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Accuracy and reliability of distance and position measurements by GNSS systems

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List of Acronyms

AGPS	Augmented/Assisted Global Positioning System
C/A	Coarse Acquisition
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
EGNOS	European Geostationary Navigation Overlay System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
KMP	Kilometer beprijzen
LORAN	LOng RAnge Navigation
MBTF	Mean Time Between Failure
NM	Navigation Message
P-code	Precision code
PRN	Pseudo Random Noise
RTK	Real Time Kinematic
SA	Selective Availability
SV	Satellite Vehicle
TTFF	Time To First Fix
TTFL	Time To First Log
UMTS	Universal Mobile Telecommunications System
WAAS	Wide Area Augmentation System

Content

1. Executive summary

The current report describes the results of Research Assignment 3 of the Dutch Ministry of Transport, Public Works and Water Management.

The objective of the current study is to determine how accurate/reliable GNSS systems are in the Dutch environment, with Dutch driving behaviour and in relation to the intended KMP distance charging scenarios. Main problem areas are identified and possible solutions for these problems are recommended.

A brief overview is given of the GPS and Galileo systems insofar relevant for measuring distances and positions for road pricing purposes. Some artefacts of GNSS in general are discussed as well as possible ways to deal with them. As the accuracy of the driven distance is to some extent depending on the accuracy of position measurements, and because no direct distance measurements are made by GNSS receivers, the focus is mainly on position, but the accuracy of distance measurements is also treated. The topic of fraud is touched, but not elaborated in detail as this is the subject of another study.

The main part of the current study focuses on the analysis of a large GPS data set. Unique characteristics of this data set are:

- the data originate from vehicles that were used for normal day-by-day trips,
- the vehicles drove in the Dutch environment (cities, rural areas, motorways) distributed over a large part of The Netherlands,
- it is detailed (a GPS-position every second) and extensive (1 month with 19 vehicles) and
- both the GPS-positions and the distance travelled as calculated from the in-car CAN-bus (based on wheel revolutions) are logged and can be compared.

During 13 % of the total travelling time was no (valid) GPS position known. The overwhelming part of this unavailability is on the account of the start-up time of the GPS receiver (Time To First Fix – TTF) and the logging system. The latter has no relevance for a road pricing system, and the unavailability because of the GPS TTFF can be reduced almost completely by additional using additional features like Assisted GPS. When the start-up unavailability is left apart, the availability during trips is about 98%. The reaming 2% missing positions is mainly due to tunnels, parking garages and other locations where no satellites can be seen at all. It is very well possible to make sure that tunnels are included in the driven distance measurements.

The position accuracy of the data set has been determined relative to a digital map of NL that is maintained by the Dutch Ministry of Transport and Water Management. The 95% level is 37 m, which is significantly larger than specified for the used GPS receiver. The noticed difference is caused by a combination of GPS inaccuracy, inaccuracies in the digital map, the fact that roads on a digital map do not have a width and incidental mismatches as a result of the rather simple map-matching algorithm that was used.

Distance accuracies have been determined for different road classes (based on maximum allowed speed) and expressed in an average GPS-deviation and standard deviations in meters per km driven on such a road class. The overall results are:

	50 km/h	80 km/h	100 km/h	120 km/h	Unknown	Total
Average GPS-deviation						
Per 1 km in meters	16 m	7 m	-2 m	0.6 m	2 m	4 m
In percentage	1.6%	0.7%	-0.2%	0.6%	0.2%	0.4%
Standard deviations						
Per 1 km in meters	92 m	6 m	16 m	10 m	23 m	22 m
Per 1 km in %	9.2%	0.6%	1.6%	1.0%	2.3%	2.2%
Per 350 km in %	0.5%	0.03%	0.08%	0.05%	0.12%	0.1%
Per 1350 km in %	0.25%	0.02%	0.04%	0.03%	0.06%	0.06%
99% confidence levels						
Per 1 km in %	24%	1.6%	4.2%	2.6%	6.0%	5.7%
Per 350 km in %	1.3%	0.08%	0.22%	0.14%	0.3%	0.3%
Per 1350 km in %	0.65%	0.04%	0.11%	0.07%	0.16%	0.16%

The main conclusions are:

1. the time-to-first-fix is the main problem, but is solvable;
2. for larger distances GNSS systems can determine the distances with enough accuracy;
3. for shorter distances (cases of exceptional rare vehicle use) the accuracy is not enough;
4. a high positional accuracy is only needed at the border or tariff zones; the combination of GNSS, a common digital map an a simple map-matching algorithm may result in mismatches at these borders; there is room for (technical) improvement, but it is also recommended to take the limitations into account when defining tariff zones.

The issues are determined in relation to the distance charging scenarios proposed by the Ministry. A number of auxiliary techniques are described and the potential relevance to KMP are given. Finally for each scenario recommendations are given on the feasibility to use GNSS systems and on the required auxiliary techniques. Summarizing, the recommendations are:

GNSS can meet the requirements, but a solution for the TTFF-problem is needed as well as an advanced map-matching at those locations where different tariffs meet (including the virtual toll locations)

The TTFF problem can best be solved by using AGPS (or comparable systems), especially if information exchange via mobile telephony is planned to be part of the OBU anyway.

2. Introduction

The Dutch Ministry of Transport, Public Works and Water Management aims to introduce distance related road charging (in Dutch: Kilometerbeprijzing – KMP) in the Netherlands.

Concept Requirements Specifications [1] have been formulated by the Ministry. Recently the Ministry has initiated seven studies (Research Assignments) to investigate the feasibility of the critical aspects in this Concept Requirement Specifications.

One of these aspects is the "Accuracy and Reliability of distance and position measurement" (Research Assignment subject 3). The current document is the final report of this study.

2.1. Scope of the document

The scope of this document is based on the statement of work of the Research Assignment subject 3, dated 22 May 2006 [2] and on the concept Requirements Specification for the KMP. This task is dedicated to the accuracy and reliability of distance and position measurement for the KMP.

The Research Assignment states:

> *" Obviously accurate measurement of distance traveled is a pre-condition for the KMP. In addition, measurement of the position of a vehicle at a certain time is required for differentiation of tariffs in position and time. It is noted that the required accuracy/reliability of the position measurement depends on the complexity ('granularity') of the differentiation that is applied.*
>
> *The focus of this subject is on GNSS (Global Navigation Satellite System) technologies, as there seem to be no realistic alternatives that can meet the requirements of the concept Requirements Specification for the KMP. Auxiliary techniques are however within the scope, as GNSS alone may not provide sufficient accuracy/reliability. "*

The objective of the current study is therefore to determine how accurate/reliable GNSS systems are in the Dutch environment, under the Dutch driving behavior and in relation to the intended KMP distance charging scenarios; to identify the main problem areas and to recommend possible solutions for those problems.

2.2. Research questions

The Ministry has defined the Concept Requirement Specifications for the KMP. This includes four distance charging scenarios (with additional sub-scenarios) and the requirement that "*99% of the monthly invoices need to be accurate within 1%*".

All four scenarios include distance charging, some of them include different rates for different parts of the road network (including motorway and inner-city roads), some of them include different rates for different areas and some include virtual tolling points.

The Concept Requirement Specifications assumes only charging at public roads. However, the consequences either to charge or not to charge private roads needs to be discussed also in the current investigation.

The main research question for the current investigation is:

"Is the distance and position measurement of the current GPS system accurate and reliable enough to fulfill the 99% / 1% specification in each of the four scenarios and if not indicate which auxiliary techniques might improve the accuracy/reliability."

Accuracy is defined here as how accurate a measured value represents the real value. I.e. the difference between a measured and a real value. The accuracy consists of two parts, the average value (also called the systemic error or deviation) and its standard deviation, which is a measure for the variance in the accuracy.

Reliability is defined here as the total of two parameters:

- Availability: how often (percentage of time) provides the system a valid value (valid as defined by the GPS system itself).
- Correctness: how often (percentage of time) provides the system a valid value that is far away from the correct (real) value (extremes). These extremes are far outside the normal random error distribution (see accuracy). Although they might occur rather seldom, they might lead erroneously to a strong deviation of an average value from the real value.

In the current study it is assumed that the requirement that "*99% of the monthly invoices need to be accurate within 1%*" means 99% of all invoices (for all vehicles) need to be accurate within 1%. An other interpretation could be that for <u>each</u> vehicle 99% of the invoices must be accurate within 1%. That would be a much stronger requirement.

It must be noted that the requirement of 99% of the invoices accurate within 1%, means in theory that 1% of the invoices (corresponding to about 80,000 invoices per month) might deviate much more than 1% from the correct road charge. This seems not acceptable and most likely additional requirements are needed to prevent that too many invoices with significant large deviations will occur.

2.3. General methodology

In order to determine if current GNSS systems might be able to meet the Requirement Specifications, the following methodology is applied (see Figure 1).

- A brief description of the GPS and Galileo systems and their specifications is given, focusing on the most relevant items for KMP. This description is based on the knowledge of the authors and on an additional literature study.

- An extensive set of GPS measurements, which recently came available from an other investigation for the Ministry (the Full Traffic project), is used to determine the accuracy/reliability of position and distance measurements with an of-the-shelve GPS system. This data set is analyzed to determine:

1. The reliability of GPS positions.
2. The accuracy of de GPS positions per road class.
3. The accuracy of the GPS distances per road class.

- The results of the analyses and the brief description of GPS and Galileo are used to identify the main issues for each of the four KMP scenarios.

- These issues are used to assess the needs and possibilities of auxiliary techniques.

- The KMP issues and the assessment of auxiliary systems are used to formulate the final conclusions and the remaining issues and uncertainties.

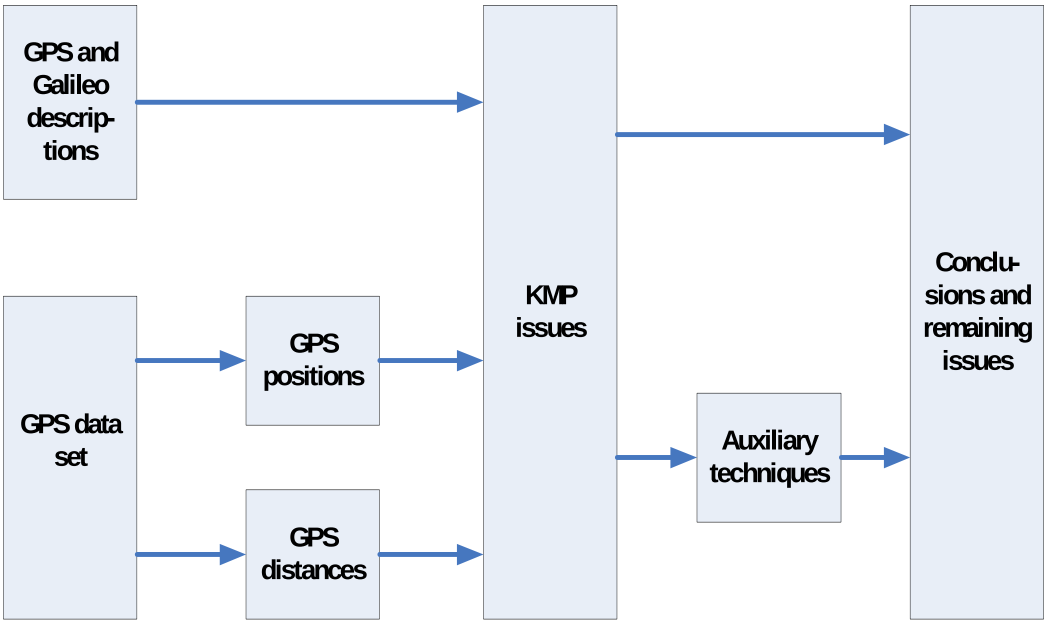

Figure 1. Schematic overview of the methodology.

The main part of the current study focuses on the analysis of the GPS data set. Many studies on GPS-measurements have been done and reported already. Unique for this data set is, however, that:

- it originates from vehicles that are used in a normal day-to-day way,
- the vehicles drove in Dutch environment (cities, rural areas, motorways) distributed over a large part of The Netherlands,
- it is detailed (a GPS-position every second) and extensive (5 months with 19 vehicles) and
- both the GPS-positions and the distance traveled according to the in-car CAN-bus are logged.

In the current study it is assumed that this data set is a good representation of the average traveling of cars in The Netherlands with one exception: the drivers were businessmen with an average mileage of 34,900 km/year, while the average mileage of the Dutch traffic is 16,500 km/year. However, it is assumed that this does not influence the analysis results in relation to the accuracies of the position and distance measurements.

The GPS-positions in the current study are map-matched to the Dutch digital map (in Dutch: Nationaal Wegenbestand – NWB); therefore the road class corresponding to these positions can be determined. This allowed to determine the results for different road classes. A straightforward map-matcher is used (projecting a position to the nearest NWB-element, taking into account the driving direction). It is known that this can be strongly improved, especially if map-matching can be done off-line, such that previous and next positions can be taken into account when matching a certain position.

Both GPS-positions and information from the CAN-bus of the vehicles are available. The CAN-bus information provides an accurate measurement of the distance travelled. The distances measured on the basis of the GPS-positions (GPS-distances) are then compared with the CAN-distances. The differences between the GPS-distances and the CAN-distances are defined here as the GPS-deviations.

Different drivers make trips of different lengths, on different road classes and with different mileages. In order to be able to compare the distance measurements from different trips, the GPS-deviations are scale per road class to a GPS-deviation expressed in meters per 1 kilometer driven. These GPS-deviations vary around an average value. Also the standard deviations of these GPS-deviations are expressed in meters per 1 kilometer driven.

E.g. on average the distance measurements via GPS on a certain road class might deviate from the real distance measurement by 50 meters per kilometer and this value might have a random variation, such that the standard deviation is 30 meters per kilometer. The GPS-deviation is then 50 +/- 30 meters per kilometer. From this the GPS-deviations and the corresponding standard deviations can be calculated for other distances and for trips including different road classes.

The GPS data set provides a unique possibility to analyze the GPS performance under normal Dutch circumstances and for different road classes, using a very large data set and to determine if this performance is sufficiently accurate for the KMP-scenarios.

In the analysis statistical methods are used and standard deviations are determined where possible and relevant. Accuracies are given then in the format "average value +/- standard deviation". The standard deviation corresponds with a confidence level of 68%. A 95% confidence level corresponds with 2 standard deviations, a 99% confidence level corresponds with 2.6 standard deviations. All input data and intermediated and final results are stored for later consultation or further analysis.

2.4. Document structure

Chapter 3 gives a description of the GPS and Galileo systems, based on the authors knowledge and some further literature investigations. Focus has been on the items relevant for KMP.

Chapter 4 presents the analysis of the “Full Traffic” data set and the corresponding results. The reliability and the accuracies for position and distance measurement for an off-the-shelve GPS-system are determined here.

In chapter 5 the KMP issues (potential problems in relation to distance charging) are identified and described. Based on the analysis results of chapter 4, the severity of each of these issues are described.

Chapter 6 gives a short description of a number of auxiliary techniques and how they can be of relevance for KMP, by solving issues that cannot be solved by GPS or Galileo alone.

