typical test cycle it may be assumed to be constant [8].

Rolling Friction Losses

The force F_r denotes the rolling resistance, mainly dependent on the tire pressure and the mass of the vehicle. There exists some different ways to model this, [8] approximates it as,

$$F_r = mg_0 \cdot c_r \cdot \cos(\alpha) \tag{4.5}$$

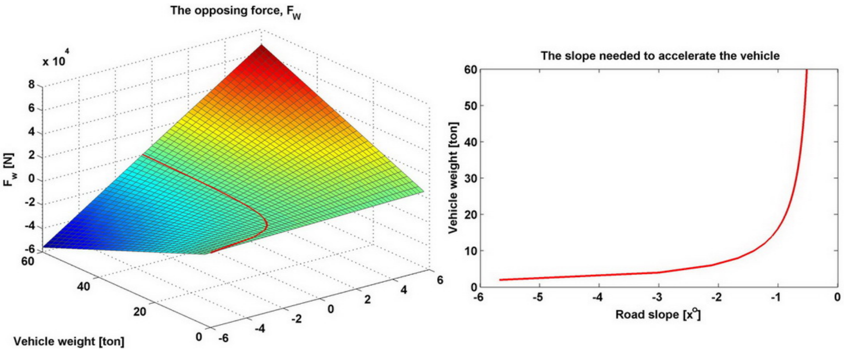

Figure 4.4. The left figure shows the effect of slope angle and vehicle train weight on the force F_W, from Equation (4.3). On the surface lies an enhanced line, showing where $F_W = 0$. Below this line, the vehicle starts to accelerate. This line is also plotted in the figure to the right.

with the rolling coefficient, c_r. This approximation uses the tire normal force, $F_{N,tire} = m_v g_0 \, cos(\alpha)$, where g_0 is the acceleration of gravity and α is the road slope from Equation (4.1).

In [4], the rolling coefficient is assumed to be a function of the vehicle speed.

$$F_r = mg_0 \cdot (c_{r,1} + c_{r,2} \cdot v) \cdot \cos(\alpha) \tag{4.6}$$

Where two separate coefficients: $c_{r,1}$ and $c_{r,2}$, is used. For this task Equation (4.6) will be used. Usually the term $\cos(\alpha)$ is assumed to be 1, but since α plays a major roll in this study, it will be kept although its influence in Equation (4.6) will be limited.

Gravitational force

The force F_g denotes the gravitational force. It is clearly dependent on the road slope α,

$$F_g = mg_0 \cdot sin(\alpha) \tag{4.7}$$

As seen, this could be both a helping and an antagonistic force, depending on the sign of α. The angle at which this overcomes the rest, making $F_w < 0$ depends on the weight of the vehicle. The effect of slope angle and vehicle weight on F_W can be seen in Figure 4.4.

4.3.2 Powertrain model

In this section, a model of the powertrain, from the wheels back to the engine will be derived. The components of the powertrain can be seen in Figure 4.5 and 4.6. These different parts will be modelled separately and then put together in Section 4.3.3.

The effect of the flexibility and oscillations in the shafts will not be modelled since this phenomena mainly impact driveability and not fuel consumption, according to [11].

Figure 4.5. Scania 12 liter powertrain

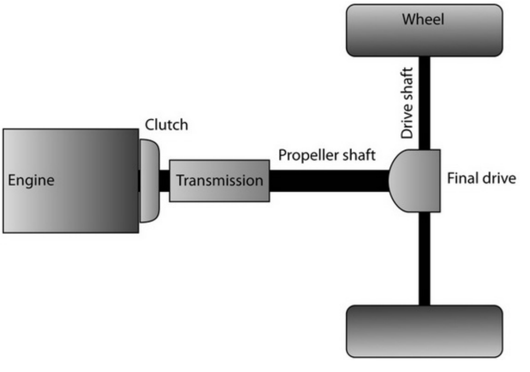

Figure 4.6. Sketch of the driveline

Wheels

For a non-zero F_t, the rolling speed of the propelling wheels differ from the longitudinal velocity, v. This difference is called the slip coefficient, denoted by s. According to [4], there are two different definitions used,

$$s = \frac{r_w \omega_w - v}{r_w \omega_w} \text{ or } s = \frac{r_w \omega_w - v}{v} \tag{4.8}$$

where r_w is the wheel radius and ω_w the rotation speed of the wheel.

