Sensor Fusion of GPS and speed information for low-cost automotive positioning and navigation

CLAUDIA AQUILANTI

KTH Electrical Engineering

Master's Degree Project
Stockholm, Sweden 2011

XR-EE-SB 2011:001

Abstract

Global navigation satellite systems, such as the Global Positioning System (GPS) are nowadays widespread in the consumer and professional fields. To guarantee the desired accuracy, availability, integrity and robustness performance, it is necessary to add to GPS receivers aiding systems, like extra sensors, which can be expensive. In order to reduce the expenses, a low-cost alternative aiding system is here presented. The main idea is to extract the information needed to support the GPS services from an easily measurable signal as the one provided by the power supply of a car. This signal has a frequency component related to the rpm speed of the engine, thus it can be used to estimate the speed, and related states, when the GPS service is unavailable for some reason. Unfortunately, the frequency component is equal to the speed measured by the GPS up to a scale factor dependent on the gear engaged, so it is necessary to estimate over time these scale factors in order to use the information. In this thesis project we implemented an off-line system which leads to the estimation over time of the scale factors. A sensor fusion solution has been used: training data consisting only of speed measurement provided by the GPS and measurements of the signal of interest are processed through a bench of five Kalman Filters (one for each gear) which leads to the estimation of the scale factors. Three measurement campaigns with three different cars have been conducted in order to collect an exhaustive amount of datasets necessary to calibrate and then validate the system.

Acknowledgements

I want to dedicate this thesis to my parents, Gaia and Enzo, to my boyfriend, Pasquale, and to my brother and sister, Giovanni and Francesca: with your unconditional support and your suggestions, you guided me through this long journey. Thank you for being by my side in every moment and in every decision, this could never happen without you.

This project has been developed at the Department of Signal Processing at School of Electrical Engineering, KTH, Stockholm, Sweden. I would like to give a special thanks to my supervisor Dr. Alessio De Angelis for his clever help and total commitment throughout the project, his enthusiasm in research and willingness have been the foundations of this work. My gratitude also goes to Prof. Paolo Carbone and Prof. Peter Händel for allowing me to realize this project, and to Dr. Isaac Skog and John-Olof Nilsson for their inputs and feedbacks (and for the cars!), it has been such an honor to work with all of you.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In this Chapter an introductory overview of the thesis project is provided. First a brief discussion about the field related to the thesis topic is presented, then the presentation of the solution adopted in the project is briefly discussed and finally an overview of the report structure is provided.

1.1 Background

On May 1st, 2000 the process of making the GPS (Global Position System) full capabilities available to all civilians started when the intentional degradation of the GPS signal (the Selective Availability process) was removed by the United States Presidential Administration.

The mass-market application of this navigation mean is the road vehicle tracking: the purpose is to support the driver by showing the vehicle's current location on a map and by giving both visual and audio information on how to efficiently get from one location to another. After ten years, a wide percentage of cars are delivered from the factory with on-board navigation systems, and at the same time the market of portable devices is constantly growing [1].

Most of the commercial in-car navigation systems match the information received from GPS with that of a digital map, so the most likely position of the vehicle on the road is estimated, comparing the trajectory and position of both sources. Unfortunately positioning technologies based on stand-alone GPS receivers are too vulnerable and have to be supported by additional information in order to obtain better performances. The performance measurements are given as follows:

- Accuracy: the degree of closeness of the information provided by the navigation system (position, velocity, etc.) to the actual (true) values;

- Availability: the percentage of the coverage area in which the navigation system works;
- Integrity: the measure of how reliable is the information received from the navigation system;
- Robustness: the ability of the system to continue to work properly even with nonscheduled interruptions of the service.

In urban environments, buildings may partially block satellite signals and the multipath propagation may occur; that's why advanced in-car navigation systems are provided with complementary navigation methods, like sensors such as accelerometers, gyroscopes and odometers, in order to perform a Dead Reckoning (DR). In a DR navigation system, the car is equipped with sensors that record the wheel rotation and steering direction. The trajectory estimated from DR is then projected onto a digital map and then, once the vehicle location has been matched to a location on the map, the navigation system can access the needed information to continue the tracking even if the signal from the satellites is lost [2] [3].

1.2 Problem Statement

A possible aiding mean can be directly found in the vehicle: the angular velocity of the engine of a motorized vehicle is linearly related with several signals easily measurable in the vehicle, like the signal from the cigarette lighter (CL) connector, the vibrations of the chassis [4] or even the sound recordable at the tail pipe of the vehicle [5].

The connection between the angular velocity of the engine and the CL signal depends on the process of transforming the alternating current (AC), supplied by the automotive alternator, into direct current (DC): the transformation is provided by three phase diodes but, due to imperfections of this rectification process, an AC component (proportional to the rotational velocity of the engine) appears in the voltage level of the CL connector output.

This signal, easily accessible, represents a very important source of information about the speed and the related states of the vehicle and it can be helpful as its use could minimize the number of sensors and connections in the vehicle. The signal is already available in every motorized vehicle, consequently it could be not necessary to add external expensive sources of information. For example the CL signal can be sent to third-part dashboard navigation systems for cars or to stand-alone navigation systems implemented on portable devices with built in GPS receivers and inertial sensors. However, to reckon the speed from the CL source two more pieces of information are required: first, the relation between the frequency component of interest and the speed, for each of the five gear of a car's gearbox; second, the cognition of which gear is engaged. On the other hand, once the estimation of the speed from the CL signal and its relation with the current speed of the vehicle are known, these signals can be used to detect which gear is engaged.

1.3 Overview of the Solution

The purpose of this Thesis Project is to study and develop an alternative aiding system to the GPS positioning and navigation system, which improves both the robustness and the availability of the service and at the same time is low cost because already available on board.

In order to have access to the two pieces of information mentioned above (the relation between speed and frequency component and the knowledge about the engaged gear), a measurement system of the easily accessible voltage signal from the CL supply has been implemented. The measurement system records the DC voltage signal acquired from the CL supply via the sound card of a pc in order to obtain a digital version of the time-varying signal, which can be processed with Matlab to extract the frequency component of interest. After a proper calibration of the measurement system, a real-time acquisition has been implemented: the frequency component obtained from the CL supply has been combined with the synchronized speed information acquired from a GPS receiver.The comparison between the frequency component and the speed value recorded by the GPS, second-by-second, gives information on the scale factor related to the gear engaged at that very second.

Starting with these results, a bench of five (each for every gear scale factor) Kalman Filters has been implemented in order to track in real-time the true scale factor related to the gear engaged.

1.4 Thesis Outline

In Chapter 2 an exhaustive description from a theoretical point of view of the system developed is provided: first the system architecture is presented, providing a block diagram of the system, then each meaningful block of it is described in detail.

In Chapter 3 a complete presentation of the implementation solution is depicted: each algorithm developed and used in the thesis project is presented and discussed.

In Chapter 4 the three measurement campaigns conducted during the thesis project and the results obtained for each one are provided.

In Chapter 5 a discussion about the conclusions is carried on; moreover the future works which can derive from the results obtained are briefly presented.

Chapter 2

System Description

In this Chapter a detailed description of the system developed during the thesis project is provided. First a perspective view of the overall architecture is shown, later on every major block of the system is presented in detail from a theoretical point of view.

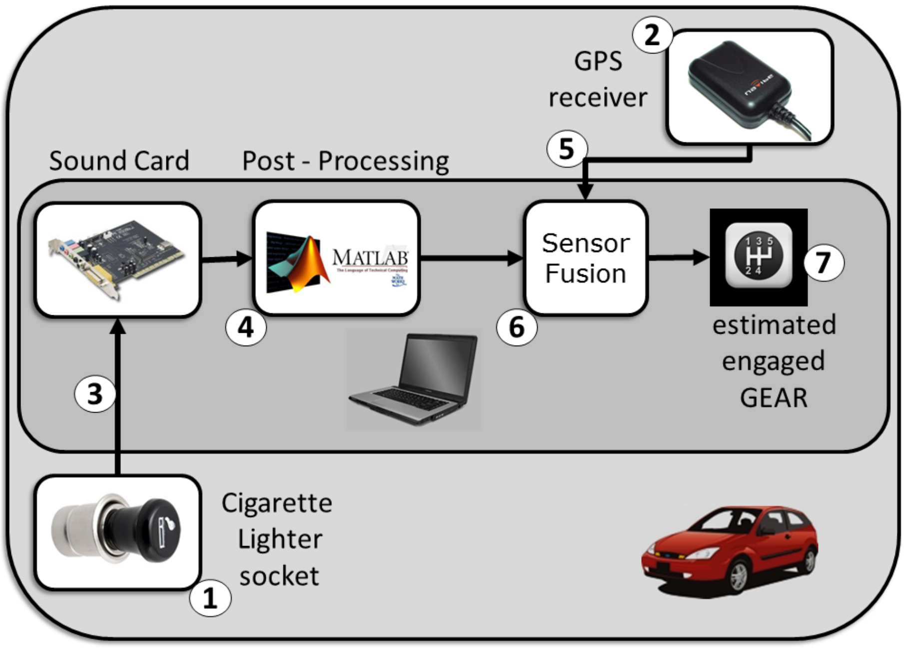

Figure 2.1: Block diagram of the overall system

2.1 System Architecture

The purpose of the depicted system in Figure 2.1 is to provide a low cost aiding system for the GPS service; the developed system is supposed to be implemented entirely on board a motorized vehicle, simply using the voltage signal provided by the CL socket and a portable GPS receiver. This allows to reduce the number of external sensors to be installed on board, and so the cost of the overall solution, and on the other hand to enforce the robustness and the availability of the positioning and navigation service. The system's task is to give information about the current engaged gear.

As can be seen in Figure 2.1, two major input signals are involved in the system: the former is the signal extracted from the CL supply (1), the second is the one provided by a GPS portable receiver (2). In order to acquire the former signal, a connector is plugged at one end into the CL socket and at the other end into the microphone input of portable pc's sound card (3); the signal is directly acquired from the sound card by a Matlab script, and then properly post-processed with Matlab as well (4). Simultaneously to the acquisition from the CL socket, using the same Matlab script, the signal provided by a GPS portable receiver (2) is acquired simply connecting the device to the pc via an USB port (5). The two acquired sources of information are combined together in the Sensor Fusion block (6) where a bench of five Kalman Filters processes the input signals and returns the estimation of the current engaged gear second-by-second (7).

2.2 The Cigarette Lighter Socket: Alternator Speed vs Engine Speed

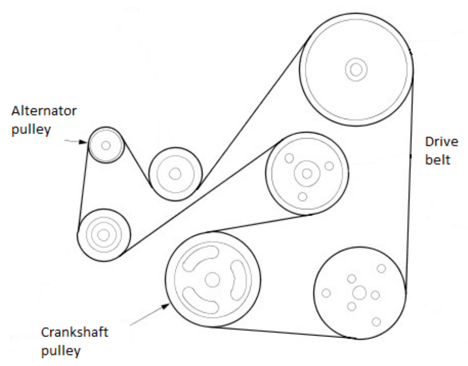

Figure 2.2: Belt diagram of the engine of a FORD Focus

Every motorized vehicle is provided with a synchronous alternator which transforms mechanical energy into alternate current (AC). The mechanical energy is provided by the engine: when it turns, it transmits the motion to the alternator through two belt pulleys. The Figure 2.2, taken from a Ford Focus service manual, is a schematic representation of the drive belt placement of the car [6].

As can be seen in Figure 2.2 the two pulleys have different diameter, so the alternator angular velocity ω_A and the engine angular velocity ω_E are different up to a transmission scale factor. Typical values of the transmission scale factor r for cars are between 2 and 3.5.

$$r = \frac{\omega_A}{\omega_E} \, . \tag{2.1}$$

An engine is formed of several cylinders and each cylinder has its own combustion cycle. When a combustion cycle is done, the speed of the engine is increased. That's why the trend of the engine speed is sinusoidal depending on how many cylinders are in the engine. The frequency of the alternator f_A is equal to the engine frequency f_E up to the transmission ratio r.

$$f_A = r f_E \, . \tag{2.2}$$

In this thesis project, three different cars were used during the measurement campaigns:

- VOLVO 940
- BMW 520i
- FORD Fiesta 1.6 Tdci

For the first two car used, Volvo 940 and BMW 520i, the transmission scale factor r between the alternator and the engine speeds has been calculated experimentally. The results can be seen in the Sections 4.1.2 and 4.2.2 of this Report.