In chapter 7 conclusions are given as well as recommendations for each of the scenarios defined by KPN. In addition an number of extra options are described and corresponding recommendations given.

Finally, chapter 8 lists the main remaining issues for further study and briefly describes the risks in relation to distance charging by a GNSS system.

3. Brief description of GPS and Galileo systems

In this chapter a brief overview will be given of GPS and Galileo insofar relevant for measuring distances and positions for road pricing purposes. Some artifacts of GNSS in general will be discussed as well as possible ways to deal with them. As the accuracy of the driven distance is to some extent depending on the accuracy of position measurements, and because no direct distance measurements are made by GNSS receivers, the focus in this section will mainly be on position. In a separate paragraph the accuracy of distance measurements will be treated. The topic of fraud will be touched, but not elaborated in detail as this is the subject of another study.

3.1. Operational principles and basic limits

All GNSS systems - the two operational systems, GPS and GLONASS, and the soon to come system Galileo - are based on the precise measurement of the time its takes for radio signals to travel from a number of satellites at a well known positions and subsequent trilateration. With the distance to three satellites known, only two positions in space are possible, but one of them can be discarded as it will be very far from the earth's surface. To measure the time of flight of the radio signals, extremely well synchronized clocks are necessary. The atomic clocks in the satellites are very precise and stable, and also closely monitored and if necessary adjusted from earth based control stations. The clock in common GNSS devices is of much lower precision and stability. A device clock that has an offset of 1 ms will lead to a distance measurement error for all satellites of roughly 300 km. By using the signals from a fourth satellite, the local time can be adjusted such that the positions calculated by all combinations of three satellites coincide. Once the local clock is properly synchronized, reliable positions can be calculated on basis of only three satellites for a limited period of time. It is up to the user if a position based on only three satellites is to be used in the application.

The time of flight of the radio waves is found by shifting a replica of a known (pseudo random noise - PRN) signal that is unique for a specific satellite with the received signals (of all satellites in view) until a match is found. All modern receivers have a large number - usually 12 - correlators that do the processing in parallel. With GPS two codes can be used to synchronize on, the so called C/A-code (Coarse Acquisition code) and the P-code (Precise code). The C/A has a chip rate of slightly over 1 Mb/s, while the P code has a frequency that is 10 times as high. This means that synchronization can be 10 times more precise with the P-code.

As a rule of thumb, synchronization is possible up to about 1% of the bit length. For the C/A-code this means that the time measurements can be made with a resolution of about 10 ns, equivalent with 3 m, while using the P-code results in a best possible resolution of 30 cm. Unfortunately in practice the accuracy is less than these values, as it is implicitly assumed that the transmission is through an ideal medium, which is not the case, especially not for the ionosphere and troposphere. More about this later.

The P-code, with its better resolution, is specifically intended for military use and is encrypted. Although expensive receivers have found ways to circumvent this, the code can be changed any time to explicitly give misleading information. For this reason it is not suitable for road pricing purposes. Galileo will use the same chip rate for its free Open Service and will consequently have the same basic resolution as GPS.

It is also possible to synchronize on the carrier of the GPS/Galileo signal. As the frequency of the carrier is about 1500 MHz, millimeter resolution is achievable, assuming synchronisation at a 1% of the carrier wave length. As the carrier will be in phase every 0.66 ns (i.e. very 20 cm) a large ambiguity problem must be resolved. This can be done by tracking the course of individual satellites while staying locked in phase. For simple geodetic receivers that may be necessary for several minutes, while the more advanced ones are capable to resolve the ambiguity within a few seconds. For moving objects this is no viable measurement method, even apart from the receiver complexity and consequently high price. Note that a similar ambiguity problem exists when synchronization is done on basis of the PRN. The sequence for C/A is repeated every millisecond, so an ambiguity of multiples of 300 km exits. When more satellites are taken into account or when the position is roughly known this ambiguity can be resolved.

Off-line post processing of collected data makes further improvements possible, but this is of course no possible solution for an in-car road pricing system.

In order to be able to make a precise calculation of the distances to the various satellites, the positions and paths of these satellites need to be known by the receiver. The receivers gets this information by means of a system wide almanac data and ephemeris data per satellite. The almanac contains relatively slow changing information about the satellite constellation, like the operational satellites and their coarse paths. The almanac is transferred in small parts, divided over 25 frames of 30 seconds, so it takes 12.5 minutes to receive the complete almanac. The ephemeris data is sent within every 30 second frame and contains detailed information of the specific satellite that sends the data. The main content is the latest expected orbit for the segment that will be traversed over the next hours. Almanac data may remain valid for up to some month, while ephemeris data have a validity of up to four hours. While in operation the receiver will update the almanac and ephemeris data in a regular fashion.

3.2. Accuracy and sources of error

The (theoretical) resolution that is achievable is not to be confused with the positional accuracy that will be experienced. Any phenomenon that results in unknown (or unpredicted) deviations of the assumed speed of the radio waves will result in an error in the calculated distance, irrespective of how refined the hardware is and how detailed the calculations are. The same holds for deviations in the assumed values of other parameters that are used in the calculation of the position. Part of the errors is caused by fast random variations (pure noise), but a large fraction is caused by slowly varying shifts in bias or plain errors. The difference is artificial and not well defined but important for the way to mitigate or eliminate the effects.

In Table 1, the most common error sources are grouped.

Error	Potential error	Type
ionosphere	5 -10 meters	slowly drifting
troposphere	0.5 – 1.5 meters	slowly drifting
multipath effect	0.5 – 2.5 meters	(fast) randomly varying
satellite clock drift	1 – 2.5 meters	slowly drifting
ephemeris (orbit prediction)	0.5 - 2.5 meters	offset
measurement noise	1 – 2 meters	(fast) randomly varying
Total	5 - 15 meters	

Table 1. Most common error sources of GNSS systems.

The figures are merely giving an impression of the order of magnitude. Different sources quote different figures, while in many cases the definition of how the error is defined is not clearly expressed or not expressed at all. Some authors mention 1-σ values, others 95% errors.

The import thing to note is that especially the static modeling of the ionosphere gives rise to relatively large potential errors. For that reason much effort has been put in schemes to eliminate this source of error. The most well known solution (Differential GPS or DGPS) makes use of the fact that the conditions in the ionosphere are changing relatively slowly, and do not differ very much over relatively a large area. By using a reference receiver at an exactly known location, it can be calculated what corrections are needed to make the standard calculation to output that known position. This information is sent regularly to receivers that are subscribed to the service, so they can use it for their next calculations. Note that DGPS in fact eliminates all common mode errors, that is, all errors that are (almost exactly) common to both the reference receiver and the “field receivers”. This is the case for all errors except for the fast random variations. Note further that the correction has to be applied per satellite, as the communication path and hence the errors, may differ considerably for different satellites. The reference receiver will calculate separate corrections for every satellite in view.

The second way to mitigate the effect of the ionosphere is the make use of the fact that radio waves of different frequencies travel at different speeds in the ionosphere. The GPS satellites transmit the P-code at two frequencies, so the time of flight will be different for both channels. This time difference allows for a better modelling of the ionosphere, resulting in a severe reduction of the error. Special “dual frequency” receivers are required to take advantage of this possibility. As pointed out before, all low-cost commercial receivers make exclusively use of the C/A signal, which unfortunately is only transmitted at a single frequency (L1 - 1575.42 MHz). The necessity to add processing of the non-public P-code, makes dual frequency GPS receivers much more complex than single frequency receivers. Galileo, on the other hand, will use two frequency bands for its Open Service form the start, and it is expected that most, if not all, new Galileo enabled receivers will use the dual frequency correction mechanism.

GPS has announced that their next series of satellites will use two frequencies as well for the C/A code. These so-called Block III satellites are scheduled to become operational by the year 2012. The Galileo consortium expects the 95% horizontal error to drop from 15 m for a single frequency receiver to 4 m for a dual frequency receiver. With a 95% error is meant that 95% of the measurements will be closer than the given distance from the real position.

After the USA decided to deactivate the selective availability (SA – an intentional error added to the publicly available signal in order to limit the accuracy to 100 m) many independent studies were done to examine the new accuracy of the GPS signal, using cheap commercial GPS receivers. The results of a few exhaustive test are given in Table 2.

Accuracy	D.L. Wilson	D. Milbert	W. S. Rupprecht
Horizontal accuracy (50%)	4.4 m.	3.9 m.	2.5 m.
• Horizontal accuracy (95%)	10.1 m.	9.3 m.	7 m.

Table 2. Measurements of independent researchers on Garmin 12XL .

There is an overall agreement that the 95% error has a value of about 10 meter. Note that all experimenters were making their measurements at fixed locations and that attempts were made to get the best results, including the use of sophisticated antennas, so these figures must be considered as the lower limit of what can be achieved with a low cost commercial GPS receiver.

A trial with GPS systems for the London congestion charging project showed a similar accuracy of 9,7 meter.

In Table 3 the effect of using a dual frequency Galileo receiver can be seen as expected by the Galileo consortium [3].

	Open Service	
	single frequency	dual frequency
horizontal accuracy (95%)	15 m	4 m
vertical accuracy (95%)	35 m	8 m

Table 3. Effects of the use of dual frequencies.

It seems logical that establishing the position of a moving receiver is more difficult and less accurate. It appears that GPS manufacturers apply a prediction and smoothing algorithm before a position is output. In the many experiments, pilots, and commercially operational applications in which positions are to be matched to a digital road map, it was noticed that a slow drift in position (with smaller fast random variations) is clearly visible when the speed is zero. On the other hand, when the vehicle with the receiver is moving, the lateral spread of positions is smaller. When driving on a straight stretch of road, the positions tend to be a nice straight line as well. Apparently some smoothing takes place by using a prediction based on the speed and previous heading. A certain degree of “lagging behind” in curves on motorways when driving fast can be seen as well, indicating the same. This smoothing may reduce the overestimation that can be expected by calculating the driven distance on a point-by-point basis. This will be elaborated further in the paragraph about driven distance calculation.

3.3. Availability and Reliability

The availability of GNSS in general is high. As a good position calculation can be made on basis of four satellites, there is some intrinsic redundancy. One or more satellites may stop operation, and still there will be enough satellites (in a perhaps less favorable constellation) to establish a position. Note that spare satellites are available to replace broken down or worn satellites if necessary, so any permanent outage will always be corrected after some time.

If there are severe problems with a ground station that updates satellites with (amongst others) clock corrections, we also experience a similar type of redundancy, because there are several ground stations spread around the globe. A complete outage of all ground stations will only become problematic if satellites are not updated in time. As the ephemeris data is valid for about four hours, there is time to correct the situation. If the outage is longer, the system still we operational, but the errors may start to grow.

All in all the system's availability form a user's perspective is near to 100%.

Though not properly fitting in the definition of availability, there are situations where the system in not available for the user, even though the system is fully operational. At all places where not at least four satellites can be seen (or three for a short time), no position can be calculated. This is obviously the case in tunnels, under bridges and within buildings like parking garages, but this situation can also happen under thick foliage and between high buildings, the well known "urban canyons".

It will be obvious that nothing can be done by the GNSS receiver in the case of the complete obstruction of signals. Still there are several possibilities to go on producing position estimates, both in-vehicle and by means of infrastructural measures. In-vehicle one can use dead reckoning, meaning that it is assumed that the last known speed and heading will be valid until a new "real" position measurement is made. Note that for driven distance calculations it does not make any difference whether the intermediate positions are calculated or not, as the dead reckoning will result in a straight line. For short interruptions this may be fine, but for longer interruptions, like in tunnels or parking garages, this is more of a problem. By installing a set of gyros or solid state accelerometers changes in speed and/or heading can be detected.

As an infrastructural measure a GNSS repeater may be installed. The signals that are received at a certain location can be retransmitted at the "hidden" location below it. This type of equipment is often used to make sure that emergency vehicles that are parked in a garage will already have a proper fix when they start a trip. As the electronics and the cable length will give additional delays, corrections need to be made. In case of tunnels (where no direct vertical cabling is possible) the whole set-up may prove to become too complicated. A simpler solution may be to install beacons in the tunnel, that transmit a code that represents its position.
In the paragraph about driven distance measurements these possibilities will be elaborated further.

In case of urban canyons several effects are to be considered.

- In the first place there may be so much shielding of satellites that not enough satellites are in view to calculate a position. For a driving vehicle this normally will be only for a short period of time (when driving in the "shadow" of a number of high buildings), resulting in the loss of a few positions. For distance calculations this will not be a major issue.

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- In the second place, using only satellites that are high in the sky, will result in a larger positional error. The "error zone" of three satellites a low angle to the surface of the earth will only overlap in a volume with small horizontal dimensions (a small HDOP – Horizontal Dilution of Precision) , while the error zones of satellites that are close together at a high angle will have a large horizontal overlap.

- In the third place, the number of multipath errors will increase. Multipath errors are produced when the signal of a satellite is received by more than one path, notably the direct path and via reflections by buildings or even truck or other reflecting surfaces. By receiving multiple copies of the signal, it is harder for the receiver to synchronise with the right one. This effect always exist, but is more of a problem in surroundings with many high buildings. Low reflecting surfaces need to be quite near the receiver to make it possible that a reflected wave reaches the receiver. The time difference and hence the error will be relatively small. High well reflecting buildings may be quite far away and still act as a mirror for the radio waves, resulting is large delays and large errors. As this is a major problem, receiver manufacturers have put a lot of effort in designing algorithms to eliminate the multipath problem, and the latest receivers claim to be considerably less sensitive for multipath signals.

Still there is the problem of signals that are received by the receiver only via a reflection, because the direct line-of-sight path to the receiver is obscured by a building. This will lead to large positional errors. When enough satellites are available, one "strange" position will be discarded, but in case of just three or four satellites in view, this internal control mechanism is not operational. The application may detect this type of error by two methods. In the first place a sudden jump in position will result in an apparent speed that does not comply with the speed measured by the receiver itself. According to literature, speed is measured by a GPS receiver by measuring the Doppler shift of the carrier signal, taking the speed of the satellite into account. Receiver manufacturers could or would not affirm this, but our own measurements have shown that the speed that is output by a GPS receiver is not (always) equal to the speed that can be calculated from the shift in position over time. The second way to check the plausibility of a position measurement is to compare the apparent movement of the receiver with realistic possible speeds and accelerations of vehicles. Note that this is slightly more complicated that is appears to be, because measures must be taken to be sure that one start form a correct baseline.

Because the "urban canyon" issue is more of a problem when only a few satellites are in view, combining more GNSS systems may come to help. When both GPS and Galileo (and perhaps even GLONASS) satellites are used, the chance that both systems run into problems at exactly the same moment becomes smaller. In Table 4, copied from [4] estimates can be seen of the effect that a combined system will have on the availability of position measurements and their error for a single system and a combined system.

Analysis Scenario & Cons-tellation	Availability of 20m 95% 2D accuracy		Accuracy and availability – satellites only		Accuracy availability differential
	28 GPS only (%)	28 GPS +27Gal (%)	28 GPS only (m/%)	28 GPS +27Gal (m/%)	28 GPS +27Gal (m/%)
Open Sky	90%	100%	7/95	4/95	1.5/95
Suburban	70%	100%	32/90	8/95	4/95
Low-rise	30%	90%	17/50	14/95	7/95
High-rise	15%	80%	-	42/90	25/90

Table 4. Accuracies comparison of single and combined systems.