However, for most cases, as well as here, a rolling condition is assumed to be sufficient enough, i.e.

$$r_w \omega_w = v \; . \tag{4.9}$$

With this, there is no power loss between the wheels and the road.

The dynamics in the wheels is modelled as in [4],

$$\left(J_w + mr_w^2\right)\dot{\omega}_w = T_w - F_w r_w \tag{4.10}$$

with the wheel inertia, J_w and the output torque from the powertrain, T_w.

Transmission and final drive

With a gear engaged, the transmission trade rotational speed for a higher torque by the drive shaft. The transfer ratio, including both gear and final drive, is denoted i. The relationship between the clutch and wheels torque and rotational speed is then given by,

$$\begin{aligned} \omega_c &= i\omega_w \\ iT_c &= T_w \end{aligned} \tag{4.11}$$

With this, the dynamics in the transmission is given according to [4],[9].

$$J_t\dot{\omega}_w = iT_c - T_w - T_{fr,t} \tag{4.12}$$

where J_t is the transmission inertia and $T_{fr,t}$ is the friction torque, depending on many influencing factors such as speed, load, temperature etc., [8]. It is here modelled as,

$$T_{fr,t} = (1 - \eta_{gb})iT_c\ . \tag{4.13}$$

Clutch

The clutch disc connects the rest of the driveline to the engine at the flywheel. When shifting gear, the friction between the disc and the flywheel is gradually reduced and increased to limit vehicle wear and enable a comfortable gear shift.

However, in this thesis work, the clutch will be assumed to be rigid and the gear shifts made instantaneous. Thus, any losses are neglected and a gear is assumed to always be engaged.

$$\begin{aligned} \omega_{in} &= \omega_{out} \\ T_{in} &= T_{out} \end{aligned} \tag{4.14}$$

Engine

The engine converts chemical energy in the fuel to a torque on the flywheel. Power losses in this process can be seen in incomplete combustions, ignition timing losses, heat transfer from gas to cylinder walls, pumping losses to push the exhaust out of the cylinder and friction between pistons and walls [4].

Here, all losses but the friction loss ($T_{fr,e}$) will be combined in an engine efficiency parameter, η_e. This is often described as a function of both engine torque and engine speed, $\eta_e(T_e, \omega_e)$. In this thesis it is however approximated with a single value. The power needed to be put into the engine from the fuel, P_f, to get the required engine power, P_e, is then given by,

$$P_f = \eta_e P_e = \eta_e T_e \omega_e \tag{4.15}$$

The engine rotation speed is determined by the torque output from the engine, T_e and the load from the driveline through the clutch, as described in [9],

$$J_e \dot{\omega}_e = T_e - T_{fr,e} - T_c \tag{4.16}$$

where J_e is the engine inertia.

The operation limits of the engine can be seen in Figure 4.7. The maximum torque is a function of the engine speed, $T_{e,MAX}(\omega_e)$.