The current provided by the alternator is alternate (AC) and it must be transformed into direct current (DC) in order to use it: this process is done via three phase rectifiers diodes. The resulting DC signal shows small amplitude pulses which are directly related to the alternator frequency and thus to the engine speed. Due to the imperfection of the rectification process, in the resulting DC signal it is possible extract the variation of the engine speed caused by the combustion cycles of the cylinders and thus to track the speed of the engine [7]. Fourier transforming the time-variant DC signal over time leads to track the frequency component of interest s_k for time instants k; the measurement $\tilde{s}_k$ is assumed to be related to the true quantity s_k via the relation:

$$\tilde{s}_k = s_k + w_k^s \tag{2.3}$$

where w_k^s is white noise.

2.3 The GPS System: Messages Received by the GPS Receiver

A GPS receiver is arranged to receive data defined within the National Marine Electronics Association (NMEA) specification. When the NMEA specification was written, the goal was to provide to every GPS receiver a line of data completely self-contained, independent from other lines of data, and which include at least the complete PVT (position, velocity and time) information; the line of data is called "sentence".

There are several types of sentences depending on the device category of use, by the way all the standard sentences begin with a two letter prefix that features the device which uses that data: for the GPS receivers category the prefix is GP. The prefix is then followed by a three letter word which defines the contents of the following sentence: each sentence starts with a dollar symbol, can be no longer than 80 characters of ascii text and ends with a carriage return/line feed sequence. The information within the sentence is separated by commas. The first part of a sentence, dollar symbol plus prefix and three letters, is called data type and defines the data which are included in the sentence: each data type has its own unique interpretation defined by the NMEA standard. Nowadays most GPS receivers understand the NMEA standard 0183 version 2. The transfer rate provided by this standard is 4800b/s, which means that only 480 characters can be sent in one second: since a sentence can be long at most 80 characters, less than 6 different sentences can be sent in one second.

During the data acquisition campaigns of this thesis project a Navibe GM720 portable GPS receiver has been used, designed with a SiRF Star III (GSC3f Base band processor with integrated flash memory and RF front end) single chipset [8]. The Navibe GM720 receiver supports standard NMEA 0183 protocol (Version 3.0, sentences GPGSA, GPGGA, GPGSV, GPRMC) and the standard sentences received by this receiver are listed below:

- GPGSA - this sentence provides details on the nature of the fix. It includes the numbers of the satellites being used in the current solution and the DOP (dilution of precision). DOP is an indication of the effect of satellite geometry on the accuracy of the fix.

- GPGGA - this sentence provides the essential fix data with 3D location and accuracy data.

- GPGSV - this sentence, which is called Satellites in View, shows data about the satellites that the unit might be able to find based on its viewing mask and almanac data. It also shows current ability to track this data.

- GPRMC - this sentence is called "the Recommended Minimum", it provides the essential GPS data (position, velocity and time) and looks like:

```
GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230394,003.1,W*6A
```

(Recommended Minimum sentence C, Fix taken at 12:35:19 UTC, Status A=active or V=Void, Latitude 48 deg 07.038' N, Longitude 11 deg 31.000' E, Speed over the ground in knots, Track angle in degrees True, Date - 23rd of March 1994, Magnetic Variation, The checksum data, always begins with *).

In our case we are interested in the velocity information, which is recorded by the GPS by measuring the Doppler effect and it's given in knots (km/h = knots x 1.852): in this work only this first sentence GPRMC has been taken as an information source [9].

2.4 The Kalman Filter

The discrete version of the Kalman filter was chosen as a method to estimate in real time the gear ratio between the speed provided by the GPS receiver and the speed measured via the CL supply of the car, properly post-processed.

The Kalman Filter is a set of mathematical equations which provides an efficient recursive solution to estimate the state of a process minimizing the mean of the squared error and it can be used for linear systems with Gaussian and non-Gaussian noise. The filter is a very useful method because it can be implemented as a smoother (estimates the past state of the process), as estimator (estimates the current state of the process) and as predictor (estimates the future state of the process), and it works also when the precise nature of the model is unknown.

The discrete Kalman filter uses a feedback control in order to estimate the state of a process: it calculates the process state at some instant and it uses the estimation as a noisy measurement feedback. The purpose of the Kalman filter is to estimate the state $x_k \in R^n$ of a discrete-time controlled process that is governed by a linear stochastic difference equation, as follows:

$$x_{k+1} = F_k x_k + G_k w_k \qquad k \geq 0 \tag{2.4}$$

$$y_k = H_k x_k + v_k \tag{2.5}$$

where $y_k \in R^m$ is the measurement, w_k represents the process noise, and its covariance matrix is Q_k, v_k represents the measurement noise, and its covariance matrix is R_k. They are assumed to be independent of each other, white and with normal probability distributions. The resulting Kalman Filter equations for the Innovation Approach used in this thesis project are:

- Prediction Phase - the time update equations

$$e_k = y_k - H_k \hat{x}_{k|k-1} \qquad k > 0 \tag{2.6}$$

$$R_{ek} = H_k P_k H_k^* + R_k \tag{2.7}$$

$$x_{k+1} = x_k + w_k \tag{2.8}$$

$$P_{k+1}^{+} = P_k^{+} + Q_k \tag{2.9}$$

- Update Phase - the measurements update equations

$$\hat{x}_{k+1|k} = F_k \hat{x}_{k|k-1} + K_k e_k \qquad k \geq 0 \tag{2.10}$$

$$K_k = (F_k P_k H_k^* + G_k S_k) R_{ek}^{-1} \tag{2.11}$$

$$P_{k+1} = F_k P_k F_k^* + G_k Q_k G_k^* - K_k R_{ek} K_k^* \qquad k \geq 0 \tag{2.12}$$

$$\hat{x}_0 = x_0 \tag{2.13}$$

$$P_0 = \Pi_0 \tag{2.14}$$

where P_k is the estimate error covariance, while (2.6) is the measurement innovation, or residual. K is chosen to be the gain of the Kalman filter which minimizes the error covariance P_k while x_0 and P_0 are the initialization values [10]. As it can be seen the equations are divided into two phases. The Kalman filtering is an iterative process, so it can be represented as a cycle where the prediction phase projects the current state and the error covariance estimates ahead in time while the update phase adjusts the projected estimation by an actual measurement at that time to obtain improved estimates [11].

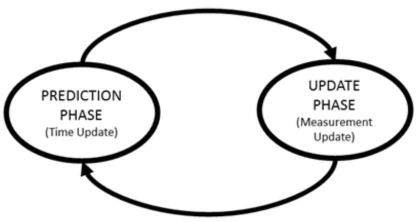

Figure 2.3: The discrete Kalman Filter cycle

In the developed system, the Kalman Filter (implemented in a bench of five blocks, one for each gear) has the task of calculate second-by-second the state variable x_k which is the scale factor of the gear, while the measurement variable y_k is the measure of the true quantity of the vehicle speed measured by the GPS portable receiver. The relation between the measurement variable y_k and the frequency component of interest s_k (2.3) is dependent on the engaged gear i and on the mode of the clutch: the gearbox is assumed to have M forwards gears and if the clutch is engaged:

$$y_k = x_{i,k} s_k \qquad i \in (1, 2, \ldots, M) \tag{2.15}$$

where $x_{i,k} > 0$ are the scale factors of the linear relations for the forward gears i. The implementation of the bench of five Kalman Filters is described in detail in the Section 3.3 of this Report.

Chapter 3

Implementation Description

In this Chapter a complete overview of the implementation solutions adopted during the project is given. The different algorithms used in the process are presented. The first algorithm is the one implemented for the simultaneous acquisition of the CL time-varying signal and the messages containing the speed information from the GPS portable receiver. Then the process of extracting the information about speed from the signal acquired via the CL supply is discussed. Finally the bench of five Kalman filters used to estimate the gear ratio, and so the engaged gear, is presented. In this thesis project an off-line version of the gear ratio estimator is proposed, but a real-time version could be easily developed starting from the results achieved in this work. Moreover the solution proposed has been developed for cars equipped with manual gearboxes consisting of five gears plus the reverse, consequently this solution has to be modified for cars with manual gearboxes consisting of six gears.

3.1 Simultaneous Acquisitions

As presented in detail on Section 2.1 of the System Architecture Chapter, two main signals are involved in the developed system: the first one is the AC time-varying signal acquired from the CL supply, the second is the speed information provided by the GPS receiver. A portable pc is used in order to acquire, and properly process, both signals. These two sources of information have two different access points to the pc: the former signal is acquired via the sound card of the pc through a connector directly plugged on the CL socket, while the GPS receiver is connected to the pc via an USB port. In order to reach the project goal, which is a continuous estimation of the gear scale factor, the two signals must be acquired by the portable computational device simultaneously: a Matlab script has been written for this purpose.

3.1.1 Data Acquisition Algorithm

The high-level technical computing language Matlab provides a Data Acquisition Toolbox which allows the user to acquire analog data with the sound card of the pc (from its microphone input) and converts automatically the analog input into a digital output which can be easily processed by the pc. A typical analog input's data acquisition session consist of four steps: creating a device object, adding channels and controlling acquisition behavior (sampling rate, trigger, duration of the acquisition), executing the device object and acquiring data, and finally deleting the device object [12].

Because the signal of interest has its peak in frequency at less than 500 Hz, and because from the datasheet of the sound card of the pc the range of the sampling rate allowed by the device is known, the sampling rate has been set to the frequency of 5000 Hz which is the lowest sampling rate supported by the sound card driver, as returned by the Matlab command: `daqhwinfo(ai, MinSampleRate)` [12]. As experimentally proven in the laboratory, the microphone input of the portable pc used in the project (Dell E6400) is AC-coupled: a series capacitor arrests the direct component of the input signal. Regarding the GPS portable receiver, it is connected to the pc via an USB connector and it is readable from Matlab simply creating an access to the serial port to which it is connected. The purpose of this acquisition is to have a simultaneous flow of information from both information sources: to do this it is necessary to mark somehow in time the two data sources, in order to have a starting point once the post-processing phase begins. This is the reason why at the beginning of every acquisition two time stamps are saved: the first depends on the internal clock of the pc and is related to the analog input acquisition, while the second is related to the time provided by the GPS atomic clock via the messages received from the portable receiver.

3.2 Frequency Estimation of the Cigarette Lighter Signal

The signal acquired from the CL socket is a DC level which derives from the rectification of the AC current provided from the generator of the vehicle, as explained in Section 2.2 of this Report.