Note that once again there is no clear and widely adapted definition of “low rise” and “high rise” buildings, so it is hard to value figures that are presented in literature. In our opinion there are hardly situation in the Netherlands that can be considered “high rise”. A lot of the investigations look at the downtown areas of cities like New York, Chicago and London, that have many more high buildings closely packed together, see for instance the (simulated) fish-eye perspective view of NYC, copied from [5].

The last, but very import issue concerning the availability of position measurements, has to do with starting the receiver and the time that it takes to get the first valid measurements, the so-called Time to First Fix (TTFF). As already explained the receiver needs to have knowledge of the almanac data, to acquire information from at least four satellites, including their ephemeris data, get its clock synchronised and has to resolve the location ambiguity because of the 1 ms repetition rate of the PRN sequence in the C/A signal.

For a brand new receiver or a receiver that has not been used for several month, the collection of the almanac may take from some 5 minutes to over half an hour depending on the number of satellites are in view. This is a one time situation, but it may prove to be an unpleasant one from an installation and logistic point of view.

When a valid almanac is available already at start-up, but the required ephemeris data is not available or outdated because the receiver has been off for more than a few hours, all ephemeris data needs to be collected from the satellites in view. The ephemeris data is repeatedly broadcast in parts over a period of 30 seconds, resulting in a typical value of about 45 seconds for this so-called warm start TTTF.

When the almanac is available, the time and position are approximately know and recent ephemeris data is available for at least four satellites that still are in view, the position calculation can start right away, using he available ephemeris data. This so-called hot start TTTF takes 2 to 15 seconds in practical situation. This short TTFF is only possible if the receiver was switched off for not more than about two hours. This period depends largely on the constellation of the satellites and may be shorter or slightly longer.

To be able to make a warm or hot start, the receiver must keep the latest data (including almanac, ephemeris, time and position) over shutdown. This usually is realized by using a back-up battery or large capacitor. To assure that always a hot start can be made at least every now and then a position fix and clock calibration must be made. Leaving the receiver on while the car is not used, will drain the batteries sooner or later, even though the power consumption of receivers has dropped over the years from about 1 W to less than 500 mW. It is likely that the power consumption will be reduced even further. To make a hot start possible more often, many receivers offer the possibility to run the receiver in a trickle mode. In such a mode the receiver is switched on every 30 minutes for ephemeris collection and clock synchronization. In this mode the power consumption is about 1 mW. This will hardly drain the battery and if powered from the back-up battery, there is no risk of an empty car battery at all.

The above measures cannot guarantee that a hot fix is always possible. When a car is parked for some time in a garage, so without the possibility to receive GNSS signals, even a warm fix cannot be guaranteed. All cars that have been parked in a garage at night will have to make a cold start in the morning, missing the first 45 seconds of the trip. A solution can be to implement a form of assisted GPS, where at start up, if the conditions for a hot start are not met, the latest almanac and ephemeris data are retrieved by GPRS or UMTS. Broadcasting this information via a regular FM transmitter is also a viable possibility. This information can be retrieved already when the car is still in the garage, so all conditions for a hot start are met when the receiver is able to see satellites. Note that even a course indication of the location can be provided by UMTS, so even if knowledge of the original location was lost, the search space can be made smaller, reducing the time to get a position fix. A combination of GPS and UMTS seems to be a likely combination anyway for a road pricing system. As both types of receivers have a lot of components in common, integration will have space and cost advantages. In the context of Galileo some manufacturers are already designing hybrid GPS/UMTS receivers to - as they call it themselves - prevent the duplication of hardware [5].

3.4. Position measurement in the context of road pricing

For road pricing the actual position is of importance to be able to detect if a car is driving on a road that has a non-standard tariff, possibly only during certain periods of time. For this purpose it is necessary to map the positions to specific road segments. This is common practice for all types of navigation systems and similar applications and can be done with high accuracy. To make the best match out of several competing possibilities, not only the position but the speed and heading are taken into account as well. In case of road pricing it is not likely that a full map of the Netherlands will be available in the car, al be it because this will lead to major update problems. To make the best matches possible, not only the roads that are "special" in the context of road pricing need to modeled, but also the nearby roads. A certain match to one of these roads, prevents a false match to a "special" road. Modeling the environment within a range of about 50 meters will do. Adding some context also makes it possible to do a local type of route planning, excluding impossible road changes.

As argued before, measurements at standstill seem to show more dwelling around the true position than points measured while moving. Also, without heading information, map matching is harder, and when standing still, there is no heading available. For this reason it is advisable to prevent to have the start end points defined at locations where there can be confusion, like at complicated crossings or at roundabouts. In a similar way it is hard to tell whether a car is driving on a motorway or on an on or off ramp. When both have a different tariff complications can be expected.

Several solutions are possible:

- The first possibility is to shift the entry and exit points to less error prone locations, at known distances from the intended ones. These fixed distance can be added to the distance driven on the "special" road and subtracted from the previous (or next) road type.

- The second possibility is to define detection zones on the special road segments in places that are good measurable. If a car detects that it is in one of these zones, the complete associated segment length is added to the special road type and subtracted from the normal one.

- The third solution waits with assigning the driven distance to a specific road type, until it is unambiguous what route was taken.

If feedback is given to the driver of the currently valid tariff, all solutions will always give seemingly faulty information for a limited amount of time. Not implementing anything, will often lead to both faulty assignments and feedback.

The best way is to minimize the number of situations where problems can arise by carefully selecting the entry and exit points of special roads.

3.5. Calculation of driven distance

When the driven distance is calculated by adding the distances between consecutive measured points, the total distance will be overestimated by definition. Because the largest part of the position error is of a slowly drifting nature, the effect will be small in practice. If a zigzag path with an amplitude of 4 meter is laid over a straight stretch of road, than the distance error will be about 1 percent at 100 km/h. Al lower speeds the effects are larger. At a speed of 30 km/h the overestimation will be about 10%. This is of course an upper bound situation in which the measurement are constantly at different sides of the road. Measurements have shown (see chapter 4) that in practice the effects are much smaller. Still improvements can be made by not calculating the distance between every single set of points, but by using larger stretches. Using every other point halves the error. It must be sure that no real turns are made in the set of grouped points, otherwise un underestimation will be made.

The driven distance also can be calculated by using the speed and multiplying it with the time intervals between the measurements. Here as well the error is small at high speeds and will become larger at lower speeds. With a specified error of about 0.5 km/h the error will be smaller than by using positions. The problem of using this approach is in the handling of missed points., like for instance in a tunnel. It cannot safely be assumed that the speed remains constant over such a period, so calculating the distance by multiplying the time in the tunnel by the last known speed may result in serious errors. A combination of both calculations may be a very good solution, but needs to be exploited in more depth.

The extreme is encountered when the speed is zero. At that speed random position dwelling is seen. When these are added the measured driven distance will slowly increase over time. The way to deal with this situation is to ignore low speeds and calculate the distance between the last point with a speed of – say – 5 km/h and the first position when that speed is reached again. It may be that a corned is cut of in this way, but at such low speeds that error in distance will not have a significant overall effect.

If it can be assumed that tunnels are without serious curves in them, it is reasonable to calculate the Pythagorean distance between the last point before the tunnel and the first point found after exiting the tunnel. Any systematic errors can be corrected for by using an in-car table, but this boils down in the end to tabulating all known large interruptions, with al its associated maintenance issues. Perhaps the best option is to ignore this type of error because the error will be relatively small and above all exactly equal for everyone passing the tunnel.

If in inner cities with high buildings positions cannot be calculated or if there is severe doubt if the result is correct, the best way is to ignore the point(s) in question. As argued above, it is not likely that this situation will persist for a long time, and a calculated straight distance between points that are more remote in time, will only lead to a possible underestimation of the driven distance. If no turns are made the distance may even be calculated more correctly than when all points were being used. Of course this opens a possibility for fraud once this mode of operation is known, but that can be remedied (see next paragraph).

Roads though woods and other “hollow roads” that have no clear view of the sky form a problem of their own, because in those situations the sky can be obscured for a long time and long distance. Manufacturers claim to have implemented measures to reduce this effect, but no independent experiments concerning the effect of the improvements are known. Using the same strategy as with tunnels and urban canyons may be effective, but in case people are living along such a type of road, they may exit at the same location as where they entered, with a zero distance as result. GNSS re-transmitters or beacons are possible but relatively expensive solutions for roads that quite likely have only very few cars passing. In view of the requirement that 99% of the road users are to be billed with a maximum error in their bill of 1% the users of these roads may just be considered lucky.

3.6. Fraud

Fraud is addressed in a separate study, so only a few lines will be spent on the subject, and only where it touches the use of GNSS. Assuming that the driven distance is calculated primarily on basis of GNSS information, it may be tempting to sabotage the readings by shielding the antenna. This can of course be detected while no measurements are being made and flagged as such. There can be valid reasons why this situation happens, for instance in a tunnel or garage. Situations in which no position measurements are possible for a period longer than a few minutes can be considered suspect (though exiting a parking garage after a large event may take a longer time). A possible solution may be to multiply the distance between the last point before and the first point after such a long outage with a correction factor. If one shields the antenna on purpose, the contrary of an advantage will be gained from it. Exiting garages and the like will not give a problem because the entry and exit points normally will not differ much in position. It will be advantageous for a driver to make sure that the system is operating well and is repaired as soon as problems arise. Of course this will not help if a round trip is made with a shielded antenna. Location information from UMTS can be used as a coarse indication, further using the above principle. A certain theoretical breach of privacy may be tolerable in this situation. If both GNSS and UMTS are not operational at the same time, then the situation becomes really suspect.

If a connection is made to an odometer distances can be measured directly, but because this link probably is even more fraud prone, it should only be used for periods that GNNS is not functional. During normal operation a permanent check can be made to see if both come to the same conclusions, so the risk of tampering becomes smaller.

Obstructing the proper operation of a GNSS system is relatively simple, though more in theory than in practice. Because the GNSS signal is very weak, sophisticated techniques are used to filter the signal from the background noise. A jammer is a radio waves transmitting device that tries to frustrate the receipt of data. A simple circuit that just outputs a random signal at the same frequency as the genuine signal, normally will not disturb the receiver too much. Problems arise when the signal strength becomes so high that the receiver circuits of the receiver cannot cope with the signal any more. This only will happen with a very nearby jammer or with a high power transmitter. The former is no severe threat for the integrity of the road pricing, while the second type of transmitter can easily be detected by governmental inspectors, so action can be taken. This may happen, but is unlikely that this will happen at a large scale.

Circuits that send a signal with the same power spectrum as GNSS transmitters can do with less power to hinder the receipt of real signals. Such devices are much more complex to design and build, but it is possible. Such devices are harder to detect by officials, but can prevent the proper operation of the road pricing system in a certain area. Even though the receivers are becoming more and more jamming-resistant (Galileo puts a lot of effort in it), the possibility of the use of jamming devices cannot be ruled out completely.

Depending on the implementation of the road pricing system, the most likely effect will be that the area of no receipt will be treated like a tunnel, so assuming that a straight line was driven. This is a minor nuisance. When at such locations a virtual tolling point is installed of which the detection area is smaller than the area without receipt, the problem for the government becomes more serious, as it may prove to be beneficial to use jammers.

4. Analysis of the GPS data set

4.1. Description of the GPS data set

4.1.1. Measurement data from the Full Traffic project

During March – June 2006 the Dutch Ministry of Transport, Public Works and Water Management did an evaluation of an in-car warning system for lane departure and tail-gating (the Full Traffic project). In this evaluation the GPS positions were measured and logged every second and the vehicle speed from the CAN-bus was measured and logged twice a second. A Holux GPS-receiver, type GM-210 was used (see annex 1 for more details). Nineteen vehicles (all new Volkswagen Pasat passenger cars) participated in this evaluation. The vehicles were used by business men in a normal way. The drivers are heavy users, they drove between 500 and 3500 km/month. The average mileage during this period corresponds to 34,900 km/year. The average mileage for the Dutch passenger cars is 16,500 km/year.

For the current investigation the data of the month May is used, in total there were 2363 trips made in May 2006 by those vehicles of which 1952 have been analyzed (see section 4.2). As mentioned in chapter 2, it is assumed that those vehicles represents the Dutch driving behavior and the Dutch circumstances sufficiently well for the current investigation, with the exception that those vehicles have a mileage double than normal and that longer trips might be over-represented.

Only data of the month May was used, because this gives enough data for the current statistical analysis. If needed for further investigations also the data from February, March, April and June are available.

Table 5 gives some statistics of the trips used in the analysis.

Total number of trips in May 2006	2,363
Number of trips used in the analysis	1,952
Number of vehicles	19
Measurement period	1-05-2006 to 31-05-2006
Total distance travelled*	55,267 km
Total time travelled*	709 hours
Total time data logged*	661 hours
Total number of logged valid GPS positions*	2,209,177
Total number of logged invalid GPS positions*	176,730

* in the 1952 trips analysed

Table 5. Trip statistics.

4.1.2. Data integrity

Not all logged data can be or should be used in the analysis. The following data has been excluded from the analysis.

- Invalid GPS-positions. The GPS-system indicates with each position whether it is a valid position or not. Only valid GPS-positions are used in the analyses.

- Trips with logging errors. Due to technical problems in the logging in the vehicles of certain trips not all information was available (mostly it was due to problems with the CAN-data). Those trips (about 15% of the total) have been excluded from the analysis.

- Trips with extreme deviations. A small number of trips (less than 1% of the trips) showed extreme deviations (tens of km) in the different distance measurements (based on GPS, NWB or CAN, see below). These trips have been visually inspected and excluded form the analysis when a explanation for the deviation was found. Explanations included for instance trips abroad (then the NWB-distance is zero) or missing CAN-data. Exclusion of those trips have been done carefully in order not to influence the average values.

In total 1,952 out of 2,363 trips have been used in the analysis.

For the determination of the position accuracy a subset of the data is used. Randomly a number of short trips have been selected, with in total 35,586 valid GPS-positions. Shorter trips were selected to be sure to have enough measurement points at all road classes. A subset of this size was used in order to be able to analyze the positions in Excel.

The logging equipment had – unfortunately - a start-up time of about 90 sec., which means that no data was logged during the first 90 sec of each trip. This is taken into account in the analysis.

4.1.3. Trip length distributions

For each of the 1,952 trips, the total GPS-distance has been calculated. The total GPS-distance is calculated as the sum of all distances between two adjacent valid GPS-positions plus 1.4 times the distance between the first valid GPS-position of the last valid GPS-position of the previous trip (to compensate for the Time-to-first-fix of GPS and/or the 90 sec. start-up time of the measurement equipment). The factor 1.4 is used as an average to compensate for the difference between the crow-fly distance and the distance via the road network.

Trips are considered to be distinct when there are more than 2 minutes between the end of one (ignition off) and the begin (ignition on) of the next trip, otherwise they are considered as one trip.

Figure 2 gives the distributions of the trip lengths (total GPS-distances). The mean trip length is 28,4 km; the mean trip duration is 21:47 minutes.