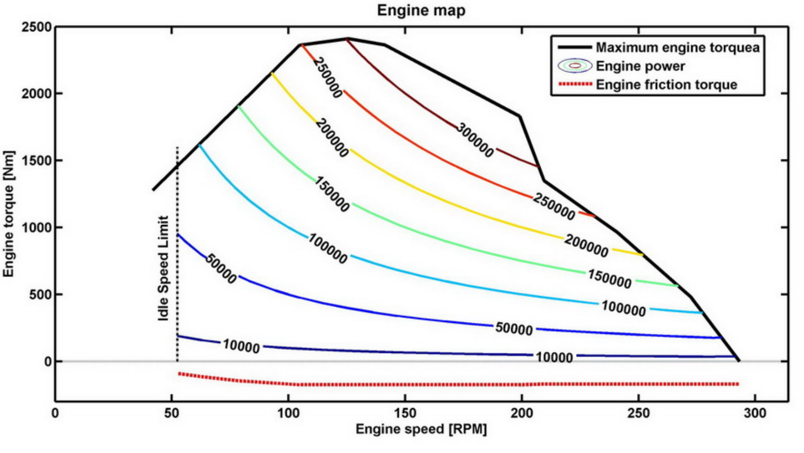

Figure 4.7. The figure shows the operation limits of an engine. The maximum engine torque, $T_{e,MAX}(\omega_e)$, is a function of the engine speed. The engine power, $P = T_e \cdot (\omega_e)$, is seen as counter lines. At the bottom the Engine friction torque (or loss) is given. As seen, the engine idle speed is 500 rpm.

Auxiliary system

Onboard on a vehicle there is a number of auxiliary systems using a part of the power produced by the engine. Such systems could be air conditioner (AC), cooling fan, compressor, servomotor etc. For some heavy vehicles, like buses, the auxiliaries can stand for up to 40% of the total fuel consumption [1].

In this thesis, the power consumed in these systems will be approximated with a constant power, independent of the vehicle speed and alternating altitude.

There could also exist external auxiliary systems, that do not draw their power from the engine but still consume fuel, e.g. an auxiliar cab heater which has its own fuel combustion to produce heat. There is assumed to be no such system in use here.

4.3.3 Combined equations

Here, the different equations of the vehicle model are combined.

$$\dot{\omega}_e = \dot{v}\frac{i}{r_w} \tag{4.17}$$

$$T_e = \mathcal{J}\dot{\omega}_e - T_{fr:e} - \frac{F_w r_w}{i \cdot \eta_{gb}} \tag{4.18}$$

where $\mathcal{J}$ is the total inertia of the vehicle powertrain

$$\mathcal{J} = J_e + \frac{J_t + J_w + m r_w^2}{i^2 \cdot \eta_{gb}} \tag{4.19}$$

4.3.4 Tank to engine

The oxidizing reaction of the fuel releases energy (heat) and emissions, e.g. carbon dioxide and water. The amount of energy stored in a unit of fuel is determined by the lower heating value of the fuel, q_{LHV}. The ”lower” appellation implies that the energy to vaporize the water is included. For diesel q_{LHV} is 42.5 MJ/kg fuel.

To produce the P_f from Equation (4.15), the fuel rate ($\gamma_{l/h}$) required is given by,

$$\gamma_{l/h} = \frac{P_f}{q_{LHV} \cdot \rho_f} \cdot \underbrace{3.6 \cdot 10^6}_{[m^3/s] \rightarrow [l/h]} \tag{4.20}$$

where ρ_f is the density of the fuel.

4.4 Simulation

The simulation is done in MATLAB with routes of different sample accuracy as an input. Each route will be divided into intervals of the same length, $d = 50$ m. Each such interval, j, has a given slope and an input vehicle speed from the previous interval. For each route, k and sample distance, ΔS, the fuel volume $V_f^{\Delta S|k}$ consumed on every such interval is calculated by using Equation (4.15), (4.20) and the time spent on that interval, $\Delta t = \frac{d}{v[j]}$.

$$V_f^{\Delta S|k}[j] = \frac{\eta_e \, T_e[j] \, \omega_e[j]}{q_{LHV} \, \rho_f} \cdot \frac{d}{v[j]} \cdot 10^3 \;\; [liter] \tag{4.21}$$

Here, the scaling with 10^3 is done to convert the unit from m^3 to liters. The total fuel volume consumed is obtained as the sum of all interval values.

$$V_f^{\Delta S|k} = \sum_j V_f^{\Delta S|k}[j] \tag{4.22}$$

To get T_e and ω_e of each interval, the vehicle model in Section 4.3 requires a reference vehicle speed and acceleration. These are given by a basic cruise control built into the simulation model.

4.4.1 Cruise control

There are three different modes for the vehicle to operate in when looking at the traction force, F_t:

- $F_t > 0$, traction
- $F_t < 0$, braking
- $F_t = 0$, coasting

During a route, the vehicle will be given a desired, target speed, v_d. This will also be the initial speed. The vehicle will be asked to deliver enough torque to keep this speed. It will however be allowed to exceed this speed when coasting downhill. If the speed becomes greater then a limit, v_{max}, the vehicle will be forced to brake. As discussed in Section 4.1, it is assumed there is no recuperation of the braking energy.