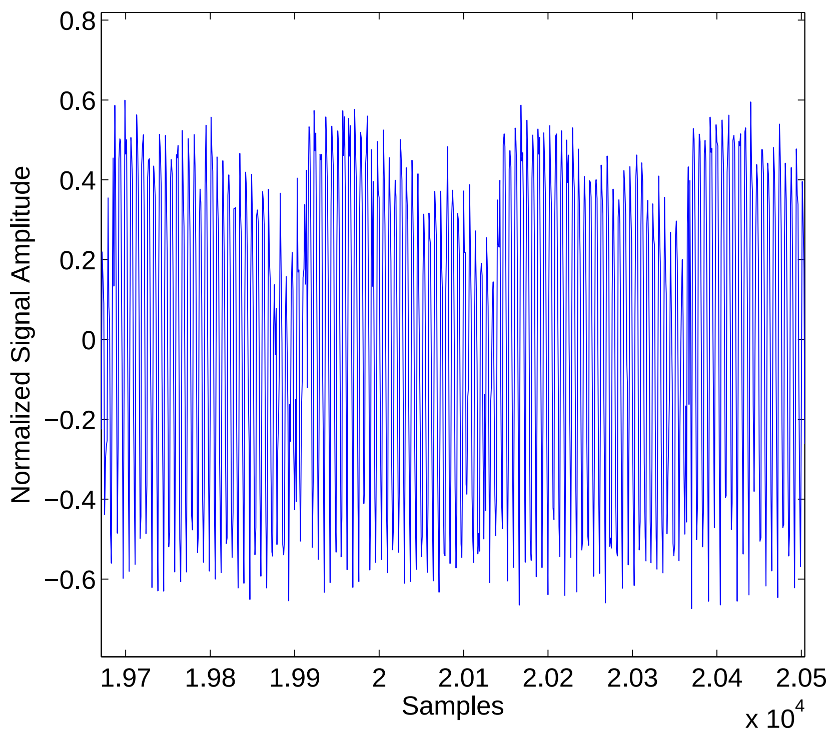

Figure 3.1: Time-varying signal acquired from the CL socket of a vehicle

A time-varying signal with small amplitude variation and a sinusoidal shape is superimposed to the DC signal as shown in Figure 3.1, due to imperfections on the rectification process mentioned above. Thus the voltage signal presents small variations which are related to the engine speed: performing a Fast Fourier Transform (fft) on portions of the signal acquired creates a spectrum (of the portion of the signal) with a peak which corresponds, up to a scale factor and depending on which gear is engaged in that portion of time, at the rpm engine speed of the vehicle: this is the signal of interest s_k as presented in Section 2.2 of this Report.

3.2.1 Detection of the Highest Peak of the Spectrum

The signal acquired from the CL supply with the sound card is a quite good one, which means that it has a high SNR, but some problems occur because its spectrum presents not only the "right" peak proportional to the rpm speed, but also harmonics of the right peak, sometimes a continuous component at very low frequencies, or other disturbances due to enabling, for example, the air conditioning fans or the position indicators of the car, or when the clutch is disengaged.

In order to compare the signal acquired from the CL socket and the one received from the GPS, the first one is windowed with a sliding window centered, iteration by iteration, in the exact same second of the received GPRMC message (see Section 2.3 of this Report) and of a length of 100 ms.

To window the signal, a rectangular window has been chosen: this is the best solution, considering the frequency resolution, because it returns very sharp peaks which are much taller than the peak's tails, as it can be seen in Figure below 3.2 which shows three different windowing of the signal acquired from the CL of a BMW 520i.

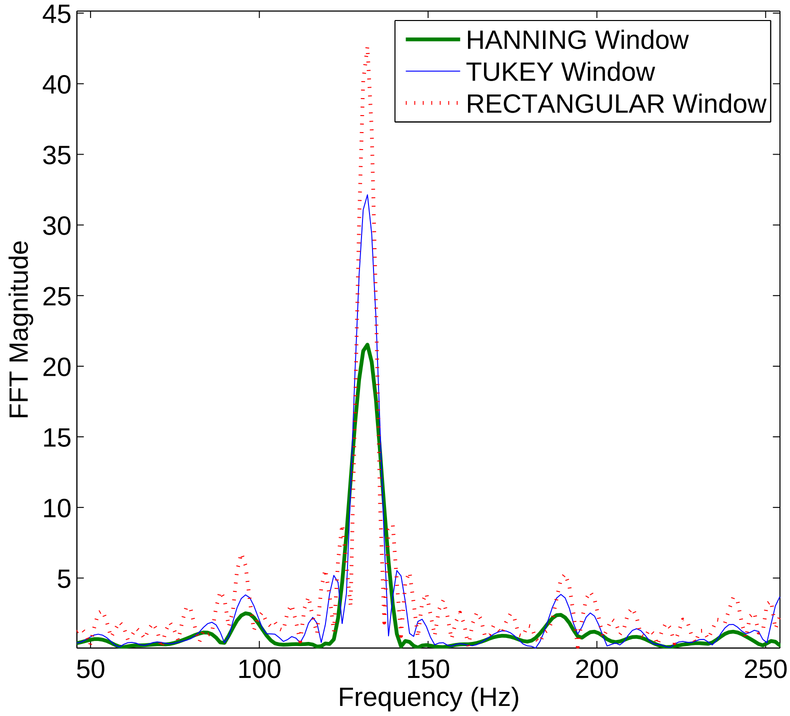

Figure 3.2: Spectra of the signal acquired from the CL socket of a BMW 520i windowed with three different windows

After the windowing, in the time domain, of the CL signal, an fft is performed on it with a sampling rate of 5102 Hz (in order to avoid time drift, as it is explained on the following Section 3.2.2 of this Report) with 4096 points. Once transformed, the main purpose is to detect the highest peak of the spectrum which is the frequency component of interest s_k: in order to do that the Matlab function `findpeaks` has been chosen; as mentioned above, some problems occur when, for some unpredictable windowing, the `findpeaks` function chooses the wrong peak which is sometimes a DC component at very low frequency and sometimes the second (or the third) harmonic taller than the first. To (partially) solve these problems some constraints have been set to force the `findpeaks` function to choose the correct peak, as follows:

- don't take the first peak if at least one harmonic for it doesn't exist;
- arrest the search after 500 Hz;
- consider only the first 8 peaks;
- consider only the peaks higher by 1/5 of the highest peak;
- the minimum distance between two harmonics must be 20 Hz.

3.2.2 Time Drift Compensation

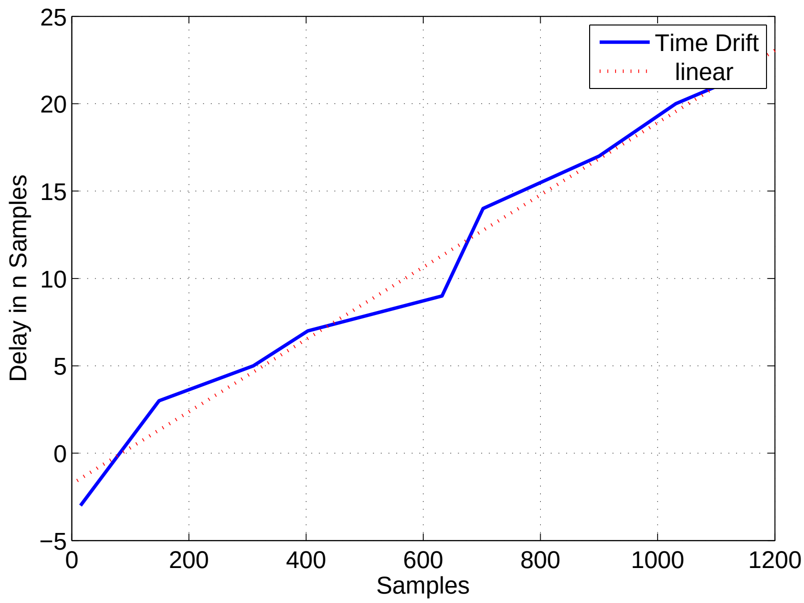

Figure 3.3: Trend of the time drift between the two sources of information and linear regression

In order to have an accurate synchronization of the two sources of information, another additional constraint must be implemented because a small time drift occurs between them: as can be seen from Figure 3.3, having more samples brings to a (linear) growing of a time delay between the two sources.

Each delay value in the graph has been obtained by manual inspection on several samples of the acquired data. Studying the trend of the delay, the drift has been quantified in time and the corresponding adjustment has been calculated, as the slope of the linear regression line, as follows:

$$y_{td} = 0.02x_{td} - 1.76 \tag{3.1}$$

$$\frac{\Delta T}{T_{nom}} = 0.02 \tag{3.2}$$

$$f_{nom} = \frac{1}{T_{nom}} = 5000\ [Hz] \tag{3.3}$$

$$\bar{T} = T_{nom} - \Delta T \tag{3.4}$$

$$\bar{f} = \frac{1}{\bar{T}} = 5102\ [Hz] \tag{3.5}$$

The adjustment has been finally applied to the sampling frequency, which is from now on 5102 Hz (3.5).

3.2.3 Post-Processing

After the application of the previous two solutions to the available datasets, a rough version of the tracking of the rpm speed compared to the speed measurement from the GPS y_k is achieved. In this rough version of the processing, for some windowing of the DC level, still some wrong detections of the right peak occur, however the filtering with five Kalman Filters works and the goal of tracking, second-by-second, the current gear engaged is achieved, even if the performances are worse (see the result on the Appendix A of this Report).

With an additional step it is possible to reach better and faster performances: that's why a post-processing block has been implemented in order to correct the detections of wrong peaks. Compare the trend of the signal of interest s_k with the speed measurements from the GPS y_k, some extreme jumps of the speed value can be seen: some of them are related to the disengagement of the clutch pedal but some others are clear misdetections of the right peak (see Figure 3.4).

The post-processing algorithm consists of comparing three elements (the current, the previous and the next) of the record of the peaks' values; it's an iterative algorithm in order to scan each element of the record. First it starts by setting the second element of the slope as the current position;

then it compares the previous and the next element (with respect to the current) and if the values of these two peaks are the same up to a range of ±10 Hz, the value of the current element is replaced by the mean of the two elements, otherwise the current element remains the same. Last the current position is shifted to the next element and the algorithm runs again. For the datasets acquired during the second acquisition (conducted on board a BMW 520i), a further enhancement has been necessary: after the post-processing algorithm, the remaining extreme values, clearly due to wrong detection of the peak (like the ones two or three times higher than the previous and the next ones, identified as harmonics), replaced by the value of the previous or the next element. A smoother version of the tracking is thus reached (see Figure 3.5), and consequently better performances are achieved in the next Kalman filtering block.

3.3 Sensor Fusion: Gear Ratio Estimation

The purpose of this last algorithm is to design a bench of five Kalman Filters in order to calculate, second-by-second, the estimation of the scale factor of the gear engaged at each second. The scale factor is defined as:

$$x_{i,k} = \frac{y_k}{s_k} \, . \tag{3.6}$$

As mentioned above, this solution is suitable for vehicles equipped with manual gearboxes consisting of five gears plus the reverse.

3.3.1 Bench of Five Kalman Filters

In order to implement the bench of Kalman Filters we used the Kalman Filter equations with the Innovation Approach, consisting of time and measurement update phases, as presented in the Section 2.4 of this Report [10]. In this implementation all the values are scalar; the gear scale factor to be estimated is $x_{i,k} \in R$ where $i = 1, ..., 5$ (the gears of the gearbox) (3.6), and the following assumptions are used: $y_k \in R$ is time variant and equal to the GPS speed in Km/h, H_k is time variant and equal to the CL speed in rpm, w_k and v_k are Gaussian, consequently we have:

$$F_k = 1, G_k = 1 \tag{3.7}$$

$$Q_k = cov(w_k) = constant \tag{3.8}$$

$$R_k = cov(v_k) = constant \tag{3.9}$$

$$S_k = noises\ crosscovariance = 0 \tag{3.10}$$

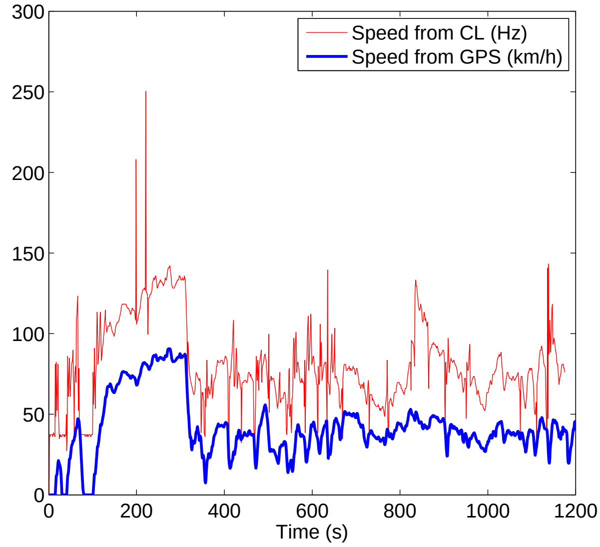

Figure 3.4: Comparison between the CL signal s_k (not processed) and y_k of a 20 minutes long dataset in moving conditions