Figure 2 shows that there are relatively many short trips in the data set used. An unexpected large part (339 out of 1,952) of the trips are less than 2 km, this might be due to the non-representative group of drivers (businessmen all working for a large car dealer in NL). Further investigation to compare this with the normal trip length distribution of the traffic in NL would be interesting.

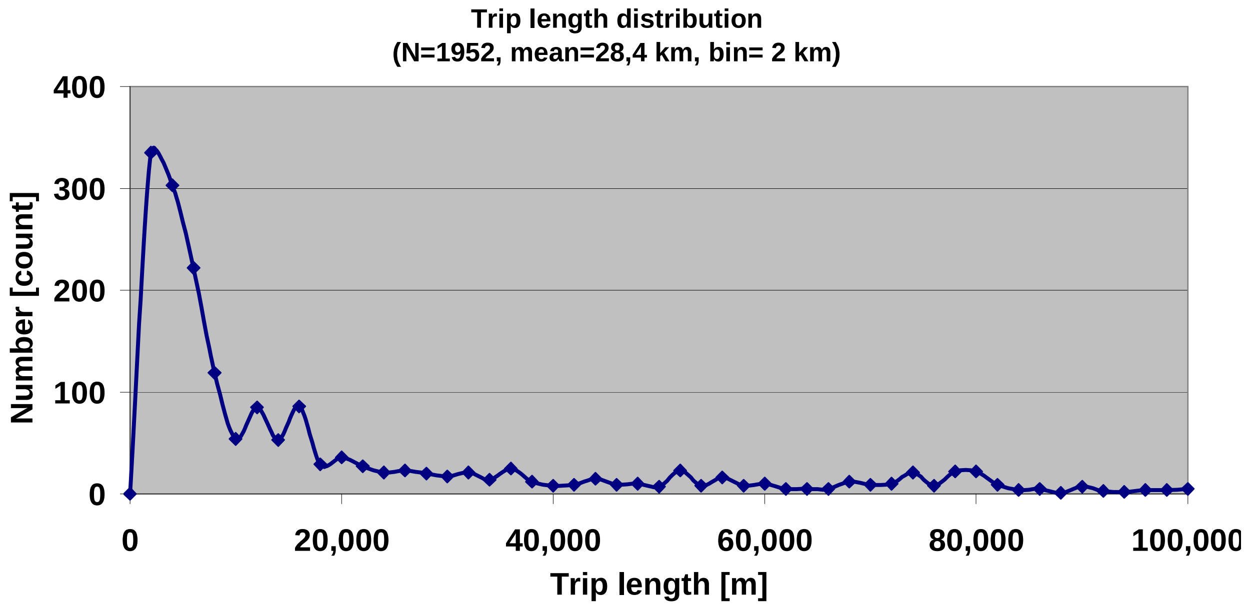

Figure 2. Distribution of the trip length.

The relevance of trips (e.g. short or long) for KMP depends on the length of the trip multiplied by the number of the trips with this length. Figure 3 gives the distribution of the product of number-of-trips and corresponding trip lengths. Each point then gives the total number of kilometers driven on trips with the corresponding trip length.

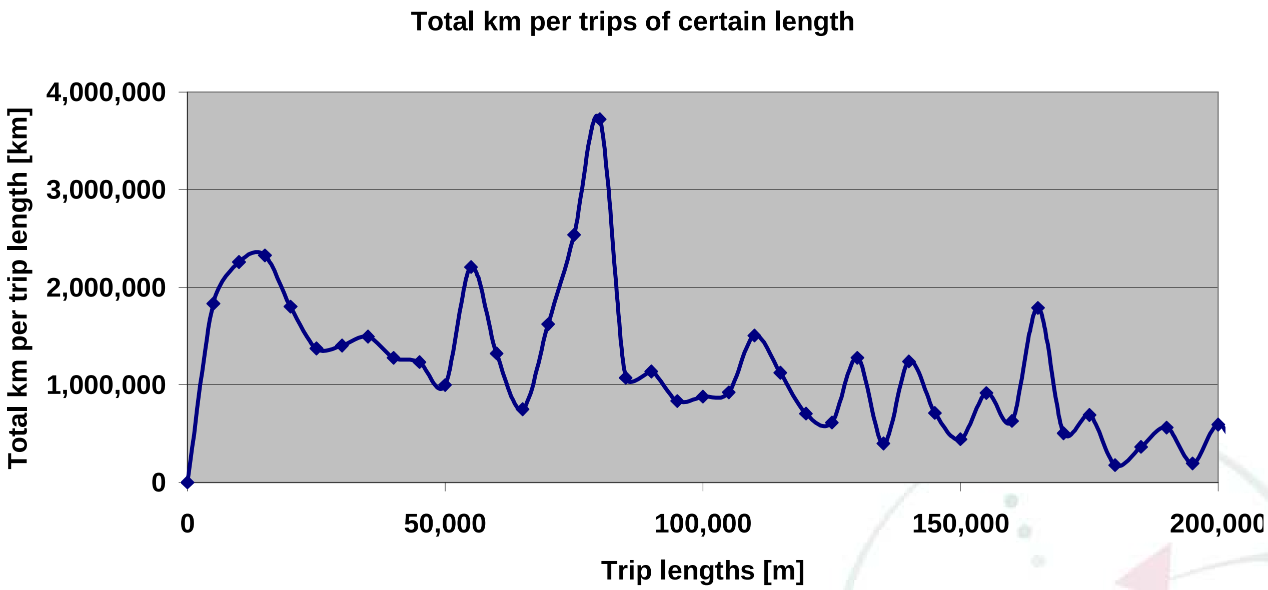

Figure 3. Mileage per trip length.

This is rather homogeneously distributed, with larger values for short trips. This means that short, middle and long trips are more or less equally important for KMP. It is thus not possible to disregard a certain group of trips (the peak at 80 km is an abnormality, since one of the vehicles drove this distance (home-work) relatively often). It is unknown if the average Dutch driver makes relatively more short trips. For KMP it is important to realise that short trips contribute significantly to the total distance driven and can not be disregarded.

4.2. Reliability

Reliability is defined as the combination of the availability and the correctness (see chapter 2).

To determine the reliability of the GPS-positions the full data set for the month May 2006 is used. In total this corresponds to 709 hrs. of traveling (2,552,400 seconds). Every second a GPS-positions is logged (valid and invalid). In the ideal situation 2,552,400 valid GPS-positions are expected.

4.2.1. Availability

There are two situations where valid GPS-positions might not be available:

1. At the start of the trip, when the GPS-receiver has not yet found the first fix (Time-to-first-fix - TTFF). In the current data set this also relates to the start-up time of the measurement equipment (Time-to-first-log – TTFL, see below).

2. During the trip, where due to e.g. shielding no valid GPS-positions can be determined. This includes disruption during the trip as well as at the end (e.g. driving into a parking garage). It should be noted that current GPS-receivers more and more extrapolate the positions and keep providing ‘valid’ positions even when the reception is shortly disrupted.

Availability at the start of the trip

Due to the start-up delay of 90 sec. of the measurement equipment, the total time that GPS-positions are not available during the start of a trip cannot be determined accurately. The time-to-first-log (TTFL) is defined as the time the first valid GPS-position is logged by the measurement system after the start of the trip (ignition on). When TTFF is less than 90 sec. the first logged valid GPS-position is at 90 sec.; when the TTFF is larger than 90 sec. the TTFL equals TTFF.

The total amount of TTFF for the 1952 analyzed trips is estimated as follows. The upper limit is 84 hours (assuming a TTFF of 90 sec. for all trips with a TTFF equal to or less than 90 sec.) and the lower limit is 54 hours (assuming a TTFF of 0 sec. for all trips with a TTFF equal to or less than 90 sec). A good estimate is 70 +/- 7 hours (assuming a TTFF of 45 sec. for all trips with a TTFF equal or less than 90 sec). This means that due to TTFF 70 +/- 7 hours out of 709 hours (10 +/- 1 %) no valid positions are available. The mean value of the TTFF is 130 +/- 13 sec.

This holds for the current data set with relatively high mileage (and thus probably with relative more longer trips). If the average trip length of the Dutch vehicles is shorter, the non-availability due to TTFF will be larger than 10 %.

Figure 4 gives the distribution of TTFL. TTFL can be as high as 20 minutes. The minimum value of TTFL in this diagram is 90 sec due to the start-up time of the measurement equipment. For values larger than 90 sec. TTFL equals TTFF. To estimate TTFF at values below 90 sec, the curve above 90 sec. is extrapolated below 90 sec.

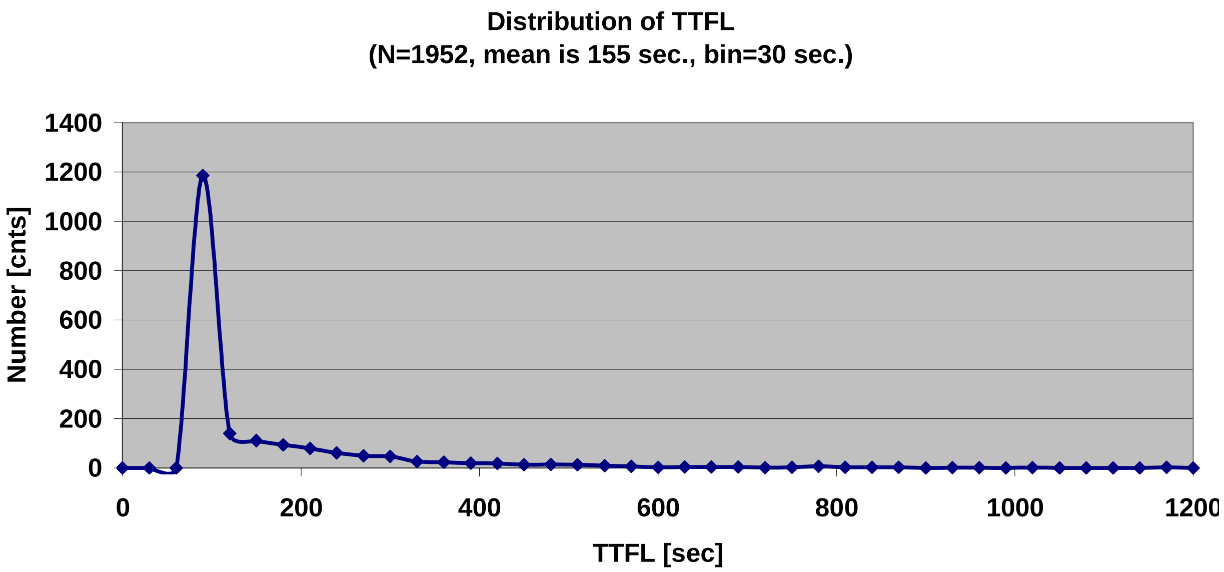

Figure 4. Distribution of the time-to-first-log.

One would expect that TTFF depends on the time passed since the end of the previous trip: larger TTFL for larger periods between trips. Figure 5 gives the TTFL versus the time between the start of a trip and the end of the previous trip.

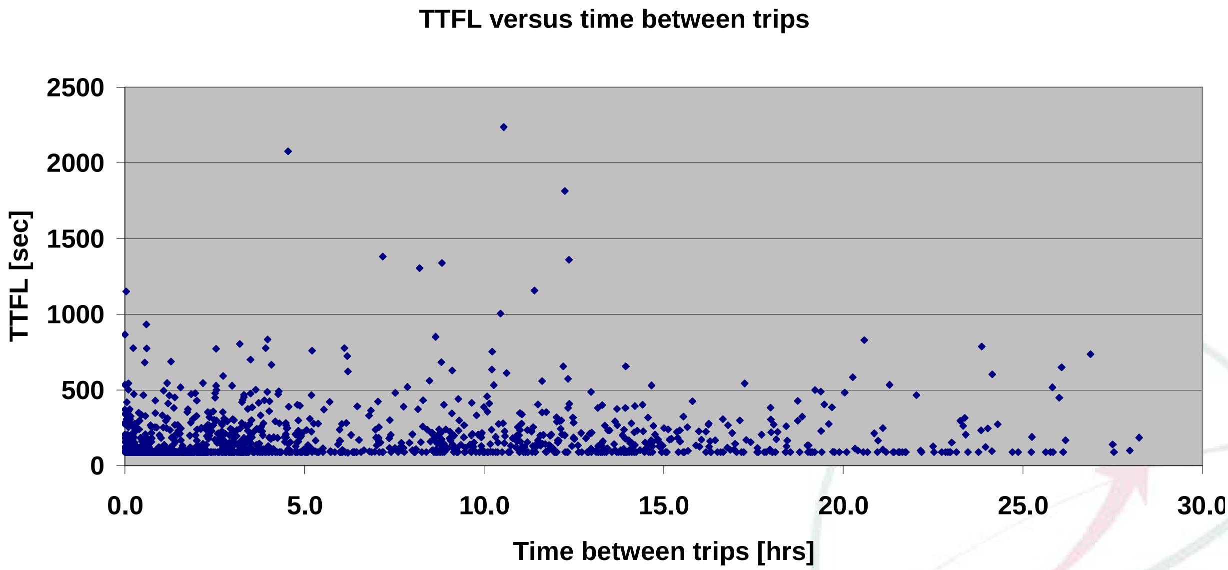

Figure 5. TTFL compared to the time between two trips.

Remarkably there is (for the current data set) not the expected relation. Also after more than 24 hours TTFL can be short and vice versa, after a short break still TTFL of 500 sec occur. Is must be noted that the data set used is measured using the vehicle in normal conditions, i.e. not under controlled driving conditions. The data set might include all kind of situations, e.g. a car is started in a parking garage, but the driver only start driving after sometime.

Availability during the trip

In total data is logged during 661 hours (for each trip the period from TTFL to the last logged position). Before the TTFF the GPS-positions are non-valid, but also after TTFF sometimes the GPS-positions are non-valid. E.g. due to tunnels, parking garages, etc. Analysis of the data shows that in total 14 hours out of the 661 hours there are non-valid GPS-positions. This corresponds to 2,1 % of the total trip duration.

4.2.2. Correctness

It is difficult to determine accurately the number of incorrect GPS-positions (positions that are indicated by GPS to be valid, but that deviates strongly from the real value). There are two analysis that provides an indication for the correctness.

1. Looking for sudden-jump, i.e. deviations between a position and its previous position that leads to unrealistic high vehicle speeds between those positions.
2. Looking for large deviations between the GPS-positions and the digital map NWB. I.e. looking for positions that cannot be map-matched within 50 m. One should note that these deviations might also be due to map-errors or driving at private or foreign roads.

Sudden jumps

The data set of 35,586 valid GPS-positions has been analyzed by determining the distance in meters between the current and the previous position. If this distance is larger than 50 meters (corresponding with a speed of more than 180 km/h) the GPS-position can be expected to be incorrect. Out of the 35,586 positions only 21 positions have been found with a distance to the predecessor of more than 50 m. This is less than 0.1 % of the number of positions. These 21 positions were in one time period of 21 sec. in one trip that took place in Belgium. None of the other trips showed a sudden jump of more than 50 m in 1 sec.