4.4.2 Gear selection

To minimize the fuel consumption, the vehicle will try to stay on a high cruising gear. If the vehicle cannot deliver enough torque to keep v_d, the algorithm will try to shift down to a gear that gives enough torque. If no such gear is found, a speed reduction is accepted, but in an attempt to minimize the effect, the gear that will give the maximum output power is chosen. This logic can be seen in Figure 4.8.

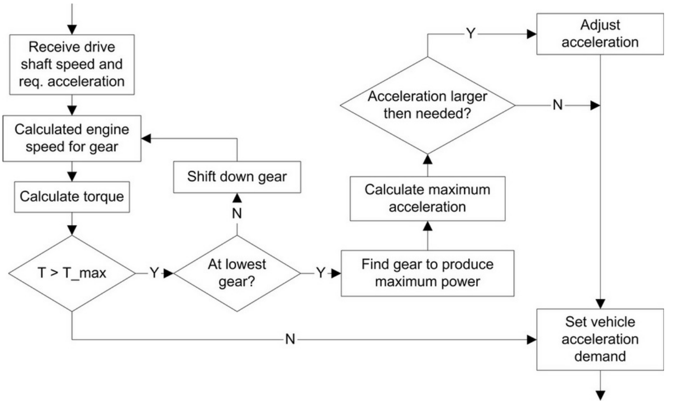

Figure 4.8. The logic of the gear shifting. Usually a high, fuel economic gear is kept. Problem occurs in steep uphill slopes when the required torque is too high. First, a down shift is tested. If that doesn't help, it is accepted that the vehicle will loose speed, but the effects will be limited by choosing the gear that gives the highest power output.

4.5 Result

In this section the result of the simulation made with the vehicle model is presented. It will be shown that the curvature of a route has significant impact on how wide a route's sample points can be set without changing the DTE estimate significantly.

A relative error measurement that is used to describe the difference in estimated consumed fuel volume for different discretizations is given in Equation (4.23). The consumed fuel volume is indexed with k for different routes and ΔS for different segment sizes, with ΔS_0 being the smallest segment size.

$$e_{rel}^{\Delta S|k} = \frac{\Delta V_f^{\Delta S|k}}{V_f^{\Delta S_0|k}} = \frac{\left| V_f^{\Delta S|k} - V_f^{\Delta S_0|k} \right|}{V_f^{\Delta S_0|k}} \tag{4.23}$$

The result of the simulations is seen in Figure 4.9. Note that all routes have been extended to the same length to make the comparison easier. The points floating alone to the far right in the figure is the result when treating the entire route as one single segment. In the figure it is seen that the sensitivity to the size of ΔS differs between the routes. It looks like a larger segment size result in a larger estimation error. This rule isn't consistent and the reason that all functions aren't monotonic is probably a result of fortunate sample points and coincidence. The trend is however that as ΔS increase, so does e_{rel}. If a route has a large e_{rel} for large ΔS, it is interpreted as if that route is sensitive to large ΔS. Table 4.1 shows the sensibility of the routes in decreasing order when looking at e_{rel} for the largest ΔS, where the entire route is treated as one segment.

Table 4.1. The routes ordered after size of e_{rel} for the largest ΔS, where the entire route is treated as one segment. This is interpreted as the route beeing sensitive to larger segment sizes. They are sorted in deacreasing order, with #1 being the most sensitive one.