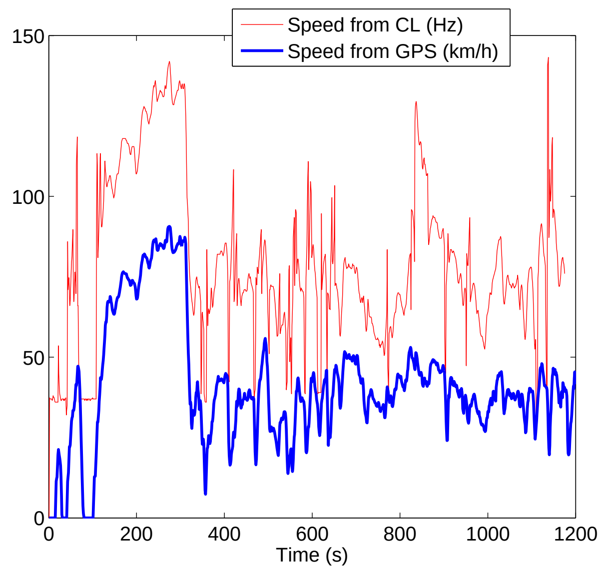

Figure 3.5: Comparison between the CL signal s_k (post-processed) and y_k of a 20 minutes long dataset in moving conditions

A Matlab script has been written: it includes five different Kalman Filters, one for each gear; second-by-second the bench of filters computes the prediction phase of every Kalman Filter. Once the bench has computed the prediction phase for every gear, it is able to calculate the decision criterion needed to decide on which of the five gears the driver is using at that very second. As decision criterion the bench computes the squared innovation over the $R_{e_{i,k}}$ and then it chooses the lowest value of the five, which is supposed to be the one related to the actual gear used by the driver at every second:

$$min\left(\frac{(e_{i,k})^2}{R_{e_{i,k}}}\right). \tag{3.11}$$

The update phase is then performed only for the filter corresponding to this gear. In addition a threshold on the decision criterion has been set, to detect when the clutch is pressed: if the value of the criterion is smaller than this threshold, none of the gears is updated. The Kalman Filters can't work without the initialization of the state variables $x_{i,0}$ and their covariances $P_{i,0}$: we choose to use values tabulated in mechanical references of the two cars used during the second and third acquisition, as reported in Section 4.2.3.2 and 4.3.2 of this Report. Moreover, in order to test the robustness of the system, other initialization values have been used: also in these cases good results have been reached. In Figure 3.6 a block diagram of the bench of five Kalman Filters.

An accurate phase of calibration of the different parameters and the initialization values of the filters has taken place after the second and the third measurement campaigns so that better performances have been reached: the results are presented in the Sections 4.2.3.3 and 4.3.2 of this Report.

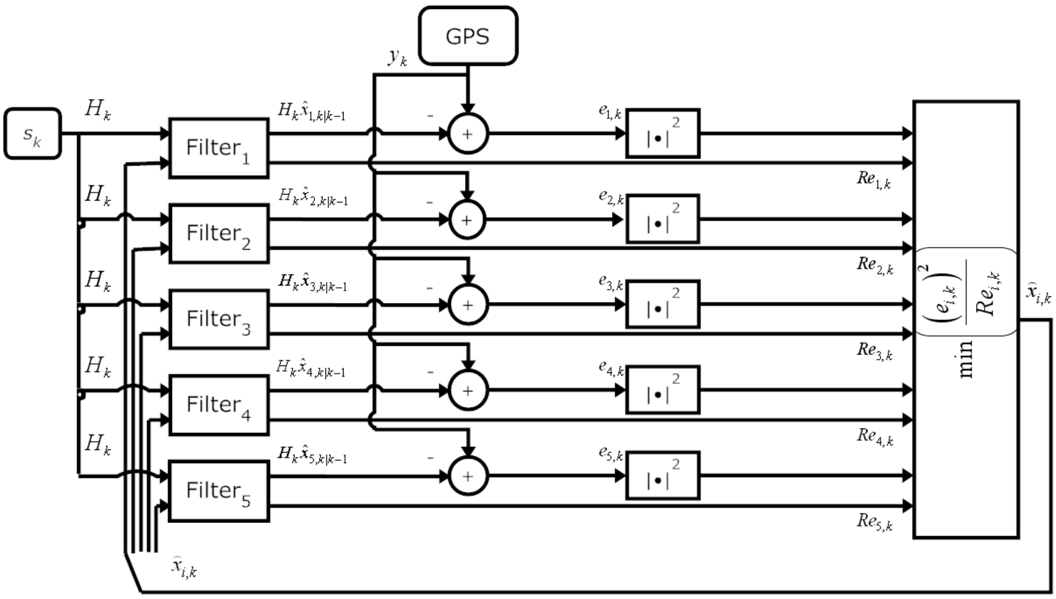

Figure 3.6: Block diagram of the bench of five Kalman filters

Chapter 4

Measurement Campaigns and Results

In this Chapter the three measurement campaigns conducted during the project, and their results, are presented. During the experimental acquisitions, which have taken place between August and November 2010 in the city of Stockholm, Sweden, and surroundings, three different cars have been used in order to provide an exhaustive validation of the algorithms developed.

4.1 First Data Acquisition - VOLVO 940

The aim of the first measurement campaign was to test the acquisition with the sound card algorithm and in particular to see how the signal acquired from the CL supply looks like. In this particular case, no GPS receiver has been used.

4.1.1 Measurement Campaign

The first measurement campaign has taken place on August the 30th, 2010 with a Volvo 940: the car has been kept in stationary condition in order to acquire different short datasets related to different rpm values. The purpose of acquiring different datasets in different rpm speeds is to have a complete overview of the transmission ratio r between the angular speed of the engine and the angular speed of the generator (for a theoretical presentation of the topic see Section 2.2 of this Report). A preliminary version of the algorithm presented in Section 3.1.1 has been used: the algorithm consists only of the analog input data acquisition session. Because it was the first experimental acquisition for this purpose, and because it wasn't easy to predict the expected values of the highest peak in frequency, the sampling frequency used has been set to a standard value of 44.1 kHz. Each acquisition length is five seconds: during these periods of time the gearbox has been kept in idle mode and the rpm speed has been brought to the almost stable values of 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500 by a visual inspection of the car's tachometer.

4.1.2 Results

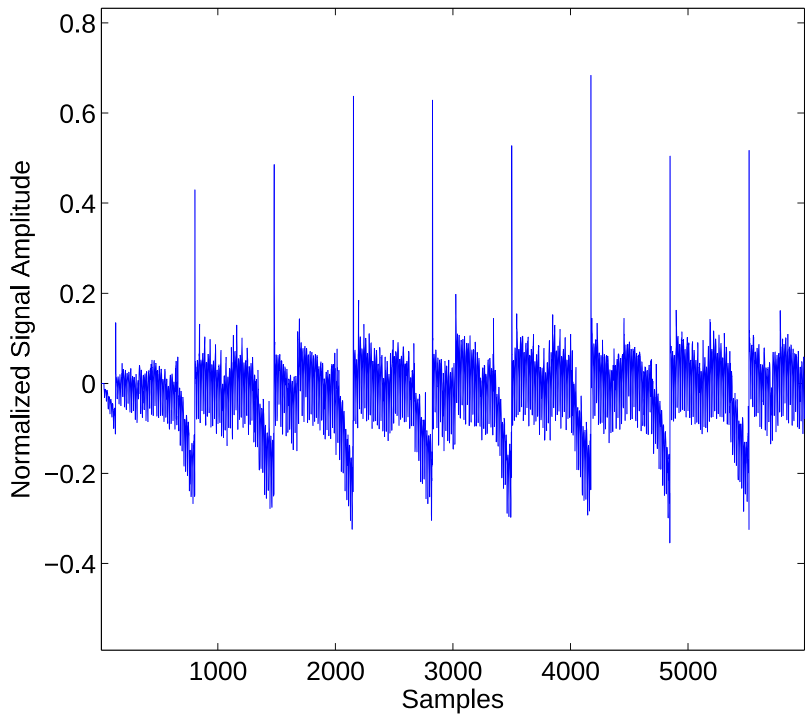

Figure 4.1: Time-varying signal acquired from the CL socket of a VOLVO 940, in stationary conditions at 2000 rpm

The Figure 4.1 shows the signal acquired from the CL socket with the sound card of a pc in the time domain, in particular the dataset for 2000 rpm. As can be seen from the Figure, the DC-level presents a time-varying signal with small amplitude variation and a sinusoidal shape superimposed, due to imperfections on the rectification process mentioned on Section 2.2 of this Report.

In Figures 4.2 and 4.3 are depicted the power spectral density (PSD) of one dataset (2000 rpm) of the signal acquired from the CL supply and its zoom in low frequency, where the highest peak proportional to the rpm speed is located. The time varying signal has been processed by the Matlab function `pwelch`.

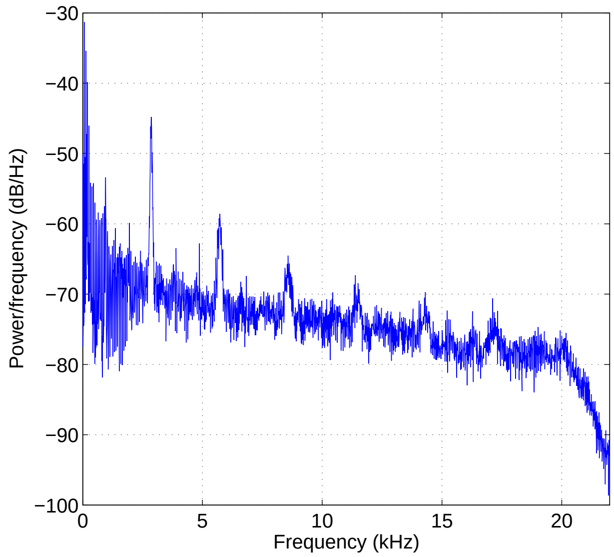

Figure 4.2: PSD of the signal acquired from the CL socket of a VOLVO 940, in stationary conditions at 2000 rpm

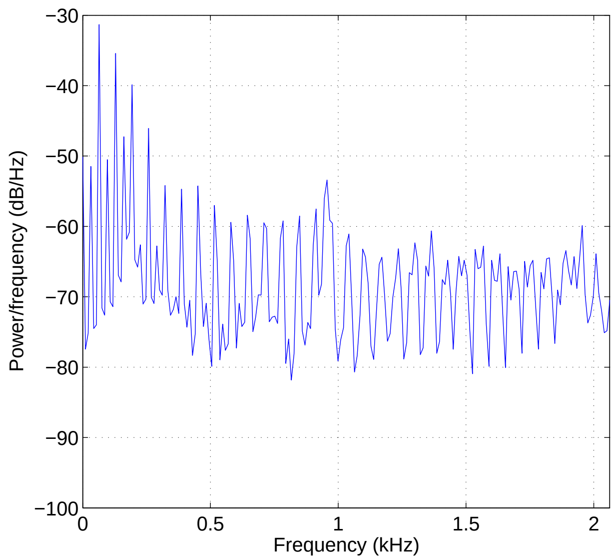

Figure 4.3: Zoom in low frequencies of the PSD of the signal acquired from the CL socket of a VOLVO 940, in stationary conditions at 2000 rpm

In the frequency domain the peak of interest is clearly recognizable in the spectrum (see Figure 4.3) where other harmonics and distrubances are present. The peak is proportional to the engine speed up to the transmission ratio. Then the values of the highest peak of the spectrum have been extracted from each dataset, in order to experimentally calculate the transmission ratio $\hat{r}$ between the two angular velocities:

$$\hat{r} = \frac{f_A}{f_E} \tag{4.1}$$

where f_A is equal to the frequency of the highest peak of the spectrum and f_E is the value of the related rpm speed normalized on 60 seconds. The Table 4.1 presents the numerical results for the experimentally calculated scale factor $\hat{r}$, which are very close to the theoretical ones presented in Section 2.2 of this Report.