Sudden jumps of GPS-positions are thus very rare. Further more, they can easily filtered away by setting a maximum to the allowed distance to the previous position, e.g. a limit corresponding with a speed of 180 km/h.

Large deviations from the digital map NWB

During the trip, when the GPS-receiver provides valid positions, sometimes positions cannot be mapped to the digital map within a reasonable distance (50 meter is used in the current investigation) due to:

a) The GPS-positions are distorted, e.g. due to multipath
b) The vehicle is on a private road or private area.
c) The vehicle is abroad (NWB is only for NL)

d) Errors in the digital map (the NWB of 2005 is used)

In total during 16 hours of the 661 hours of valid GPS-positions could not be mapped to the digital map. This corresponds to 2,4% of the time. This includes all four mentioned error sources a) to d). All four error sources have been found in the data set by visual inspection of the measured positions in Google Earth (see Figure 6 as an example). This indicated that errors due to b) to d) occur much more often than errors due to a). Further detailed analysis of the data is needed to separate the error source a) of distorted GPS-position from the other error sources. The amount of distorted GPS-positions is estimated to be less than 1%.

Figure 6. Example of GPS-positions shown with Google Earth.

4.2.3. Conclusions on the reliability

The following reliability factors have been determined for the data set used:

Availability before TTFF	10 +/- 1 %
Availability during the trip	2.1%
Sudden jumps	Very rare
Large distortions of GPS-positions	Less than 1 %
Total reliability	**13 +/- 2 %**

During 13 +/- 2 % of the time no valid GPS-position is available in the current data set, mainly due to the unavailability before TTFF. The unavailability during the trip (less than 3%) is hardly a problem, as will be shown in the next chapter. Interpolation between the valid GPS-positions still leads to accurate measurements of the distance traveled. The unavailability before TTFF is a severe problem that needs to be solved for an accurate distance charging scheme.

4.3. Position accuracy

4.3.1. Methodology

To analyze the accuracy of the GPS positions a subset is taken from the Full Traffic data, with randomly selected short trips (less than 5 km). Only valid GPS-positions are considered.

It is assumed that the used digital map (Nationaal Wegen Bestand – NWB) reflects the 'true' positions and that deviations between the GPS-positions and the NWB is a measure for the GPS-position accuracy in the lateral direction. The NWB is not really the 'true' position, but also has a deviation from the actual locations of the roads (map errors). The deviation between GPS-positions and NWB-positions is the sum of the deviations between GPS-position and reality and that between NWB-positions and the reality. Therefore the deviations measured in this way are overestimations.

The NWB also contains the maximum speed limits per road segment. The speed limits are used as identifiers of the road classes (NWB does not contain road classes itself). The following speed limits (and thus road classes) occur: 30, 50, 60, 70, 80 90, 100 and 120 km/h.

In total there are 35,586 valid GPS-positions that are matched to the NWB in this data set.

4.3.2. Lateral accuracy per road class

For each of the valid, matched positions the distance between the GPS-position and the NWB-position (the GPS-position projected to the NWB) in the x-direction (dx) is plotted against the distance in the y-direction (dy), see Figure 7 . The center is almost at (0, 0), the standard deviation in the x-direction is 7,0 meter, in the y-direction is 7,9 meter.

The straight lines in Figure 7 are due to the fact that the difference between GPS-positions and matched positions are used. At longer stretches of road they sometimes slowly drift away from each other. The maximum distance in Figure 7 is 50 m, since this limit is used in the map-matching process. Positions further away than 50 m are considered as non-matchable.

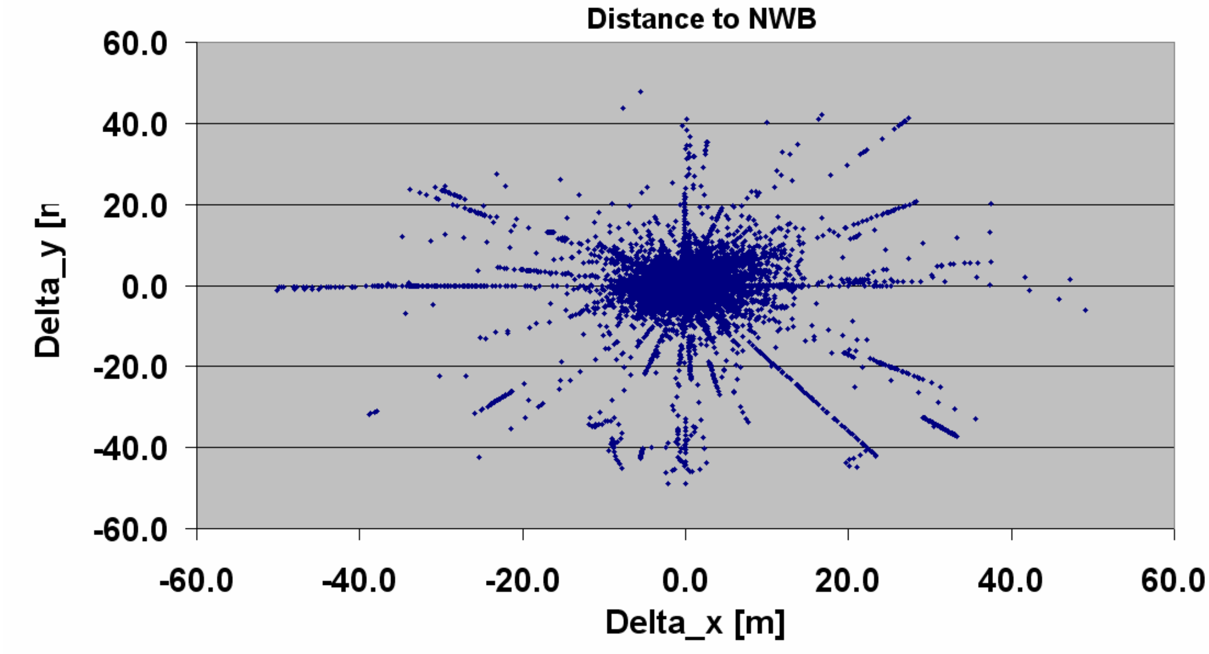

Figure 7. Distances between GPS-positions and the NWB network.

For each of the valid, matched positions, the road class is known (given by the speed limit). This allows to determine the position accuracy for different road classes. Table 6 gives per road class (identified by the speed limits 30, 50, 60, ... km/h) the number of GPS-positions used, the average distance to the road (indicated by D(dx,dy)) and the 95% confidence level. The latter is defined here such that 95% of all distances are less than this value.

Road class	Number of GPS_positions	Average distance D(dx,dy) [m]	95% conf.level [m]
30 km/h	7,734	7.4	35
50 km/h	18,114	6.0	27
60 km/h	1,462	8.1	35
70 km/h	984	3.4	8.5
80 km/h	4,160	6.2	25
100 km/h	220	4.9	11
120 km/h	2,912	4.0	8.5
Total	**35,586**	**6.2**	**26**

Table 6. Lateral GPS-position accuracies per road class.

Table 6 shows that the lateral GPS-position accuracies varies significantly with the road class. The 95% level at road class 120 km/h is less than one third of the ones for road classes of 60 km/h and less. This is partly due to the fact that roads with a lower road class generally are urban roads with more reception problems due to multi-path, canyon, tunnels, etc. But the main cause is expected to be the straightforward map-matching, which is not advanced enough for the current application, small inaccuracies in the digital map (NWB 2005 was used) and the fact that cars usually do not drive exactly at the center line of a carriageway.

The GPS-positions do not randomly vary. There is a clear correlation between a GPS-position and its previous position as was expected and explained in chapter 3. As D(dx,dy) denotes the distance between the GPS-position and the NWB-position, D(ddx,ddy) is defined as the difference in this distance between the actual and the previous point.

Figure 8 displays the distributions of D(dx,dy) and D(ddx,ddy).

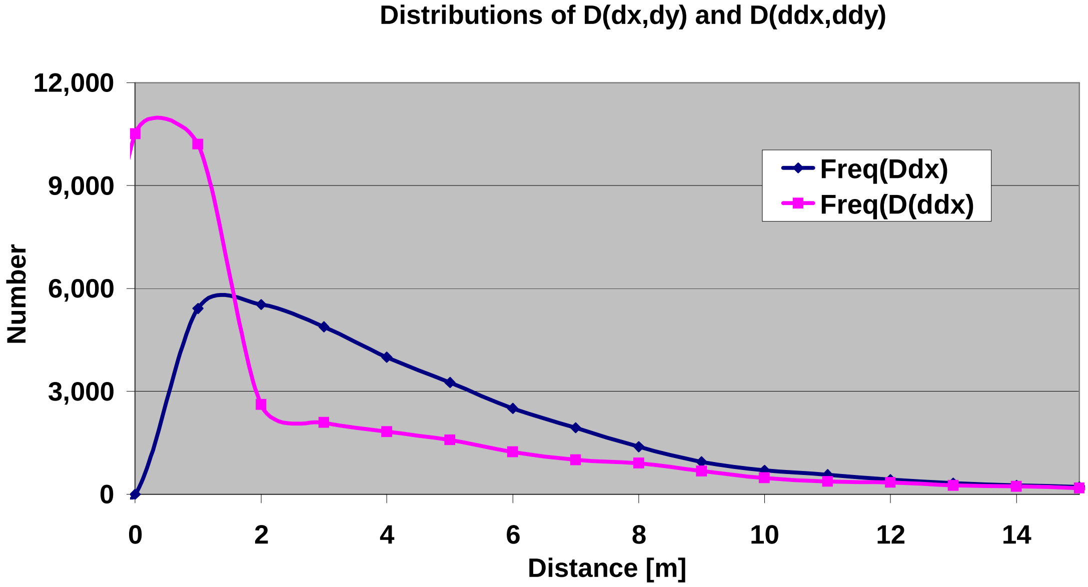

Figure 8. Distribution of D(dx,dy) and D(ddx,ddy).

The average of D(ddx,ddy) is 2.8 meter with a 95% level 10.3 meter (compared to 6.2 and 26 m of D(dx,dy)). More than half of the D(ddx,ddy) values (20,718 out of 35,586) are less than 1 meter. This is relevant for the accuracy of the distance measurements, since the larger the spread around the real trajectory is, the larger the error in the distance measurement.

4.3.3. Longitudinal accuracy

The longitudinal accuracy is less relevant for the overall distance measurements in KMP, since a longitudinal error in the distance between two consecutive positions is compensated by the distance to the next position.

The longitudinal accuracy is, however, relevant for KMP at the border between road elements with different costs, and when virtual toll locations are used in a scenario.

The longitudinal accuracy can be determined by comparing the CAN-distance driven between two GPS-positions with the corresponding GPS-distance. However, this detailed analysis is outside the scope of the present investigation.

An estimate for the longitudinal accuracy is given by the lateral accuracy. There is no reason to assume that the longitudinal accuracy will differ much from the lateral one. As mentioned above, GPS-receivers filter and extrapolate the measured positions while driving, this improves both the lateral and the longitudinal accuracy.

4.3.4. Determination of the road class

From the current data set it cannot be determined in a straightforward way how accurate the assignment of the road class via the map-matching algorithm is, i.e. how often is a valid GPS-position assigned to a wrong road class. A strong indication that this happen very rarely is, however, the fact that out of the 1,950 GPS-positions in this data set with an actual speed larger than 90 km/h only 2 GPS-positions are matched to a road with a speed limit of 30 km/h and none to a road with a speed limit of 50, 60 or 70 km/h. Further analysis of the current data set can determine the road class assignment accuracy, but that is outside the current scope of the study.

4.3.5. Conclusions on the position accuracy

The 95% level of the lateral deviation and the longitudinal deviation is 26 m, the combined accuracy (from both directions) is then about 37 meters. Literature and equipment specifications typically state a stationary accuracy of 10 - 15 meters.

The difference is most likely due to inaccuracies in the map-matching algorithm and in the digital map. The results include these accuracies and is thus an overestimation of the real position accuracy. Furthermore only short trips are used (generally with vehicle speeds between 0 and 60 km/h) in this analysis, which leads to a further overestimation of the 95% level.

More detailed analysis is needed to separate the real accuracy from the accuracies due to the map-matching / NWB.

The position accuracy is mainly of relevance for KMP if virtual toll points are used in the KMP scenarios and if those toll positions are at a location with dense road network around it. This can be prevented by choosing suitable locations for those points.

The accuracy to determine the road-classes is high, also with the used straightforward map-matching algorithm. This means that also private roads can be discriminated properly from public roads under the condition that the digital network of public roads is sufficient accurate.

4.4. Distance accuracy

4.4.1. Methodology

For this analysis 1952 trips from the month May are used, the total length is 55,267 km.

Trips consists of two parts, the part from the start of the vehicle (ignition on) to the First Log (see above) and the part after the First Log to the end (ignition off).

About the first part not much is known, also the CAN-data is not logged here. Known is the crow-fly distance to the last valid GPS position of the previous trip.

For the analysis of the distance accuracies only the second parts of the trip are used. Distances are determined per trip and per road class. Road classes are determined per GPS position by matching to the NWB. When two positions are more than 1.8 sec apart (i.e. one or more valid GPS-positions are missing), the distance between those two positions is assigned to road class 0 (‘unknown’).

Per trip and per road class three distances are measured: GPS-distance, NWB-distance and CAN-distance and there differences calculated: GPS-CAN, NWB-CAN and GPS-NWB.

The GPS-distance is determined as the sum of all distances between two consecutive valid GPS-positions. The NWB-distances as the sum of all distances between two consecutive map-matched positions on the NWB.

The vehicle speed from the CAN-bus (2 times per second) provides an accurate measurement of the distance travelled. The CAN-distance (the distance measured on the basis of the output of the CAN-bus) is measured in the vehicle by pulses coming from the four wheels. Their could be a systematic error in the conversion from pulses to distance, therefore this is calibrated by comparing the CAN-distance with GPS-distances (distance measured on the basis of the GPS-positions) on long parts of highways. Most correction factors are less than 1% (see annex A), they have been applied to correct the measured CAN-distances.

As basis for the analysis a table is generated from the data set with in each row the information from one trip. This information contains among others:

- The vehicle identification (car-id).
- Start and end times, as well as time of first GPS-log.
- Total number of valid and non-valid GPS-positions, number of non-matched positions.
- Total GPS-distance, NWB-distance and CAN-distance (all after TTFL).
- The same distances but per road class. Within one trip the distances of different parts of the trip on a road class are taken together. Distances that cannot be assigned to a road class are assigned to road class 0 (‘unknown’).

From the GPS-distances, the NWB-distances and the CAN-distances the differences between those distances are calculated.

Analysis showed that the differences between the GPS-distance and the NWB-distance and between the CAN-distance and the NWB-distance are significantly larger (in order of a factor 2) than the difference between GPS-distance and CAN-distance. This is most probably due to the straightforward map-matching algorithm and the inaccuracies of the NWB digital map

At the start of the investigation it was expected that the distance measured via the positions matched on the NWB (NWB-distance) would be more accurate than the GPS-distance. Matched positions do not vary in the lateral direction as GPS-positions do. The results show, however, the contrary. In the further analysis only the differences between GPS-distances and CAN-distances have been considered.