#	*Route*
1	Oslo-Haugesund
2	Koblenz-Trier
3	Jönköping-Södertälje
4	Zwolle-Apeldoor

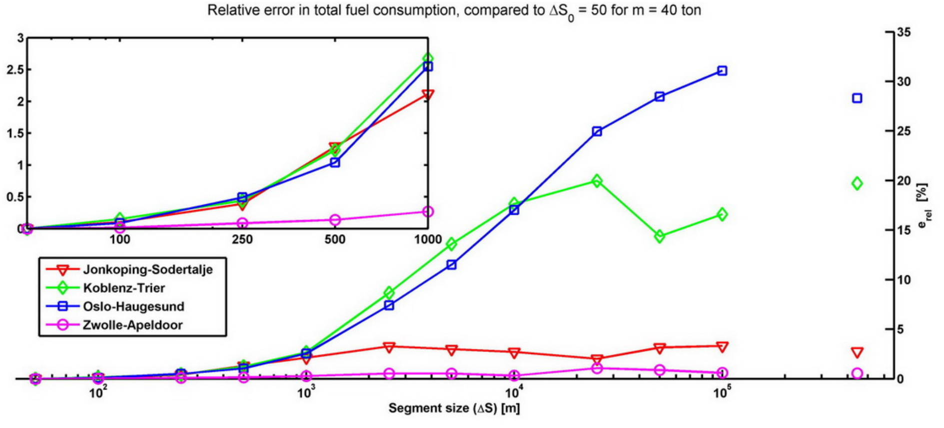

Figure 4.9. The figure shows the result of Equation (4.23) in percent for different routes k and segment sizes ΔS. Note that the X-axis has a logarithmic scale. The single point at the right shows the result using only the end points of the route. In the small, infolded box the same plot is shown, but with a zoom for smaller segment sizes. The simulation is done with a vehicle weight of 40 tons.

4.5.1 Weight influence

One aspect that hasn't been discussed so far is the effect of different vehicle train weights. In the vehicle model, see Equation (4.7), the weight is a major factor. In Figure 4.4 it was seen that as the weight increases, the slope required to overcome the other opposing losses (F_a and F_r) gets flatter. It would therefore be interesting to see how the result in Figure 4.9 looks when adding the weight as one additional dimension.

In a new simulation, the train weight is set to vary between 8 and 60 ton. By the same principle as in Equation (4.23) the estimate with the highest resolution (ΔS_0) is withdrawn from the others, and so separately for each weight. As Figure 4.10 shows, the weight do affect the estimate error. The larger train weight a vehicle has, the more sensitive the estimate becomes to larger segment sizes. There are some exceptions from this rule, where e_{rel} doesn't grow monotonic with increasing train weight or ΔS, seen in route Jönköping-Södertälje and especially

Zwolle-Apeldoor. The size of e_{rel} is however so small that it could be seen within the error margin of the estimation.

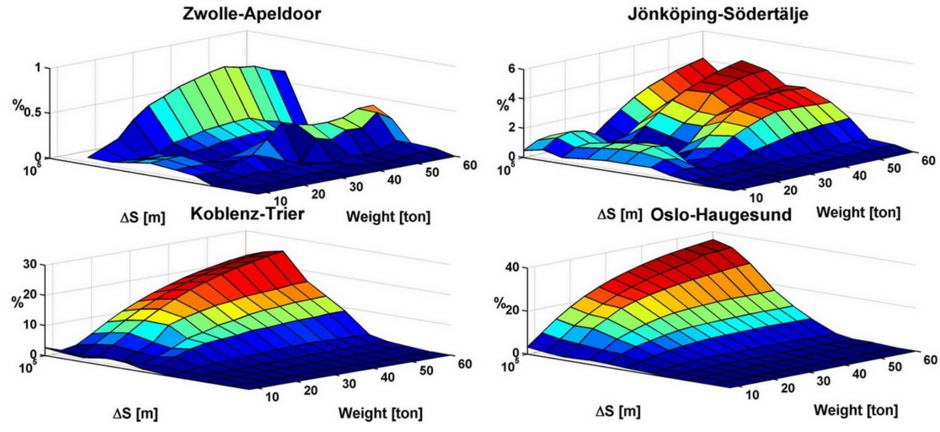

Figure 4.10. Figure shows an extension of Figure 4.9 as an extra dimension with weight is added. As seen, a larger vehicle weight will result in larger estimation error. Note the different values of the Z-axis.

4.5.2 Correlation with altitude dispersion

As seen in Figure 4.9, the estimation of V_f vary with different routes. To find out if this is correlated with the different altitude variances of the routes, the variance (σ^2) is calculated according to Equation (4.2). In Figure 4.11 the standard deviation ($\sqrt{\sigma^2}$) for different ΔS is plotted. The reason for plotting σ instead of σ^2 is that the standard deviation here has the unit meters, and easier can be understood.