Table 4.1: f_E,f_A,$\hat{r}$ values for a VOLVO 940 in stationary conditions

rpm	f_E (rpm/60)	f_A (Hz)	$\hat{r}$
1000	16.67	31	1.86
1500	25	51	2
2000	33.33	65	1.95
2500	41.67	81	1.94
3000	50	101	2
3500	58.33	111	1.90
4000	66.67	129	1.93
5500	75	150	2

Representing the results on a slope, it is possible to see from the Figure 4.4 below that the trend is linear as expected.

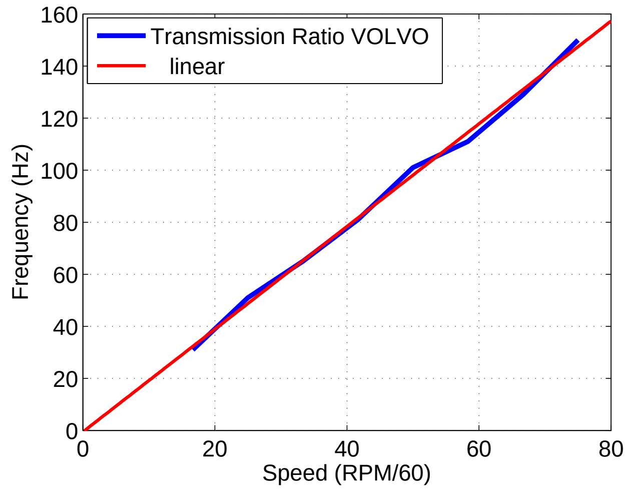

Figure 4.4: Slope of the frequency peaks vs normalized rpm values and linear regression (VOLVO 940)

4.2 Second Data Acquisition - BMW 520i

The aim of the second measurement campaign was to acquire different datasets in mixed driving conditions in order to have an exhaustive amount of data to test and properly calibrate both the post-processing algorithm and the bench of five Kalman Filters.

4.2.1 Measurement Campaign

The second measurement campaign has taken place on October the 4th, 2010 and a BMW 520i has been used for this purpose: first the car has been kept in stationary condition in order to acquire short datasets related to different rpm speeds, then two 20 minutes long datasets in moving conditions have been acquired and finally some short acquisitions on a specified gear, have been made. Because a change of the car occurred between the first and the second campaign, the decision has been made to acquire again data in stationary conditions to experimentally calculate the transmission ratio $\hat{r}$ for the BMW 520i: we performed 5 seconds long different captures with the gearbox kept in idle and the rpm speed brought to 1500, 2000, 2500, 3000, 3500, 4000, 4500. Then the acquisition campaign in moving conditions has started: driving around the city of Stockholm and its surroundings, two 20 minutes long acquisitions in exhaustive mixing driving condition plus some short acquisitions for a specified gear have been performed. In order to acquire the data both from the CL socket and the GPS receiver, during this campaign the data acquisition algorithm presented in Section 3.1 has been used. Then the datasets related to the moving conditions have been processed and filtered, after a proper calibration phase, with the algorithms presented in Sections 3.2 and 3.3 of this Report.

4.2.2 Results of Stationary Acquisitions

The stationary conditions captures have been performed in order to calculate the transmission ratio $\hat{r}$ for the BMW 520i: extracting the highest peak of the spectrum of the signal acquired from the CL supply (f_A) for different rpm speed values (f_E - rpm normalized on 60 seconds), it is possible to draw the transmission ratio $\hat{r}$ as in (4.1). The table below presents the numerical results for the experimentally calculated scale factor $\hat{r}$ of the BMW 520i, which are very similar to the theoretical ones presented in Section 2.2 and to the ones calculated for the Volvo 940 in Section 4.1.2.

Table 4.2: f_E,f_A,$\hat{r}$ values for a BMW 520i in stationary conditions

rpm	f_E(rpm/60)	f_A (Hz)	$\hat{r}$
1500	25	84	3.3
2000	33.33	111	3.3
2500	41.67	122	2.9
3000	50	158	3.2
3500	58.33	170	2.9
4000	66.67	195	2.9
5500	75	230	3.1

4.2.3 Results of Moving Acquisitions

In the following are presented some meaningful results obtained from the real datasets acquired in moving conditions during the second measurements campaign.

The Two Sources of Information

The trend in time is shown of the two concurrent sources of information of our system (the frequency component of interest s_k and the speed from the GPS receiver y_k) in Figure 4.5.

As can be seen from Figure 4.5, the frequency estimation of the CL signal, consisting on the algorithm used to detect the right peak of the spectrum of the CL signal plus the time drift compensation and the post-processing solution (presented in Sections 3.2.1, 3.2.2, 3.2.3), works properly and provides satisfactory results according to the smoothness of the slope and to the good correspondence with the real speed value recorded by the GPS.

Comparison of the two trends leads to an important result: as can be seen from the histogram in Figure 4.6, depicting the speed measurement of the GPS above the correspondent speed derived from the CL signal, five groups of clusters are easily recognizable. The clusters of the histogram are interpreted to correspond to the five different gear scale factors and the spread out values correspond to time instants during which the clutch is disengaged. The values of the five gear scale factors x_i experimentally obtained and depicted in the histogram above (0.15 for the first gear, 0.25 for the second, 0.38 for the third, 0.52 for the fourth, 0.64 for the fifth) have been used as real values to which the estimated scale factors should converge.

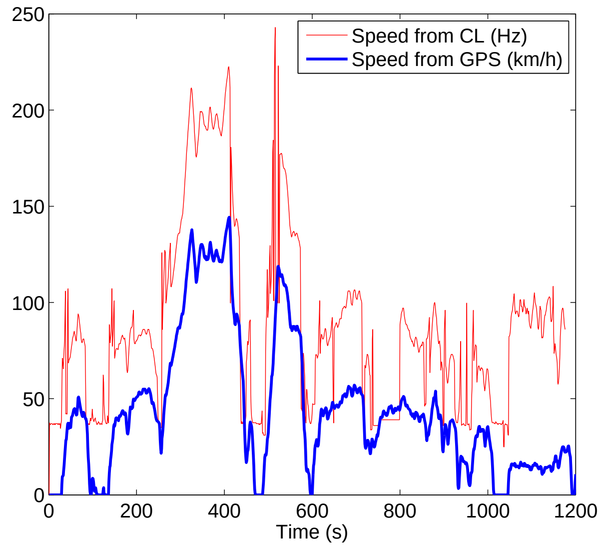

Figure 4.5: Comparison between the CL signal s_k (post-processed) and y_k of a 20 minutes long dataset in moving conditions on board a BMW 520i

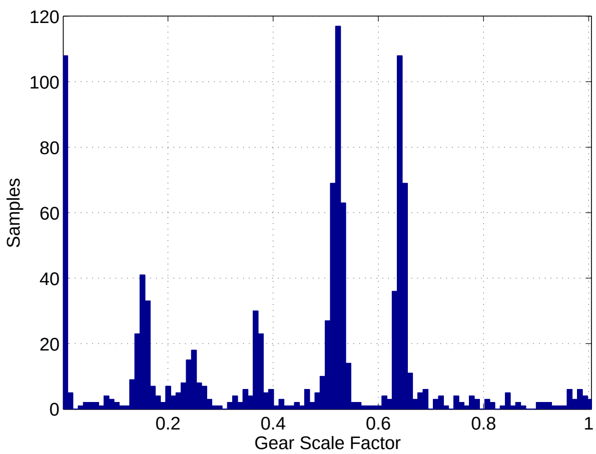

Figure 4.6: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a 20 minutes dataset in moving conditions on board a BMW 520i.

Calibration of the Kalman Filters Parameters with Synthetic Data

Once properly processed and synchronized, the two sources of information are sent to the bench of five Kalman Filters in order to perform the sensor fusion which estimates the gears scale factors: the implementation of the filters is presented in detail in Section 3.3.1, and, as it is highlighted there, a calibration phase has been necessary in order to obtain meaningful results. For the calibration phase, the second dataset acquired (20 minutes long) has been processed in order to create a synthetic dataset with *a priori* quantized five gears: the results are shown is Figure 4.7. Using these quantized gears, synthetic values of the engine speed (in rpm) have been generated, dividing the GPS speed by the fixed scale factors; then a random noise has been added to the synthetic dataset. A synthetic dataset like the one created for this project is a very useful mean in order to calibrate a system because it enables the knowledge of which gear is engaged at every second; later on, after the application of the filters to the dataset, it's easier to correct eventual misdetections of the filters with a careful calibration.

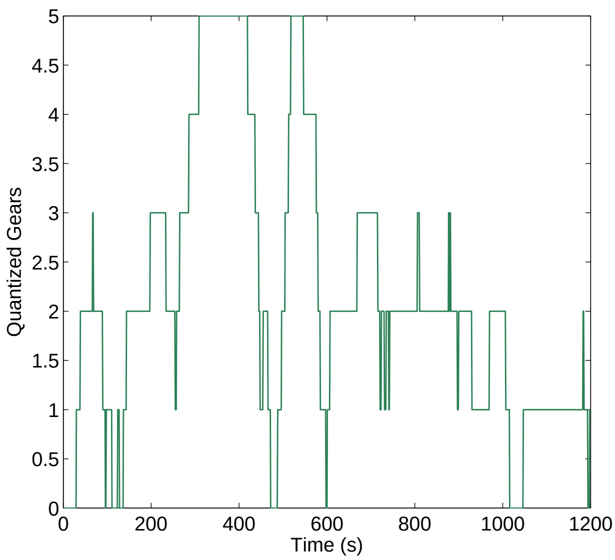

Figure 4.7: Trend of a 20 minutes dataset (BMW 520i) quantized into five values

The calibration of different parameters, like $x_{i,0}$, $P_{i,0}$, Q, R and the threshold for the detection has been conducted as follows. In order to initialize the state variables $x_{i,0}$ some tabulated values of the gear scale factor ratios have been used: those ratios have been calculated from the mechanical references of the gearbox specification of the BMW 520i as follows [13]:

$$\frac{x_2}{x_1} = 1.68; \; \frac{x_3}{x_2} = 1.51; \; \frac{x_4}{x_3} = 1.37; \; \frac{x_5}{x_4} = 1.22; \tag{4.2}$$

For the covariance of the state variables' initialization $P_{i,0}$ a fixed value of (2×0.3^2) $\forall i$ has been chosen. This means the state variables' initializations values are very reliable.

For the covariance of the measurement noise R, under the assumption that it is constant, a value of 30 $(\mathrm{km/h})^2$ has been chosen. This means the measurements are not too reliable.

For the covariance of the process noise Q, under the assumption that it is constant, the value of 0.00000025 has been chosen, which means the model we developed is very reliable.

Finally a threshold for the detection of the "clutch engaged" condition in the criterion $\frac{(e_{i,k})^2}{R_{e_{i,k}}}$ has been set equal to 5.

The application of the bench of five Kalman Filters to the synthetic dataset with *a priori* quantized five gears is shown in Figure 4.8: in red the real values of the scale factors $x_{i,0}$ extracted from the histogram as explained in Section 4.2.3.1 (0.15 for the first gear, 0.25 for the second, 0.38 for the third, 0.52 for the fourth, 0.64 for the fifth), in green the trend of the covariance of the state estimation error $P_{i,k}$, in blue the trend of the scale factors $\hat{x}_{i,k}$ (blue stars when the scale factor is updated). As can be seen from Figure 4.8, for the synthetic dataset the Kalman filtering works properly and the values of the estimated gear scale factors converge quickly to the real values for all the five gears.