GPS-deviations are defined as the differences between the measured GPS-distances and the measured and corrected CAN-distances since the CAN-distances (after calibration) are regarded as an accurate measurement of the real distances.

As a first step the distances measured via GPS and via CAN are compared per vehicle; both the total distance traveled per month as well as the distances traveled per road class per month are determined. The differences between the GPS-distance and the CAN-distance is the GPS-deviation.

Secondly an analysis is made to determine the variations in the GPS-deviations (standard deviations) in order to determine how much the distance measurements may vary from the real distances.

The distances traveled in a certain trip and at a certain road class varies strongly over all trips. Therefore the GPS-deviations are expressed in meters per 1 km (e.g. a GPS-deviation of 100 meter on a distance of 5 km, leads to 20 m per 1 km).

Per road class the average GPS-deviations per km between are calculated as well as the corresponding standard deviations.

4.4.2. Comparison of GPS- and CAN-distance of the vehicles in the data set

As a first step the measured GPS-distances and CAN-distances are compared for the 19 vehicles in the data set. For this analysis only trips are used where the valid GPS-logging started at the same time as the CAN-logging (this is at TTFL), since then both distances can be compared correctly. In trips where the valid GPS-logging started after the start of the logging of the CAN information, CAN-distance is accumulated in this first part, while no GPS-distance is accumulated. In a more detailed analysis this could be taken into account, but that has not been done in the current investigation. There are 754 trips (out of 1952) for which the logging of GPS and CAN stated at the same time.

Car id	Uncorrected				Corrected						
	GPS-distance [km]	CAN-distance [km]	Distance difference [m]	Distance difference [%]	GPS-distance [km]	CAN-distance [km]	Distance difference [m]	Distance difference [%]	Cost (5 cent/km) [euro]	Cost deviation [euro]	Cost deviation [%]
3	212.7	211.0	1,674	0.8%	211.9	209.7	2,184	1.0%	**€ 10.59**	**€ 0.11**	**1.0%**
4	415.1	415.2	-73	0.0%	413.5	412.1	1,358	0.3%	**€ 20.67**	**€ 0.07**	**0.3%**
6	570.6	570.4	274	0.0%	568.4	568.7	-340	-0.1%	**€ 28.42**	**-€ 0.02**	**-0.1%**
7	124.4	123.8	593	0.5%	123.9	123.4	551	0.4%	**€ 6.20**	**€ 0.03**	**0.4%**
8	246.0	243.8	2,196	0.9%	245.0	242.8	2,173	0.9%	**€ 12.25**	**€ 0.11**	**0.9%**
9	330.0	329.8	227	0.1%	328.7	325.9	2,755	0.8%	**€ 16.43**	**€ 0.14**	**0.8%**
12	235.6	236.2	-561	-0.2%	234.7	235.4	-751	-0.3%	**€ 11.73**	**-€ 0.04**	**-0.3%**
13	512.1	513.3	-1,179	-0.2%	510.1	509.6	436	0.1%	**€ 25.50**	**€ 0.02**	**0.1%**
14	398.3	395.9	2,454	0.6%	396.7	396.1	675	0.2%	**€ 19.84**	**€ 0.03**	**0.2%**
15	322.9	322.6	265	0.1%	321.6	321.5	124	0.0%	**€ 16.08**	**€ 0.01**	**0.0%**
19	180.8	180.0	789	0.4%	180.1	178.4	1,683	0.9%	**€ 9.00**	**€ 0.08**	**0.9%**
21	424.4	425.0	-644	-0.2%	422.7	422.8	-127	0.0%	**€ 21.13**	**-€ 0.01**	**0.0%**
22	128.7	128.1	549	0.4%	128.1	127.7	485	0.4%	**€ 6.41**	**€ 0.02**	**0.4%**
23	1,198.8	1,201.5	-2,712	-0.2%	1,194.0	1,196.3	-2,304	-0.2%	**€ 59.70**	**-€ 0.12**	**-0.2%**
24	3,197.1	3,191.7	5,379	0.2%	3,184.4	3,190.3	-5,905	-0.2%	**€ 159.22**	**-€ 0.30**	**-0.2%**
26	988.3	986.6	1,664	0.2%	984.4	983.0	1,353	0.1%	**€ 49.22**	**€ 0.07**	**0.1%**
27	348.9	350.1	-1,137	-0.3%	347.5	348.1	-598	-0.2%	**€ 17.38**	**-€ 0.03**	**-0.2%**
29	396.2	395.0	1,280	0.3%	394.7	392.0	2,684	0.7%	**€ 19.73**	**€ 0.13**	**0.7%**
31	1,917.8	1,926.8	-9,004	-0.5%	1,910.1	1,916.3	-6,147	-0.3%	**€ 95.51**	**-€ 0.31**	**-0.3%**
All cars	**12,148.8**	**12,146.8**	**2,035**	**0.0%**	**12,100.4**	**12,100.1**	**291**	**0.0%**	**€ 605.02**	**€ 0.01**	**0.0%**

Table 7. Comparison of GPS and CAN-distances per vehicle.

Table 7 show the results of this comparison. The second and third column of this table gives per vehicle the distances determined directly from the measured valid GPS-positions and from the CAN-data without any correction factor. The fourth column gives the difference (in meters) between those two values. Without any correction the GPS-distance is within 1% from the CAN-distance.

For both GPS and CAN correction factors have been applied. Section 4.4.3 shows that the average GPS-deviation is 0.4%, in column 6 the GPS-distances are corrected for this value. In section 4.4.1 correction factors for the CAN-distances (also in the order of 0.5%) are discussed, the values in column 7 are corrected for this. Both the uncorrected and corrected data are accurate within 1%. Since only a part of the trips made in the month May are used here, the distances given here are less than the total distance those vehicles drove in this month. As explained in the next section, the GPS-deviations decreases further (in %) with larger distances. This is confirmed by the data in Table 7 the largest distances have the smallest GPS-deviation in %.

The last three columns show what these distances would mean in terms of an invoice, assuming a flat rate charge of 5 eurocent/km. Cost deviations are all less than 0.5 euro and less than 1%.

Table 7 also shows that there is only a small variation between the different vehicles, indicating the consistency of both the GPS and the CAN distance measurements.

Note that this relates to parts of the trips after the first valid GPS-position (TTFF) and does not include the deviations due to the missing measurements until TTFF. However, the parts after TTFF do include all other data, thus including potential deviations due to multi-path, tunnels, parking garages, drift while stopped, etc.

4.4.3. Distance accuracy per road class

As described in section 4.4.1, the GPS-deviations per km traveled are determined per trip and per road class. In total 1,952 trips and 5 road classes are analyzed leading to thousands of measured GPS-deviations (not all trips contained distances on all road classes). Figure 9 to Figure 12 give the calculated GPS-deviations versus the total distance traveled at the corresponding road class.

From those GPS-deviations the average values and standard deviations are determined per road class.

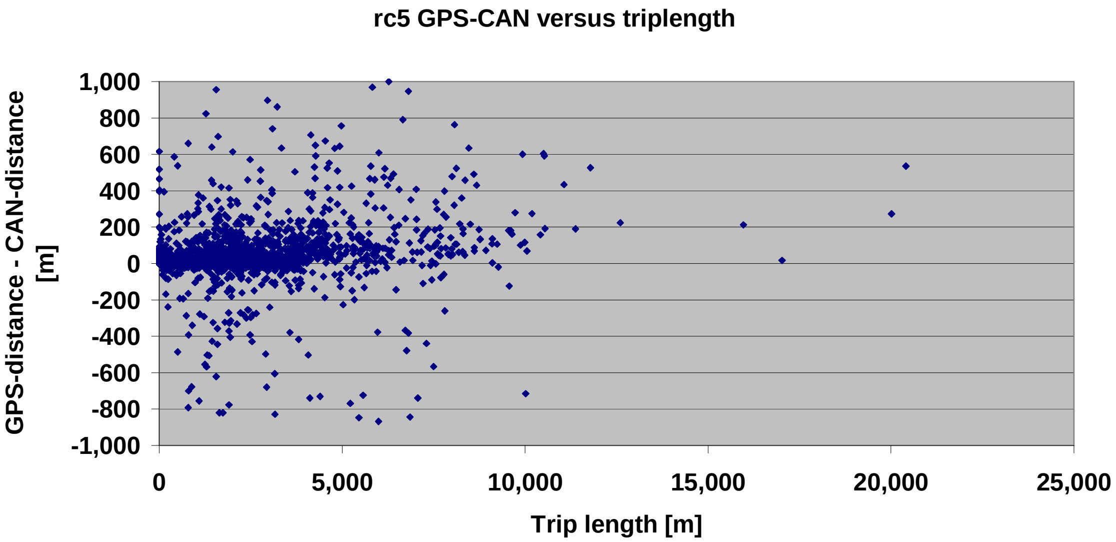

Figure 9. GPS-deviations for roads with a speed limit of 50 km/h.

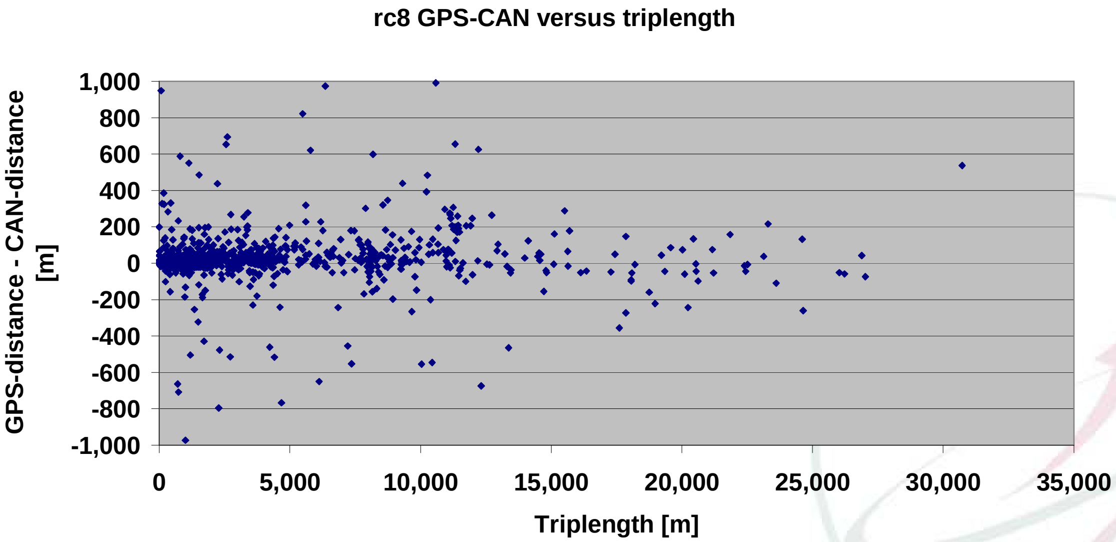

Figure 10. GPS-deviations for roads with a speed limit of 80 km/h.

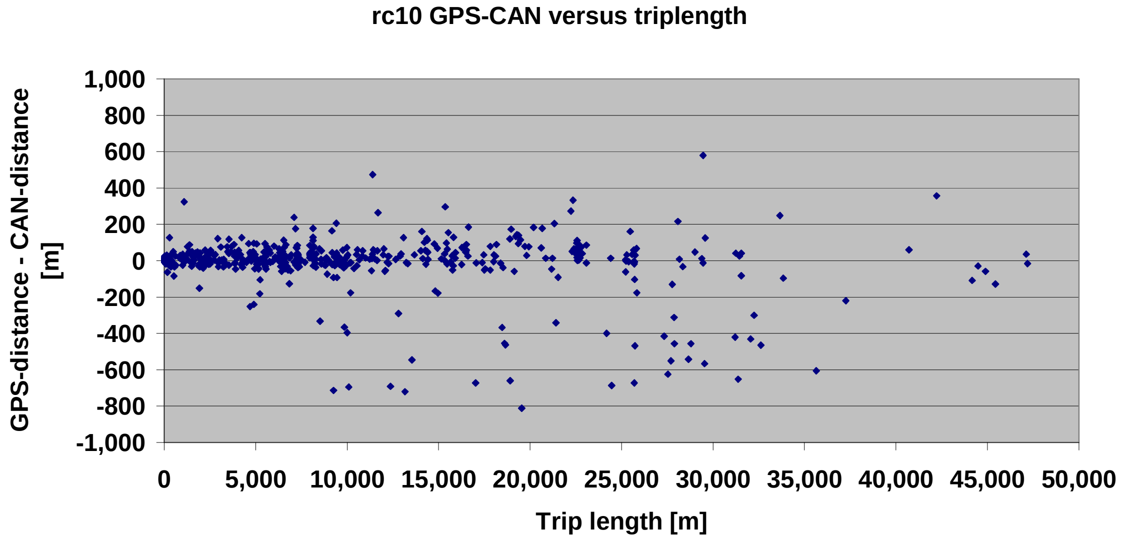

Figure 11. GPS-deviations for roads with a speed limit of 100 km/h.

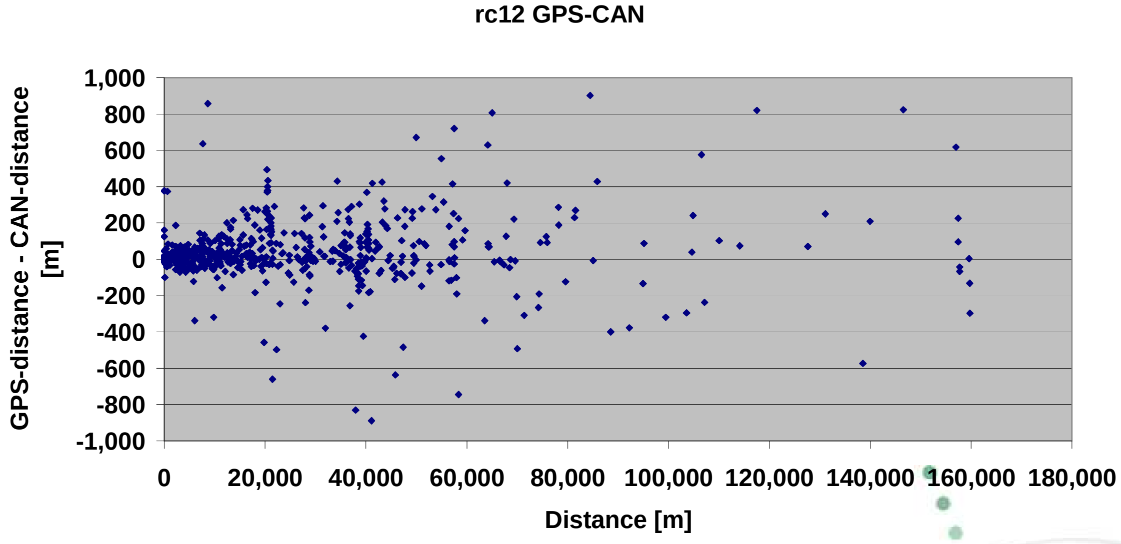

Figure 12. GPS-deviations for roads with a speed limit of 120 km/h.

The values in Figure 9 to Figure 12 seems to be randomly distributed and spread symmetrically around zero or close to zero. This is shown in a different way in Figure 13 and Figure 14, where the distributions of the differences are drawn for road class 5 and road class 12, respectively.