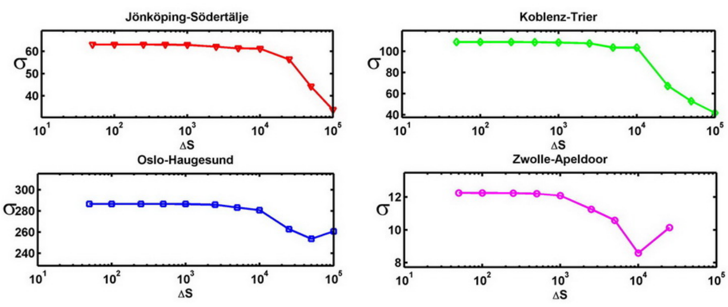

Figure 4.11. The standard deviation (σ) for the different routes' altitude.

When ranking the routes after the standard deviation with the highest first, they appear in the same order as in Table 4.1. It would therefore be legitimate to say that a routes sensitivity to a larger ΔS depend on the size of its standard deviation or variance.

The result in Figure 4.9 could then be said to depend on how much of the information about variation or hilliness on the route that is lost when (re)sampling it with a certain segment size, ΔS. To measure this loss two different approaches are used:

$$\text{The absolute error of the variance: } \Delta\sigma^2 = \left|\sigma^2_{\Delta S} - \sigma^2_{\Delta S_0}\right| \tag{4.24}$$

$$\text{The relative error of the variance: } \Delta_{rel}\sigma^2 = \frac{\left|\sigma^2_{\Delta S} - \sigma^2_{\Delta S_0}\right|}{\sigma^2_{\Delta S_0}} \tag{4.25}$$

Theses two measurements are plotted in Figure 4.12. The result shows that it is the absolute and not the relative size of the sampling error that matters. Although the route Zwolle-Apeldoor has a relative error of about 200% for $\Delta S = 10^4$, as seen from Figure 4.1, the altitude is small compared to the other routes and the topography data lost when sampling is too small to affect the fuel consumption significantly. A lost part of a mountain from the Oslo-Haugesund route has a much greater influence although the relative error is smaller.

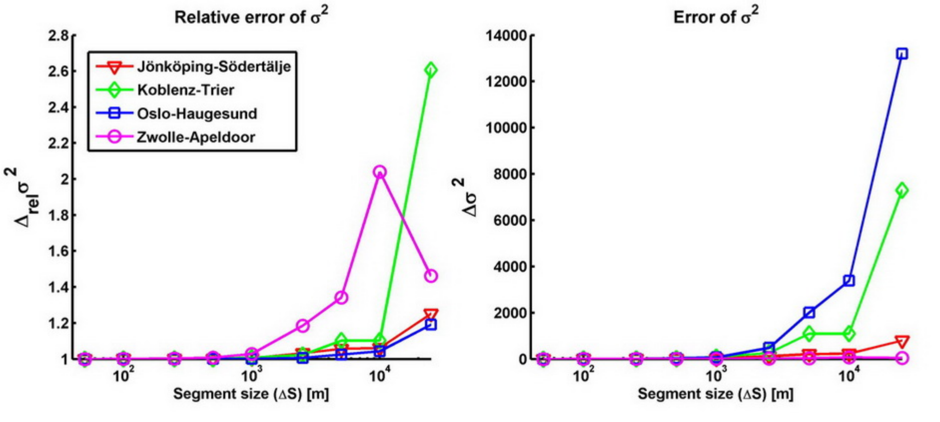

Figure 4.12. Figure show the plots of Equation (4.24) and Equation (4.25). In the right sub plot no correlation with the results in this section is seen. The left sub plot however, showing $\Delta_{rel}\sigma^2$, has some correlation with Figure 4.9 indicating that it is the absolute size of the lost altitude information that is important for the relative error in the V_f estimation.