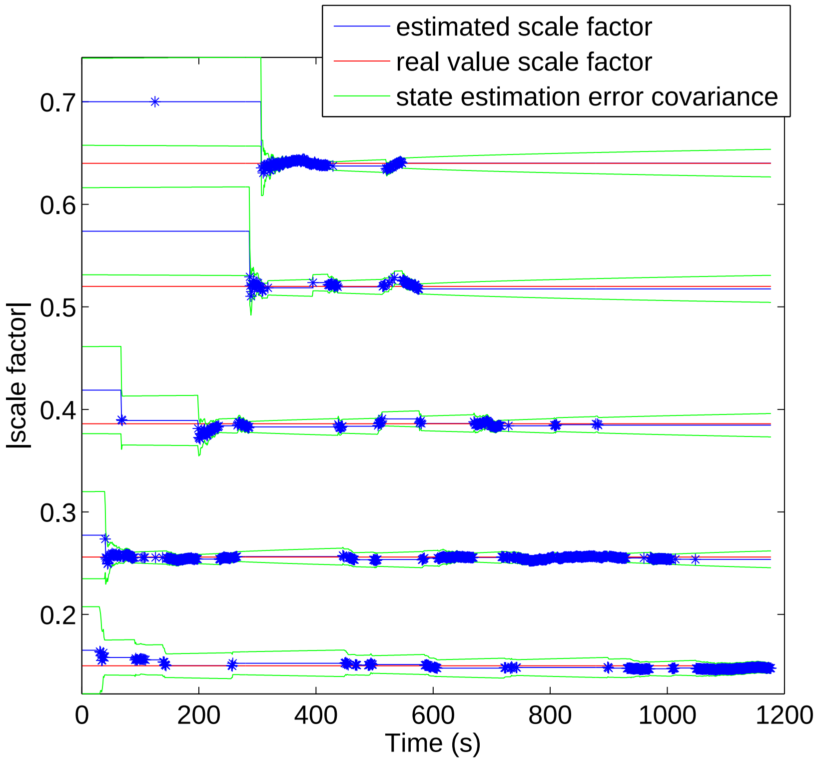

Figure 4.8: 20 minutes long synthetic dataset (BMW 520i) filtered with the bench of five Kalman Filters

Kalman Filtering of a Real Dataset

In Figure 4.9 below is presented the application of the calibrated bench of Kalman Filters to a combination of the two 20 minutes long datasets (40 minutes in total) acquired during the second measurement campaign; the values of the calibrated parameters used are the following:

- Covariance of the state variables' initialization $P_{i,0} = (2 \times 0.3^2)\ \forall i$
- Covariance of the measurement noise $R = 30\ (\mathrm{km/h})^2$
- Covariance of the process's noise $Q = 0.00000025$
- State variables $x_{i,0}$ initialized by small variations (at maximum $\pm 20\%$) of tabulated values of ratios between different gears scale factors (4.2). The decision to try small variations has been taken in order to validate the filter for a wide range of different cars: indeed cars can be equipped

with different gearboxes which present different gear ratios. The typical gear ratios values of different cars differ from each other by at most a $\pm 20\%$: for example a Land Rover Defender GFT MT-82 (example of wide-ratio gearbox) has ratios less than 20% larger than those for Porsche GT3 911 G96.96 (example of close-ratio gearbox).

As can be seen from Figure 4.9, for the 40 minutes long dataset the bench of five Kalman Filters developed and calibrated works properly and the values of the estimated gear scale factors converge quickly to the real values for all the five gears. In order to test the algorithm, the bench of filters has been calibrated with different values of the parameters, in particular different initialization of the state variables $x_{i,0}$ have been used and good results have been obtained as well. The bench has also been tested with an un-processed dataset (see Figure 3.4): the results are still good even if misdetections of some peaks occurred and lead to a slower convergence to the true values of the scale factors (for the results, see Appendix A of this Report).

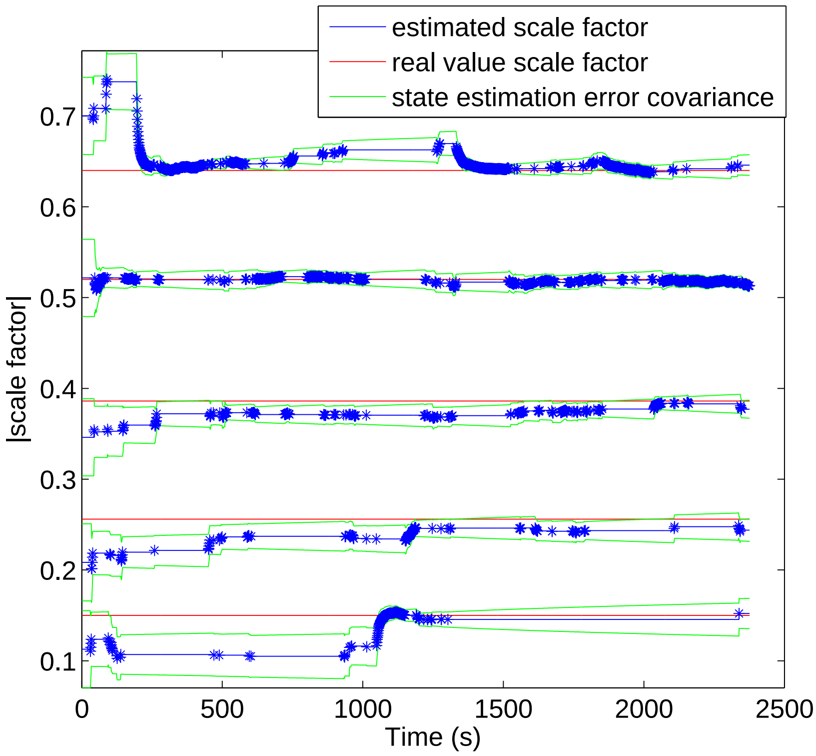

Figure 4.9: 40 minutes long dataset (BMW 520i) filtered with the bench of five Kalman Filters

Finally a "switching off" of the GPS signal has been done in order to validate the robustness of the algorithm: the switching was made in a period of approximately 100 seconds and this period was chosen from one of the dataset where the constant use of the same gear was clearly recognizable. Figure 4.10 shows that the tracking of the speed provided by the bench of five Kalman Filters works properly even when the main source of information (the speed from the GPS receiver) is missing. As can be seen in Figure 4.10 the maximum error between the speed measurement provided by the GPS and the speed extracted from the CL signal, when the gear engaged is constant, is ~ 1 (km/h).

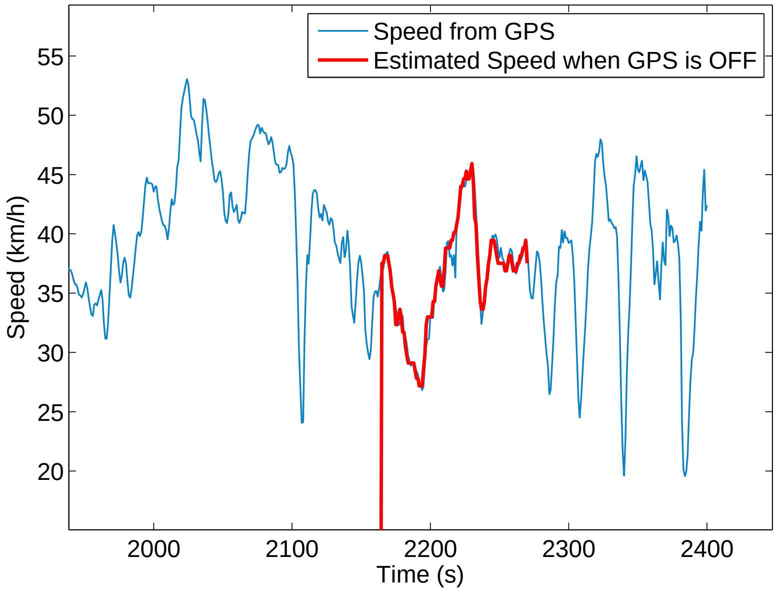

Figure 4.10: Tracking of the speed value provided by the bench of Kalman Filters when the GPS is OFF (BMW 520i)

4.3 Third Data Acquisition - FORD Fiesta 1.6 Tdci

The aim of the third measurement campaign was to acquire more datasets, in mixed driving conditions, in order to have a good amount of data to provide an exhaustive validation of results reached with the bench of five Kalman Filters developed.

4.3.1 Measurement Campaign

The third measurement campaign has taken place on November the 19th, 2010 and a Ford Fiesta 1.6 Tdci has been used for this purpose: the car has been driven around the surroundings of Stockholm in order to acquire many datasets in mixing driving conditions and five datasets in single specified gear, one for each gear. During this campaign the algorithms presented in Sections 3.1, 3.2, 3.3 have been used to acquire the data and then to process and filter them.

4.3.2 Results

In Figures 4.11 and 4.12 two plots related to one of the dataset acquired in moving conditions are provided, depicting the relation between GPS provided speed and the measurement via the CL. Furthermore, an histogram of the speed measurement of the GPS above the correspondent speed derived from the CL signal is presented.

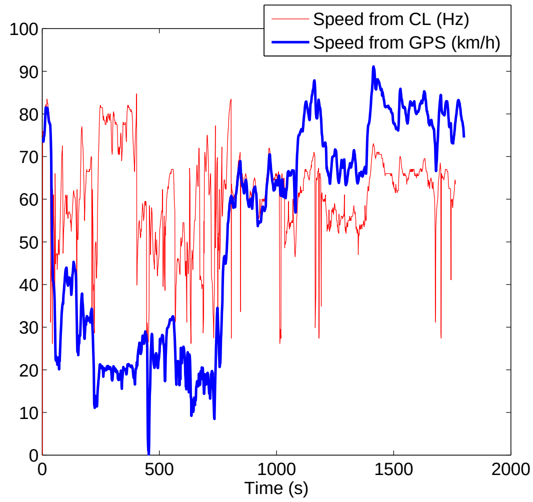

Figure 4.11: Comparison between the CL signal s_k (post-processed) and y_k of a 30 minutes dataset in moving conditions on board a FORD Fiesta 1.6Tdci

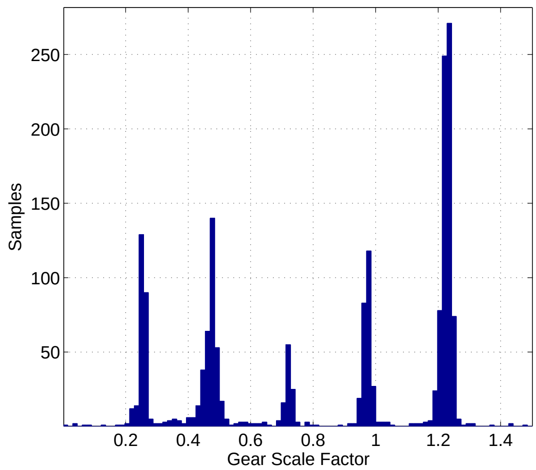

Figure 4.12: Histogram of the speed values provided by the GPS y_k over the speed from the CL signal s_k, for a 30 minutes long dataset in moving conditions on board a FORD Fiesta 1.6Tdci

The values of the five gear scale factors experimentally obtained and depicted in the histogram above (0.25 for the first gear, 0.48 for the second, 0.72 for the third, 0.98 for the fourth, 1.23 for the fifth) have been used as real values to which the estimated scale factors should converge. The same processing procedure has been applied to the other datasets acquired during the campaign: in particular, interesting results about the datasets recorded on specified single gears are presented in the Appendix B of this Report. Because a change of car occurs between the second and the third acquisition, the calibration made for the bench of Kalman Filters used to filter the data acquired with the BMW 520i is not entirely valid in this case. The values of the covariance of the state variables' initialization $P_{i,0}$, of the covariance of the measurement noise R and of the covariance of the process's noise Q have been chosen to be the same as for the BMW 520i, respectively (2×0.3^2), $30(km/h)^2$ and 0.00000025. In order to initialize the state variables $x_{i,0}$ small variations (at maximum $\pm 10\%$) have been used for tabulated values of ratios between different gears scale factors; those values have been taken from the mechanical references of the gearbox specification of the FORD Fiesta 1.6 Tdci as follows [6]:

$$\frac{x_2}{x_1} = 1.88; \ \frac{x_3}{x_2} = 1.44; \ \frac{x_4}{x_3} = 1.27; \ \frac{x_5}{x_4} = 1.26; \tag{4.3}$$

As can be seen from Figure 4.13, for the 30 minutes long dataset the bench of five Kalman Filters developed and calibrated works properly and the values of the estimated gear scale factors converge after a few samples to the real values for all the five gears.