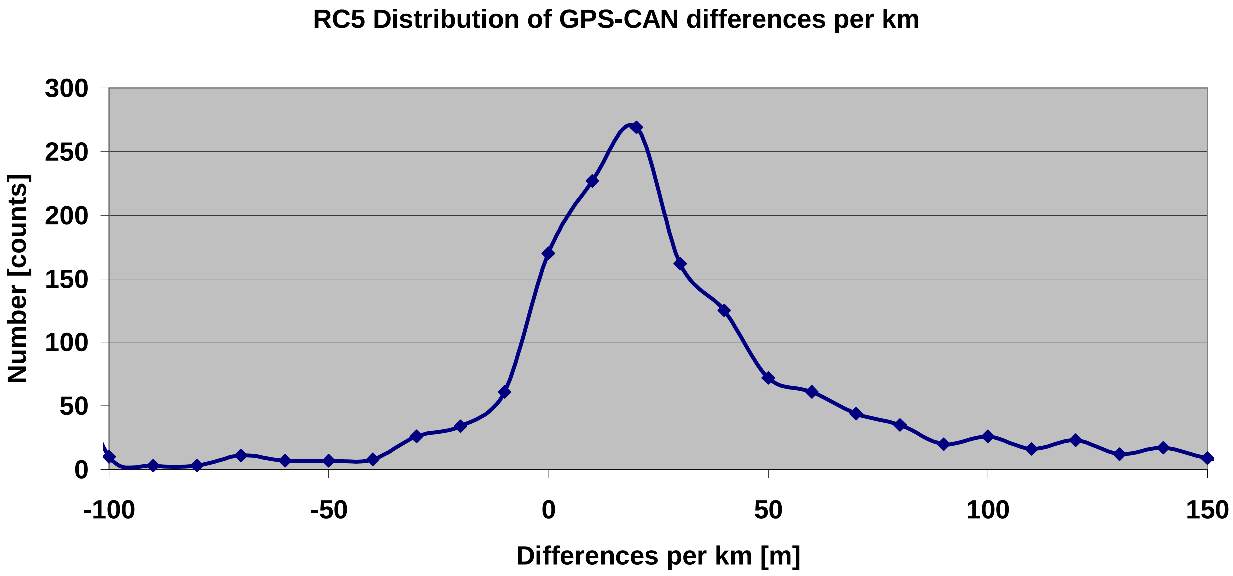

Figure 13. Distribution of the GPS-deviations for roads with a speed limit of 50 km/h.

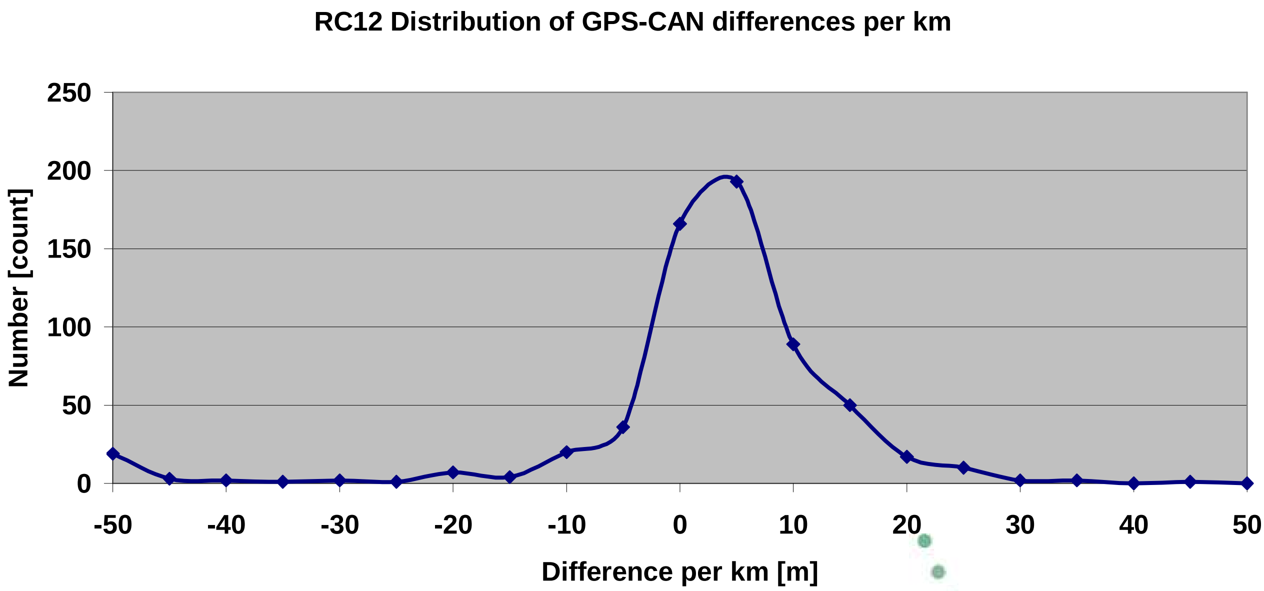

Figure 14. Distribution of the GPS-deviations for roads with a speed limit of 120 km/h.

Figure 13 and Figure 14 indicate that the GPS-deviations vary randomly and with a Gaussian distribution, suggesting that the standard deviation of the GPS-deviations will scale with the inverse square root of the distances (e.g. a standard deviation of 8% at a distance of 1 km leads to a standard deviation of 2% at 16 km).

However, this is likely, but not guaranteed. Subsets of the data could exists that have much higher standard deviations and or large systematic errors. Further investigations are needed to determine if there are dependencies with respect to e.g. different vehicles, trip length, etc.

In the analysis no reasons have been found that would indicate that the scaling with the square root would not be valid. In the further analyses the scaling with the square root will be used.

Per vehicle and per road class the average GPS-deviations and the corresponding standard deviations are calculated.

Table 8 gives the results per road class averaged over all the vehicles. Only road classes 0, 5, 8, 10 and 12 are analysed separately, since much less time is driven on the other road classes (3, 6, 7 and 9). The total distance contains all road classes, while road class 0 contains the values for the distances with an unknown road class.

	GPS-deviations per km	
Road class	**In meters**	**In %**
50 km/h	16 +/- 92	1.6 +/- 9.2
80 km/h	7 +/- 6	0.7 +/- 0.6
100 km/h	-2 +/- 16	-0.2 +/- 1.6
120 km/h	0.6 +/- 10	0.06 +/- 1.0
Unknown	2 +/- 23	0.2 +/- 2.3
All road classes	**4 +/- 22**	**0.4 +/- 2.2**

Table 8. Calculated GPS-deviations in meters per km per road class.

The GPS-deviations are calculated in meters per 1 km distance. The values in Table 8 show that indeed the GPS-distance is larger than the CAN-distance. GPS-positions vary in the lateral direction leading to a longer distance than that of a straight line. The GPS-deviation for the total analyzed distances (including parts for which the road class is unknown) is 4 +/- 22 meters per kilometer or 0.4 +/- 2.2 %.

The average values of the GPS-deviations for 100 km/h and 120 km/h roads are remarkably small (-2 +/- 16 and 0.6 +/- 10 meters per km). This is partly due to the fact that the CAN-distances are calibrated using the GPS-distances for larger parts of 120 km/h roads. But, as mentioned in section 4.4.1 the correction factors are small: less than 1% and thus play a minor role.

As expected, the accuracy for 50 km/h roads is much less, the average GPS-deviation is 16 +/- 92 meter per km (1.6 +/- 9.2%). This means e.g. that 5% of the trips of 1 km on 50 km/h roads will differ more than 18% from the real distance.

Also the accuracy for road class 0 (unknown road class) is high. This is explained by the fact that most of the unknown road class distance is due to driving long trips abroad. The NWB only covers NL, such that outside NL no road classes can be determined in the current analysis and hence the road class is 0. But the GPS-deviations (difference between GPS-distance and CAN-distance) remain low.

The results per vehicle and per road class are given in the annex. From the annex it can be seen that the results do vary over the different vehicles, but the variations are consistent with the corresponding standard deviations.

In Table 8 the GPS-deviations are given for distances of 1 km. In the planned charging scheme an invoice per month is expected, thus over longer distances. From the given standard deviations per 1 km, standard deviations for larger distances can be calculated (scaling by SQRT(distance)) and the 99% confidence levels can be calculated (2.6 times the standard deviation).

Table 9 gives average, standard deviations and confidence levels of the GPS-deviations in percentages for distances of 1, of 350 and of 1.350 (the average mileage per month in NL) kilometer for different road classes.

	50 km/h	80 km/h	100 km/h	120 km/h	Unknown	Total
Average GPS-deviation						
Per 1 km in meters	16 m	7 m	-2 m	0.6 m	2 m	4 m
In percentage	1.6%	0.7%	-0.2%	0.6%	0.2%	0.4%
Standard deviations						
Per 1 km in meters	92 m	6 m	16 m	10 m	23 m	22 m
Per 1 km in %	9.2%	0.6%	1.6%	1.0%	2.3%	2.2%
Per 350 km in %	0.5%	0.03%	0.08%	0.05%	0.12%	0.1%
Per 1350 km in %	0.25%	0.02%	0.04%	0.03%	0.06%	0.06%
99% confidence levels						
Per 1 km in %	24%	1.6%	4.2%	2.6%	6.0%	5.7%
Per 350 km in %	1.3%	0.08%	0.22%	0.14%	0.3%	0.3%
Per 1350 km in %	0.65%	0.04%	0.11%	0.07%	0.16%	0.16%

Table 9. Average, standard deviations and 99% confidence levels of GPS-deviations for different distances and road classes.

Table 9 gives standard deviations and confidence levels below 0.1% for some distances and road classes. These are unrealistic accurate values, although they follow straightforward from the current analysis. At this level of accuracies (below 1 per mill) other effects and/or details of the calculation (e.g. the error-distribution is not for 100% Gaussian) starts to play a role.

The results of Table 9 can be compared with the results of Table 7. The GPS-deviations in Table 7 are there in the order of less than 1% for all vehicles and less than 0.3% of the vehicles that drove more than 400 km. The results are in line with each other, with in Table 7 slightly larger deviations.

4.5. Conclusions on distance accuracy

The above analysis of the accuracy of the measurement of distances via GPS leads to the following conclusions:

- For short distances the accuracies of the distances calculated from the GPS-positions are significantly larger than 1%. The reason for this is the variation of the GPS-position with respect to the actual positions. This variation is fairly random, it depends on a large number of factors (satellite constellation, buildings/trees in the surrounding, speed of the vehicle, atmospheric and weather conditions, etc.)
- Due to the random variation, the relative accuracy (in percentages) of larger distances becomes more and more accurate and generally is then accurate enough to meet the KMP requirements.
- For distances of about 1 km the 99% confidence level is in the order of 2 to 24 % in the current data set.
- For short distances the variance is thus fairly large, but averaged over the typical distance driven in one month this leads to accuracies meeting the specified requirements.
- These accuracies of the GPS-deviation contain all effects after TTFF, such as multi-path, tunnels, drifting while stopped, etc.
- Vehicles driving only a few hundred km per month and mainly on 50 km/h roads do not meet the requirements. Exceptional situations like this need to be considered, but are not part of the current study. A standard correction of e.g. 1 euro per month could solve many of those problems.
- When the same route is driven again (e.g. a trip of a few km) the results for that single route might vary significantly. This might lead to confusion for e.g. commuters driving the same trip regularly, but noticing then differences in the costs.
- The NWB-distance showed to be less accurate than the GPS-distance. This is mainly due to the map-matching algorithm used, which was rather straightforward, and the quality of the used NWB (version 2005). The authors believe that with an advanced map-matcher and a more up-to-date digital map higher accuracies can be reached, even better than the accuracies of the GPS-distances. Furthermore, it is expected (but further research is needed) that distances calculated using the map-matched points vary less than those calculated directly from the GPS-positions.
- These conclusions holds only for the part of the trips after TTFF.

5. KMP issues

5.1. The KMP scenarios

Purpose of the current investigation is to determine if a GNSS system can meet the KMP requirements, i.e. to determine the accuracy in relation to the intended charging scenarios. The Ministry of Transport, Public Works and Water Management has defined four different scenarios. They contain the following components:

a) A flat fee for every kilometer driven in The Netherlands
b) A different fee (or no fee) for private roads/areas
c) A different fee for roads in a certain area, e.g. a city
d) A different fee for certain pieces of roads (e.g. certain parts of the motorway or throughways in cities.
e) A fee when passing a virtual location

All scenarios assume an invoice per month.

The different scenarios are combination of those components. To access the feasibility to use GNSS systems it is, however, better to discuss the GNSS accuracy in comparison to those components. For each of those components the TTFF is the main problem. Another issue is to determine if the vehicle drives in NL and not abroad, but this is solvable.

Scenario component	Potential problems according to the analysed data set
A flat fee for every kilometer driven in The Netherlands	In this case only the total distance needs to be measured, no distinction needs to be made between different road classes and/or between public and private roads. Distance measurement after TTFF is within the requirements, as long as the average mileage is more than 400 km/month.
A different fee (or no fee) for private roads/areas	There are no digital maps with a good representation of private roads and areas. This means that the position needs to be matched to a network of public roads to establish the difference of km driven on public and on private roads. This network needs to be complete (i.e. include all public roads in the vicinity of the private roads/areas). Matching to this network can be done sufficiently accurate (there are relatively few non-match positions), but it will remain difficult to differentiate between a public and a private road less than 50 m apart. For those cases where this can become a problem, this might be solved by including those roads in the digital network, marked as private road.
A different fee for roads in a certain area, e.g. a city	No problems are foreseen here, as long as the area is selected with some care. If the area is chosen such that the border is for a large part between two roads that are less than 50 m apart, some problems might occur. Although even then these problems are expected to disappear in the average over one month.
A different fee for certain parts of the roads (e.g.	Distances for different road classes need to be determined in this case. Matching the GPS-positions to the digital network can be done

certain parts of the motorway or throughways in cities	and the current analysis shows that also for each road class the distance accuracy is sufficient for the given requirements. The current data set indicates also that only very rarely a position is map-matched to the wrong road class. Still much attention should be given in the selection of such road segments with respect to the limitations of GNSS based position measurements.
A fee when passing a virtual location	To determine on the basis of a few GPS-positions near this virtual location if the location is passed (yes or no) might lead to some difficulties. Driving 180 km/h (50 m/s) there are only one or two positions near the virtual locations. But when the positions are analyzed over a much longer part of the road before and after the virtual location, then the passing of this location can be determined accurately and much better than 99%.

5.2. Identification of main issue with GPS

From the data analysis, the discussion in section 5.1 the main potential issues can be summarized:

5.2.1. Start of a trip

The main issue is the time-to-first-fix (TTFF). As shown in Figure 5 in section 4.2.1 TTFF can be as high as 15 min. For 5% of the trips, the TTFF is 415 sec. or higher. In total 10 +/- 2 % of the total driven time in the current data set, GPS-positions are not available due to TTFF. Without additional measures, this is unacceptable in all scenarios.