Chapter 5

Summary and conclusions

The distance to empty estimation is an estimate of how long the vehicle can travel due to the current amount of fuel in the tank. The estimate uses a number of input signals, the most important being the fuel consumption $\gamma_{l/h}$, the vehicle speed v, the fuel level V_f and the gross train weight m.

The algorithm uses a forgetting filter instead of a moving average filter to calculate a representative estimate of the mean fuel consumption. With a correct choice of the forgetting filter parameters, the output of these filters are similar but the memory use is substantially smaller.

By using mapped average fuel consumption, based on the current vehicle weight, a DTE estimate can be achieved even during phases when there are not enough information to estimate the current mean fuel consumption. To save memory, a linear approximation of the map is recommended to be used. The two map parameters are adapted continuously by an online algorithm in the vehicle.

At low speed or idling, when the fuel consumption in liters per kilometer does not supply any useful information, the time to empty is calculated instead. The switch between the two modes could be done by an online algorithm or simply be controlled by the driver.

It is shown that the vehicle weight is a major influencing factor of the fuel consumption. Therefore, a weight change detection is implemented. It compares the mean and a filtered value of the signal and set the detection alarm when those two differ above a threshold value. After a weight change, the mapped fuel consumption should be used as the change in the conditions make the old estimate incorrect.

A future option is to, through a navigation system, equip the algorithm with topographic data of the route. If such a look ahead system were implemented, the sample resolution of the route will affect the accuracy of the estimated total fuel consumption. The effect is larger if the route is hillier.

5.1 Conclusions

The algorithm relies on good quality of the most important input signals. Good quality in the sense that the signals should be unbiased. A small variance, possibly varying, is accepted and will be smoothed out by the filters in the algorithm. Especially important is the avoidance of a larger absolute error in V_f, as such an error will have the largest affect on the DTE estimate.

The configuration of the distance to empty algorithm parameters is a balance between robustness and adaptability. The parameters could be tuned to give a steady output, based on a large amount of data, presume a long haulage vehicle driving on equal road types. But for a vehicle used in a mixed highway-urban environment this would occasionally lead to bad estimates.

To get a good initial estimate of the fuel consumption from the map requires a good initial estimate of the vehicle train weight. Because it rely on a lot of signals which are relevant only during propulsion, the accuracy of that estimate could however be varying initially. So, if the weight estimation signal is considered to be of bad quality, either a mean template weight could be used or the DTE should also be considered to be of bad quality and don't be displayed at all.

If a look ahead system were to be added, the sample resolution of the route amplitude could be set wider than that used in the look ahead functions intended for cruise controls and fuel optimization. For sample distances up to 1 km the difference in estimated fuel consumption compared to the estimate with the highest resolution is only a few percent. This would be within the error margin of the estimate.

When going above 1 km between every sample point, the hillier route with a higher altitude variance quickly get a higher estimation error. But for almost flat routes like Zwolle-Apeldor, no significant difference is seen in the estimate. The variance of the topology profile of a route could therefore give information about how to choose the sample resolution.

5.2 Further development

The problem with robustness versus adaptability has to be solved. This could be done by either finding a golden mean of parameter settings by numerous of testing or supplying different sets of parameter settings, gathered into different choices, selected at production, service halls or by the driver.

As mentioned in Section 2.2.1, there exist a certain amount of redundancy in the fuel measurement. Very simplified, an increase in the fuelRate signal $\gamma_{l/h}$ should be seen in a faster decrease in the fuelLevel V_f signal. Using this to change the V_f is not an option as it would be to redo the work of the Kalman filter in the V_f estimation algorithm. However, in the case of a biased $\gamma_{l/h}$ signal, a background algorithm could compare the total fuel spent according to both of the signals and adjust the $\gamma_{l/h}$ input. This adjustment would probably be very small, and the comparison will have to be done on a vast amount of data over several routes.

When doing so, the use of external auxiliary system must be known. If this system has its own power supply instead of using power from the engine, the extra fuel consumption will be seen in V_f but not in $\gamma_{l/h}$. This makes the adaptation proposed above more difficult as the fuel consumption of all external system will have to be estimated.