The bench has also been tested with an un-processed dataset: the results are still good even if misdetections of some peaks occurred and lead to a slower convergence to the true values of the scale factors (for the results, see Appendix A of this Report).

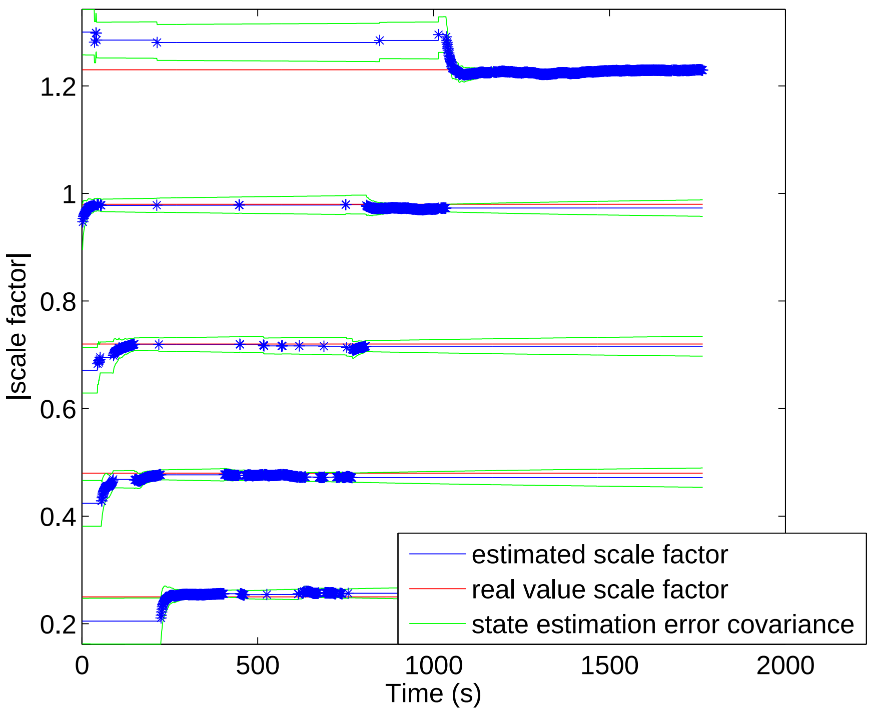

Figure 4.13: 30 minutes long dataset (FORD Fiesta 1.6 Tdci) filtered with the bench of five Kalman Filters

Chapter 5

Conclusions and Future Work

The purpose of this thesis project was to develop a low cost aiding system to the GPS service in order to enhance the robustness and the availability of the positioning and navigation functions. The idea was to use as an on board source of information the signal acquirable from the CL socket of a vehicle. This signal, Fourier transformed, presents a peak in frequency which is proportional to the engine speed of the car [7] and in particular is a ready-to-use source (no extra sensors are needed). Combining this information with the vehicle's speed value provided by a portable GPS device, is it possible to experimentally see that the two signals are equal up to a scale factor which is related to the gear engaged at every instant. Tracking this scale factor second-by-second offers the possibility to provide the speed information even if the GPS service is missing (in tunnels, in case of multipath, etc.) and thus support its positioning and navigation functions.

The system consists of three algorithms implemented in Matlab: it provides a simultaneous acquisition of the two pieces of information, their proper processing and finally their fusion through a bench of Kalman Filters whose output is the estimated gear scale factor at every second.

In order to provide an exhaustive validation of the system, three different measurement campaigns, using three different cars (VOLVO 940, BMW 520i, FORD Fiesta 1.6 Tdci), have been conducted during the thesis project. The first campaign has been made in order to test the data acquisition algorithm while the following two campaigns have been conducted to acquire a satisfactory amount of real datasets to test the sensor fusion algorithm.

Furthermore, a paper has been written on an alternative gear scale estimation method based on the datasets acquired for this thesis project [14].

The results are exhaustively presented in Chapter 4 of this Report: the whole system works properly and good results have been reached. In particular for the datasets of the second and third acquisitions, the filtering consisting of five Kalman Filters, one for each gear, provides excellent results: by the adopted calibration of the parameters (see Sections 4.2.3.2 and 4.3.2), after only a few samples all the five scale factors of the real datasets start to converge to the true values, and the few updating errors can be referred to the wrong detection of the peak in the CL signal.

Consequently an interesting future enhancement of the system can be the development of a more performing peak detection algorithm in order to completely eliminate the updating errors which may have occurred. Additionally in this thesis project an off-line version of the system has been implemented: in the future an extension employing a real-time version could be a very interesting challenge.

Appendix A

Bench of five Kalman Filters applied to un-processed datasets

- BMW 520i

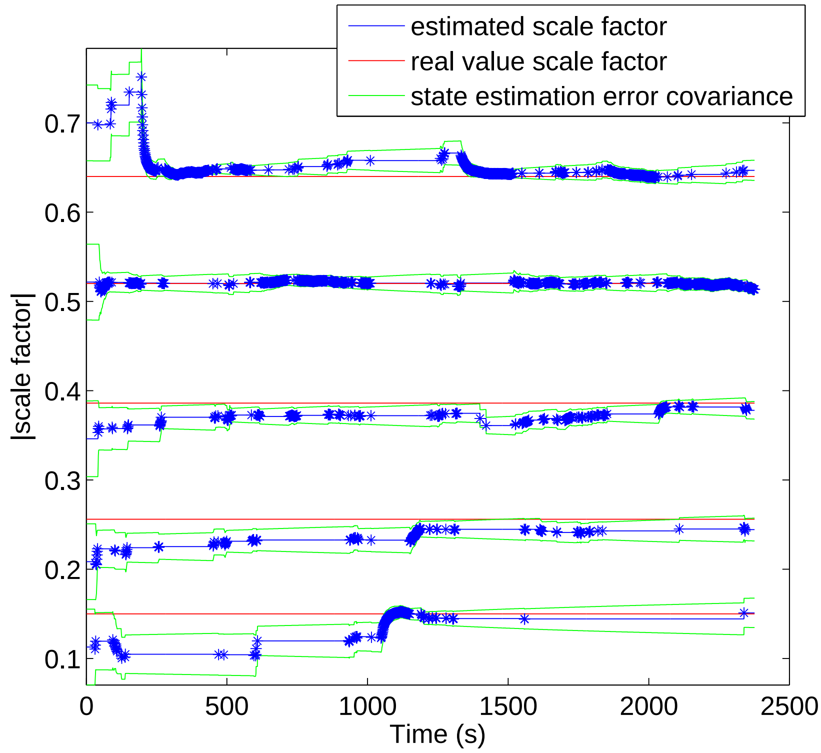

Figure A.1: 40 minutes long dataset un-processed (BMW 520i) filtered with the bench of five Kalman Filters

- FORD Fiesta 1.6 Tdci

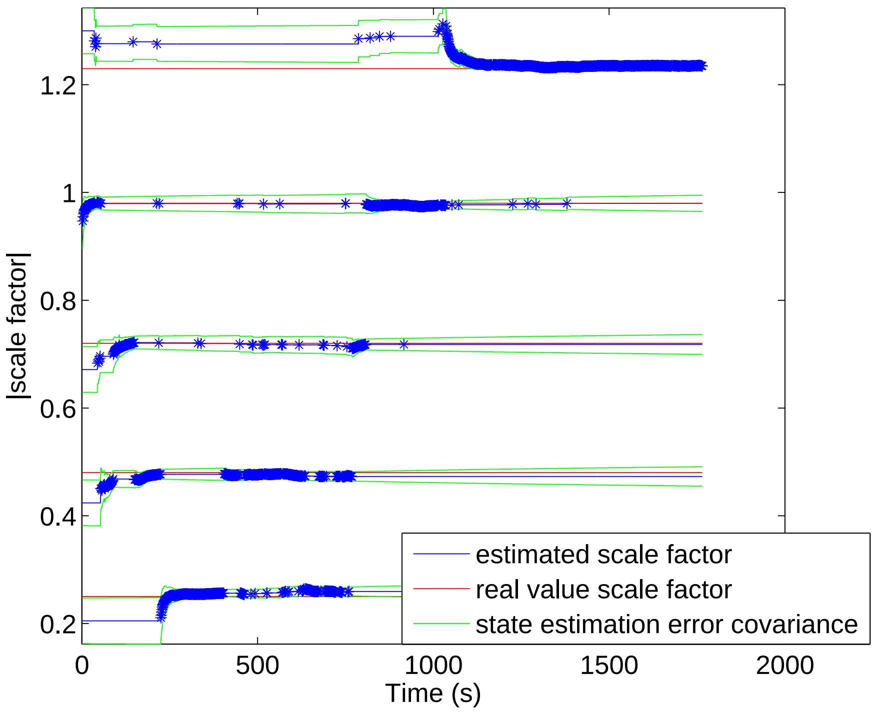

Figure A.2: 40 minutes long dataset un-processed (FORD Fiesta 1.6 Tdci) filtered with the bench of five Kalman Filters

Appendix B

Trends and Histograms of five single gear datasets (FORD Fiesta 1.6 Tdci)

- First gear

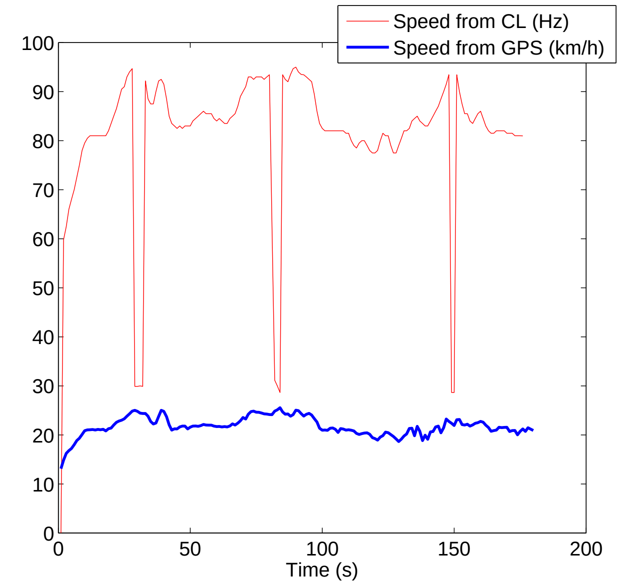

Figure B.1: Comparison between the CL signal s_k (post-processed) and y_k of a dataset in moving conditions on the first gear

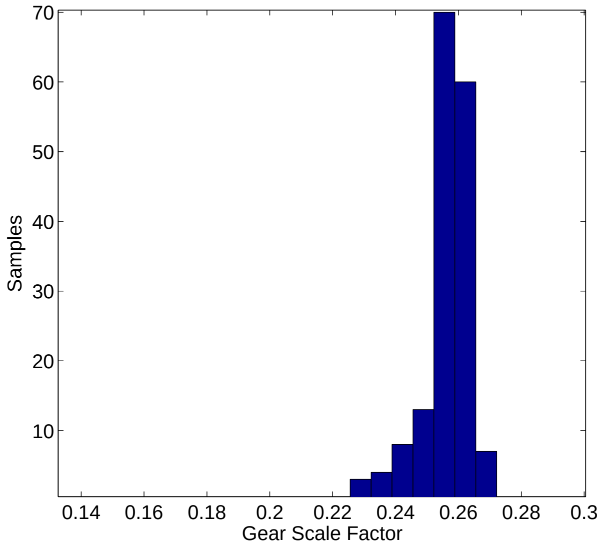

Figure B.2: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a dataset in moving conditions on the first gear

- Second gear

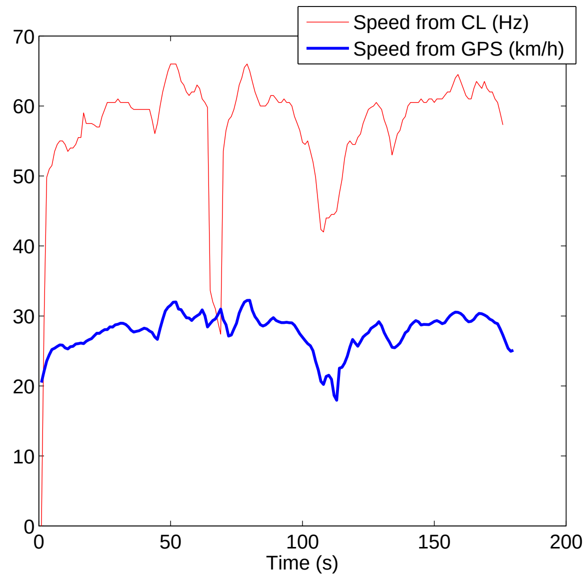

Figure B.3: Comparison between the CL signal s_k (post-processed) and y_k of a dataset in moving conditions on the second gear

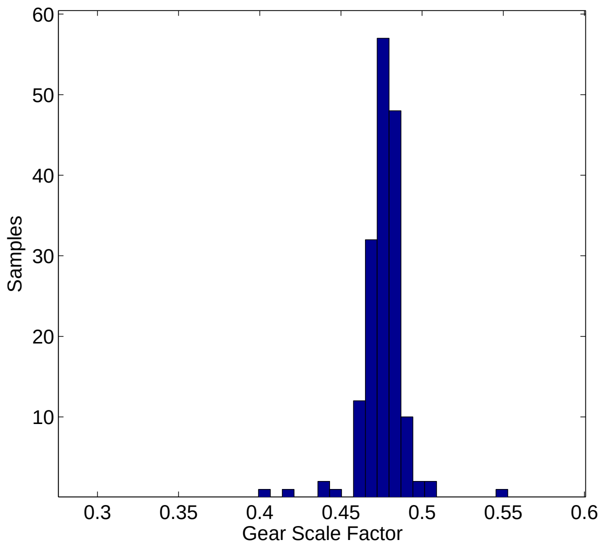

Figure B.4: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a dataset in moving conditions on the second gear

- Third gear

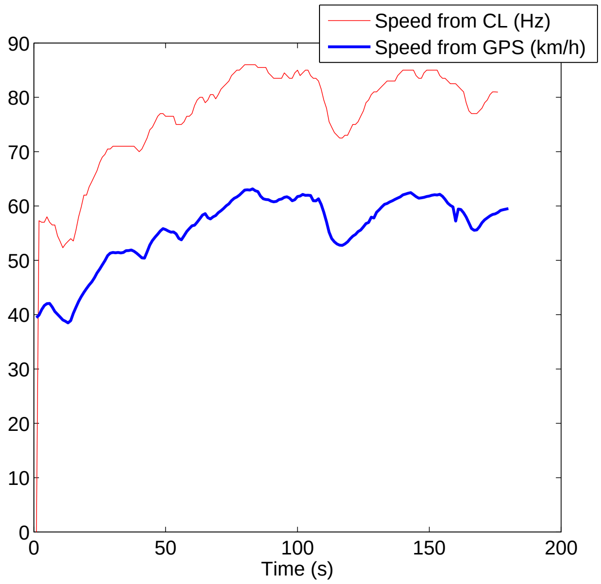

Figure B.5: Comparison between the CL signal s_k (post-processed) and y_k of a dataset in moving conditions on the third gear

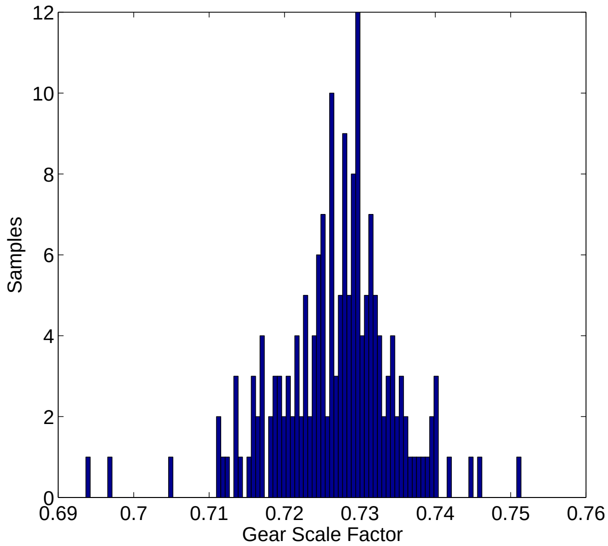

Figure B.6: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a dataset in moving conditions on the third gear

- Fourth gear

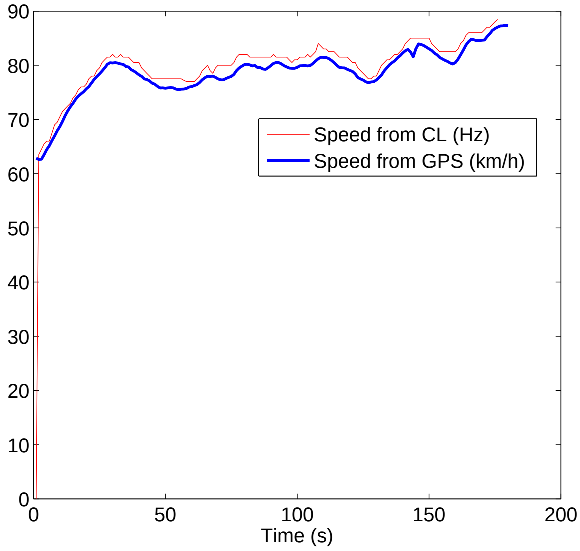

Figure B.7: Comparison between the CL signal s_k (post-processed) and y_k of a dataset in moving conditions on the fourth gear

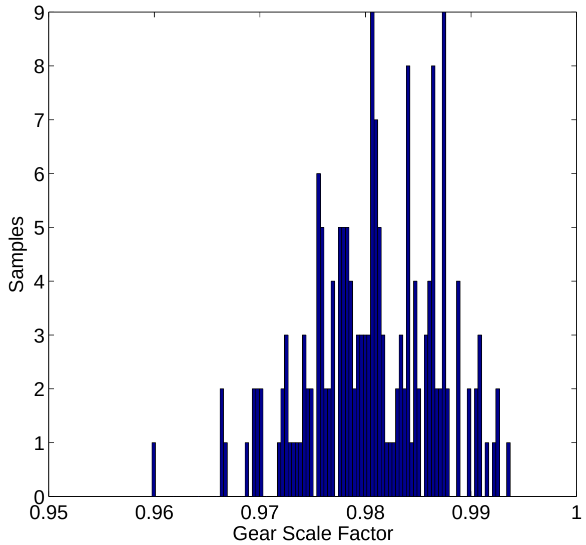

Figure B.8: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a dataset in moving conditions on the fourth gear

- Fifth gear

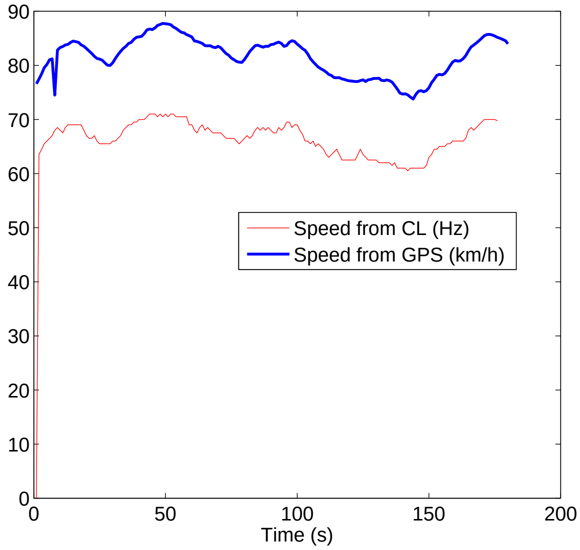

Figure B.9: Comparison between the CL signal s_k (post-processed) and y_k of a dataset in moving conditions on the fifth gear

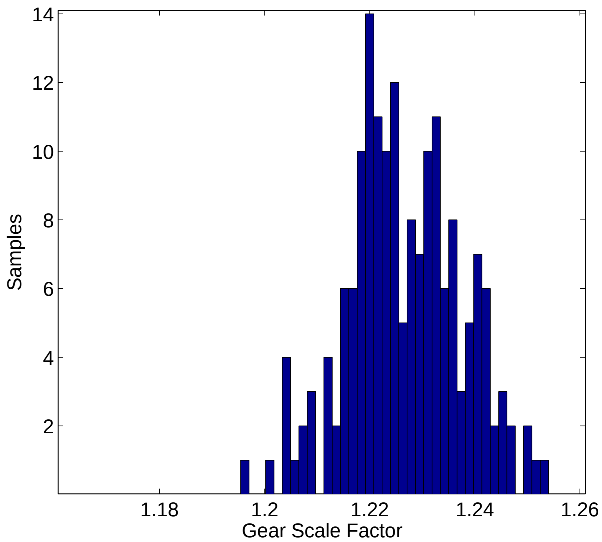

Figure B.10: Histogram of the speed values provided by the GPS y_k over the CL signal s_k, for a dataset in moving conditions on the fifth gear

Bibliography

[1] GFK, “Portable satellite navigation systems on the road to success.” [Online]. Available: http://www.gfk.com/group/press_information/press_releases/002095/index.en.html, 2010.

[2] I. Skog and P. Händel, “In-car positioning and navigation technologies - a survey,” *Trans. Intelligent Transportation Systems. IEEE*, vol. 10, pp. 4–21, march 2009.

[3] E. Abbott and D. Powell, “Land-vehicle navigation using gps,” *Proceedings of the IEEE*, vol. 87, pp. 145 –162, january 1999.

[4] C. Bohn, A. Cortabarria, V. Hartel, and K. Kowalczyk, “Active control of engine-induced vibrations in automotive vehicles using disturbance observer gain scheduling,” *Control Engineering Practice*, vol. 12, august 2004.

[5] V. Cevher, R. Chellappa, and J. McClellan, “Vehicle speed estimation using acoustic wave patterns,” *IEEE Trans. Signal Process*, vol. 57, january 2009.

[6] FordItaly, “Mechanical References.” [Online]. Available: http://www.ford.it, 2010.

[7] J. Chicharro, A. Morales, R. Moreno, A. Nieto, and P. P., “Sensorless automotive engine speed measurement by noise analysis,” in *Proceedings of ICM, 2009, Malaga, Spain*, 2009.

[8] Csr, “SiRFstarIII GSD3tw data sheet.” [Online]. Available: http://www.csr.com/products/26/sirfstariii-gsd3tw, 2011.

[9] TheGPSInformation, “NMEA.” [Online]. Available: http://www.gpsinformation.org/dale/nmea.htm, 2011.

[10] T. Kailath, A. Sayed, and B. Hassibi, *Linear Estimation.* Prentice Hall, 2000.

[11] G. Welch and G. Bishop, *An Introduction to the Kalman Filter.* University of North Carolina, 2006.

[12] MathWorks, "Data Acquisiton Toolbox." [Online]. Available: `http://www.mathworks.com/products/daq/demos.html?file=/products/demos/daq/acquiring_data/acquiring_data.html`, 2011.

[13] BMWSweden, "Mechanical References." [Online]. Available: `http://www.bmw.se`, 2010.

[14] J. Nilsson, I. Skog, A. De Angelis, C. Aquilanti, and P. Händel, "Gear scale estimation for synthetic speed pulse generator," in *ICASSP2011 accepted for presentation, Prague, Czech Republic*, 2011.