An obvious further development is the implementation of a look ahead DTE algorithm. With a known vehicle position and a given target destination, this would cancel out the uncertainty of the road topography. With satellite connection, providing traffic data, also the uncertainty in surrounding traffic events (e.g. traffic accidents and bridge openings) would be solved, leaving only the variation in the driving behaviour as an unknown factor.

Regardless of the use of look ahead, different drivers characteristic driving behaviour could be stored in each drivers own driver card. Other information, such as choice of parameter settings could also be stored.

5.3 Notations

Fuel parameters	
$\gamma_{l/h}$	Fuel consumption [liter/hour], raw signal
$\bar{\gamma}_{l/h}$	Filtered fuel consumption [liter/hour]
$\bar{\gamma}_{l/km}$	Filtered fuel consumption [liter/km]
$\bar{\gamma}_{mean}$	Mean of raw input signal [liter/km]
$\bar{\gamma}_{MA}$	Raw input signal filtered with a moving average [liter/km]
$\bar{\gamma}_{\lambda}$	Raw signal filtered with a forgetting filter [liter/km]
V_f	Fuel volume [liter]
$V_f^{\Delta S\|k}[j]$	Fuel consumed over segment j [liter]
$V_f^{\Delta S\|k}$	Total fuel consumption on a route k with segment size ΔS [liter]
$V_f^{\Delta S_0\|k}$	Same as $V_f^{\Delta S\|k}$ but using segment size $\Delta S_0 = 50m$ [liter]
$\Delta_i V_f$	Difference in total fuel between ΔS_0 and ΔS_i [liter]
e_{rel}	Relative error between $V_f^{\Delta S\|k}$ and $V_f^{\Delta S_0\|k}$ [%]
ρ_f	Density of the fuel $[kg/m^3]$
q_{LHV}	The lower heat value of the fuel [J/kg]

Route parameters	
α	Road slope [rad]
h_j	Altitude above sea level at the start of part j of a route [m]
ΔS	A segment of a route [m]
ΔS_i	The specific segment size with index i [m]
ΔS_0	The smallest segment / the highest resolution [m]
Δt	Time required to travel a segment [s]
σ^2	Variance (of a route's altitude) $[m^2]$
σ	Standard deviation (of a route's altitude) [m]
$\sigma^2_{\Delta S_i}$	Variance of a route sampled with the segment size i $[m^2]$
$\Delta\sigma^2$	Absolute error of the variance, compared to $\sigma^2_{\Delta S_0}$ $[m^2]$
$\Delta_{rel}\sigma^2$	Relative error of the variance, compared to $\sigma^2_{\Delta S_0}$ [-]

Vehicle parameters

F_t	The traction force at the wheel, propelling the vehicle [N]
F_w	All the ambient [N], external forces acting upon the vehicle
F_a	The air drag force [N], included in F_w
F_r	The rolling resistance force [N], included in F_w
F_g	The gravitational force [N], included in F_w
m	The total mass of the vehicle (train weight) [kg]
v	Vehicle speed [m/s]
v_d	Desired speed to be held during a route [m/s]
v_{MAX}	Maximum speed allowed [m/s]
A_f	Frontal area of the vehicle [m^2]
c_d	Aerodynamic drag coefficient [-]
c_r	Rolling resistance coefficient [-]
$c_r, 1$	First rolling resistance coefficient [-]
$c_r, 2$	Second rolling resistance coefficient [-]
g_0	Gravitational acceleration [m/s^2]
ρ_a	Density of ambient air [kg/m^3]
r_w	Wheel radius [m]
ω_w	Wheel revolution speed [rad/s]
s	Slip coefficient [-]
η_e	Efficiency of the engine [-]
P_e	Power from the engine [W]
P_f	Power from the fuel [W]

Remaining DTE parameters

Γ_{DTE}	The raw calculated DTE signal [km]
Γ_{TTE}	The raw calculated TTE signal [h]
Γ	A signal interpreted as either Γ_{DTE} or Γ_{TTE}
$\bar{\Gamma}_{DTE}$	Filtered DTE signal [km]
$\bar{\Gamma}_{TTE}$	Filtered TTE signal [h]
T_{MAP}	Threshold time of the mapped fuel consumption [min]

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