5.2.2. Intrinsic accuracy

The fact that the GPS-positions vary randomly around the driven trajectory makes that the GPS-distance is longer than the straight line. The analysis showed, however, that this can be compensated for and that the standard deviation is small enough to meet the specified requirements. This is thus not a main issue, when considering all invoices per month. However, exceptional cases do exist (e.g. someone driving only very few km per month or mainly at private roads, etc.). These cases can never be solved completely, but an improved accuracy would reduce potential problems with those cases. It can be expected that newer receivers and the combined use of GPS and Galileo will reduce this issue to a large extent.

Also a standard correction factor (discount) on the monthly invoice, e.g. 1 euro reduction, would prevent problems from many of the exceptional cases.

5.2.3. Short trips and low mileage

When looking at the average over all vehicles and over one month the specified requirement can be met easily (except for TTFF). As exceptional cases exists, these may lead to problems in individual cases.

However, this should also be put in perspective. Road charging schemes as in London and Stockholm charge a fixed amount of money for entering the city centre, irrespectively of the distance driven. So someone driving only 1 km in the city centre pays the same as someone driving e.g. 10 km. While in the KMP scenarios one pays for every km and for short distances there might be an variation of a few percent.

5.2.4. Reception in difficult areas (high buildings, trees, tunnels, etc.)

The data set used showed only very little cases where there are strong deviations of valid GPS-position that could not be matched or had unrealistic large distances between two consecutive positions. And in those rare cases the distance is interpolated, such that the error in distance measurement is marginal. Also from a theoretical point of view no large problems are to be expected in the Netherlands.

5.2.5. Acquiring distance when stationary

When stationary the GPS-positions still vary around the real position, acquiring erroneous a traveling distance. The current analysis did not investigate this in detail, but it could be part of the explanation for the larger deviations at low road classes (more traffic lights, etc.). This could be catered for by not accumulating distance when the speed is under a certain threshold or by other algorithms.

5.2.6. Private roads and private terrains and abroad

In the current data set 2,4 % of the valid GPS-positions could not be map-matched within 50 m tot the digital map. Although not analyzed in detail, the data indicates that this relates mostly to private roads/terrains, trips at the country border and to roads missing in the NWB. Trips with very large differences (tens of km) between the GPS-distance and the NWB-distance have not been taken into account in the analysis. Driving abroad can be solved by checking if the position is within NL or not.

Driving on private roads might be an issue when they are charged differently form public roads. In the data set used this is not an issue when the data is average over a month and over all vehicles. But it is not clear if these vehicles are a good representation of the Dutch vehicles with respect to the amount of km driven on private roads.

5.2.7. Determining trajectories with a different tariff

Determining a trajectory with a different tariff is equivalent with determining the road class. In the current analysis a slightly older version (2005) of the NWB is used and a rather straightforward map-matching algorithm. The main purpose of map-matching is to determine the road class. Although not analyzed in detail, the results indicate that only very seldom a wrong road class is assigned to a GPS-position. But distances determined on the basis of the map-matched positions are much less accurate than those determined directly from the GPS-positions.

NWB will improve the coming years. The map-matching algorithm can be improved significantly, especially considering the fact that map-matching does not need to be done real-time, such that both previous and next positions can be taken into account.

With a perfect digital map and a perfect map-matching one would assume that determining the distance using the map-matched positions should be more accurate than using the raw GPS-positions. With the current map and algorithm this is not the case. It is still to be investigated if such an improved algorithm could lead to higher accuracies.

5.2.8. Jamming the GPS-system

Local jamming (areas up to several hundreds of meters) at a few places will hardly influence the results. It should be expected that jamming lead to either non-valid GPS positions or to large sudden jumps of valid GPS-positions. Both can be easily filtered away and the trajectory interpolated. This holds also for virtual toll locations, as long as the whole road segment is used to identify that a vehicle has passed that location (not only the positions near the virtual location).

5.2.9. Fraud

Fraud and misuse are not part of the current study. The analysis shows, however, that in general short periods of disturbances do not disturb the distance measurement significantly. There are, however, many ways a system can be disturbed. Further research is recommended here.

5.3. Summarizing of the main issues

- TTFF problem must be solved.
- For short trips the distance accuracy is low
- Private roads needs to be identified
- A digital map is needed to determine segment with different tariffs. This is only needed for the specific segment and a small area around this area.
- Fraud issues need further investigations.

6. Auxiliary techniques

This chapter briefly describes a number of auxiliary techniques that could improve the accuracies and/or contribute to decrease the potential problems with the issues identified in the previous chapter.

6.1. Overview of other relevant techniques

GPS improvements and Galileo
As mentioned in chapter 3 the GPS-system will be further improved by adding two extra channels. This will improve the position accuracy, but not improve the TTFF. Galileo has more or less the same position accuracy as GPS, although most likely slightly better since more satellites are used. There is no reason to suspect that the TTFF for Galileo will differ much from the from GPS.

The fact that Galileo provides extra services (mainly providing extra certainty about the correctness of the signal) is not relevant for KMP, since the results from the current data set show that the availability of GPS-positions (after TTFF) is sufficient.

A combined receiver of GPS and Galileo can be foreseen, resulting in a further improvement of the accuracy.

GLONASS
GLONASS, GLObal NAvigation Satellite System, is the Russian counterpart of GPS. It is similar in approach and constellation. The system was finished in 1995, however due to Russia's poor economic situation it was neglected since then, resulting in a meager coverage. In 2002 new life was put into the program and the system is expected to be fully operational. But the accuracy is not as high as GPS, because SA is still activated.

Conclusion: not relevant for KMP.

AGNSS/DGNSS
Assisted or Differential GNSS describes an addition to a GNSS to improve the performance of the GNSS receivers. The stationary GNSS receiver broadcasts the difference between the positions indicated by the satellite systems and the known fixed positions via an existing network like GSM or FM. This reduces the TTFF significantly and increases the sensitivity of the GNSS receiver.

Below an example of test results of one single Garmin 12 XL receiver with and without DGPS is given.

Garmin 12XL without DGPS	Lon
50.00% confidence	2.5 meters
68.27% confidence	3.8 meters
95.45% confidence	7.0 meters
99.73% confidence	**9.8 meters**

Garmin 12XL with DGPS	Lon
50.00% confidence	1.6 meters
68.27% confidence	2.2 meters
95.45% confidence	4.2 meters
99.73% confidence	**6.7 meters**

Table 10. Test results of DGPS.

Conclusion: Very relevant for KMP. This will reduce TTFF and also improves the position accuracy.

WAAS, EGNOS
WAAS and EGNOS are specific examples of systems which use DGNSS. The system includes not only ground stations but also geostationary satellites to send out their corrections to the WAAS/EGNOS enabled receivers. A satellite in geostationary orbit always stays visible for any fixed point on earth, so a receiver on earth can maintain a direct link with the satellite. Both systems can be accurate to a 7-meter level.

WAAS, Wide Area Augmentation System, is developed for civil use (mainly aviation). It is based on GPS and available in the US and Alaska with 25 ground stations and two master relay stations. A ground station sends its measured difference to the master relay stations, which send the corrections to two geostationary satellites. Those satellites beam the correction signal back to earth, where WAAS-enabled GPS receivers use the correction to calculate GPS position.
LAAS - LAAS is the *local* area system used for airport approaches and landings. LAAS can be disregarded for the purpose of KMP.

Garmin GPSMAP 76 without WAAS	Accuracy
Horizontal Accuracy (50%)	3.1 meters
Horizontal Accuracy (95%)	7.7 meters
Garmin 12XL with WAAS	Accuracy
Horizontal Accuracy (95%)	6.4 meters

Table 11. Comparison of accuracy improvement by WAAS.

EGNOS, European Geostationary Navigation Overlay Service, is the European counterpart of WAAS. The EGNOS system is has been operational since 2006 and it is compatible with not only GPS but also GLONASS It consists of 34 ground stations, four mission control centers (only one active, the others serve as back up) and uses three geostationary satellites with global coverage.
SISNeT – SISNeT provides EGNOS real time GNSS differential correction data and integrity information via the Internet. This eliminates the need of a special EGNOS receiver and a link with a geo stationary satellite. A practical application for SISNeT was recently demonstrated in Madrid. A pilot guiding visually impaired with an audible map was carried out with success.

Conclusion: Very relevant for KMP. This will reduce TTFF to a minimum (several seconds) and also improves the position accuracy. Especially when the information is communicated via a terrestrial communication (e.g. UMTS, which is part of KMP anyway) the extra cost and complexity would be limited.

GSM / MTS
By tracking the mobile terminals the position of vehicles can also be determined. Depending on the location (inner city / rural areas, etc.) the position accuracy is 50 m to several hundreds of meters. This is not relevant for KMP.

Beacons
Beacons provide a very accurate position determination at specific points. It is difficult to imagine how beacons can support the distance measurements. At the virtual toll locations beacons could be of use, but as indicated the use of GPS-positions is accurate enough to do this without beacons.

Loran-C

LORAN-C is the current version of LORAN, LOng RAnge Navigation, a terrestrial navigation system mostly used in marine applications. The system is based on trilateration just like GNSS, a LORAN receiver needs signals from three or more LORAN stations to calculate its position. A LORAN station sends out its signal via low frequency radio transmission, 90 to 110 kHz. 40 or 50 stations are installed all over the world. On average the accuracy of LORAN-C is 50 meters. Availability of the signal depends on weather conditions, it heavily decreases in case of magnetic storms.

Since GPS became active it was no longer useful for the US military so a large part of the LORAN stations changed hands. In North western Europe 4 stations were taken over by NELS (North West European Loran-C system) a cooperation between Denmark, France, Germany, Ireland, Norway en The Netherlands. Currently it is uncertain NELS will remain active, due to lack of users.

Conclusion: Loran-C could be of use during the period TTFF, but it is not expected that the position accuracy is sufficient to determine the distances in this part accurate enough and also not to determine the road classes (when then are different tariffs at different parts of the road).

Gyroscope
With a gyroscope the changes in direction of a vehicle can be measured. Stand-alone, this is not relevant for KMP.

Accelerometer
Cheap, stand-alone accelerometers exist. From their readings changes in speed and also in distances can be determined, however all relative to the known starting point. The error grows with the distance and time travelled. Accelerometers could help e.g. to measure the distance travelled while driving in a tunnel. However, the analysis of the current data set showed that this is not a main problem when using GNSS systems. Accelerometers (eventually in combination of a gyroscope) could be supportive during the TTFF period. However, further research is needed to determine how accurate distances and road classes can be determined in this way. Finally an accelerometer could be an indicator that the vehicle is moving. This could help to prevent fraud when people manage to disturb the GPS-reception.

Speedometer/odometer
Speedometer measures the speed of the vehicle, an odometer the distance traveled. By measuring the time speed can be transferred in distance and vice versa. This might be of use in KMP to determine that the vehicle is driving or not (e.g. preventing to accumulate erroneously travelling distance at low speed and e.g. determining that the vehicle is moving, which might be of help in preventing fraud) and might be used to determine the distance (by integrating the speed over time) when the positions are not valid. Speedometer/odometer readings are often taken from the vehicles equipment (e.g. the CAN-bus). This leads to extra complexity and extra costs for the OBU.

Map matching/route planning
A straightforward map-matching has been used in the current study. Much more advanced map-matching techniques are possible. Especially since map-matching can be done off-line, using both previous and next positions to determine a point position. This can support to distinguish between private and public roads and might help improve the position accuracy at the rest of the trip. Map-matching is further required to determine the road class and to distinguish between private and public roads.

Route planning might be used during TTFF (from the end of the previous trip to TTFF). But long TTFF needs to be prevented anyway.

6.1.1. Summary of auxiliary techniques relevant to KMP

Table 12 gives an overview of the auxiliary techniques and the relevance they have for the different KMP issues mentioned in chapter 5. A minus sign indicates that there is no or hardly an improvement to be expected of this techniques for this issue. A plus sign indicates that there is an improvement to be expected, but that this improvement is not very relevant, since the current accuracy seems to be accurate enough. A double plus sign (extra highlighted in light green) indicates that the technique possibly can lead to improvements relevant to KMP.

	Start of trip	Intrinsic accuracy	Short trips and low mileage	Reception in difficult areas	Acquiring distance when stationary	Private roads and terrains and abroad	Determining trajectories with a different tariff	Jamming the GPS-system	Fraud
GPS-improvements	-	+	+	+	+	+	-	-	-
Galileo	-	+	+	+	+	+	-	-	-
AGNSS/DGNSS	++	+	++	+	-	-	-	-	-
WAAS, EGNOS	++	+	++	+	-	-	-	-	-
GSM / MTS	-	-	-	-	-	-	-	-	-
Beacons	-	-	-	-	-	-	+	-	-
Loran-C	+	-	-	-	-	-	-	-	-
Gyroscope	-	-	-	-	+	-	-	-	+

Accelerometer	**++**	**-**	**-**	**-**	**+**	**-**	**-**	**-**	**++**
Speedometer/odometer	**++**	**-**	**++**	**+**	**+**	**-**	**-**	**+**	**++**
Map matching / route planning	**++**	**+**	**++**	**+**	**+**	**++**	**++**	**+**	**+**

Table 12. Comparison of possible auxiliary techniques versus the identified KMP issues.

Summarizing, the following auxiliary techniques might be of relevance for KMP:

1. AGPS/DGPS/EGNOS/SIS-net. Strongly reducing the TTFF and improving the accuracy of the positions leadings to some improvements of the distance measurements of short distances.

2. Accelerometer. Might support the measurement of distances before TTFF. It also might support the prevention of fraud by indicating that the vehicle is moving.

3. Odometer/speedometer. If accurate enough (as in the analyzed data set) this can help to measure distances during TTFF and during other periods where there are no valid positions. However, no road class (read segments with different tariffs) can be distinguished. Furthermore, a connection to the cars-equipment increases complexity and costs. Can also support the prevention of fraud.

4. Advanced map-matching is needed to distinguish between private and public roads and to determine trajectories with different tariffs. Advanced map-matching might potentially improve the distance accuracy (needs to be investigated). The advanced map-matching only need to be done around segments with a different tariff (e.g. private roads, congested segments, borders of city-areas, virtual toll locations). And thus only the digital map of those areas need to be used. If different tariffs are used in a city (e.g. through ways different from the other city roads) a complete digital network of that city needs to be used.

7. Comparison with literature

The main conclusion of the current study is that GNSS systems are accurate enough (after TTFF) to measure the distance traveled (also discriminating properly different road classes and public/private/foreign roads under the condition that the digital map is accurate enough). In [7] it is described that "Dedicated Short Range Communication (DSRC) systems are no longer the natural choice", but that "GNSS technology combined with Cellular Network communications have proven to be a better approach for some scenarios, and a unique solution for national systems with complex road class-dependent tariffs schemes". This is confirmed by the current investigations. GNSS provides the flexibility for scenarios where the tariffs can vary any where and any time.

In the trials for the London Congestion Charging system [8] an extensive investigation on the accuracy of GPS-systems has been done. The measured GPS position in the current research is an average deviation from the digital map (NWB) of 6.2 meters and the 95% confidence level corresponds to 26 meters (see 4.3.5). The London trials reports an average location error of 9.7 meters with a 90% confidence level of 28 meters and a 99% confidence level of 57 meters. The London location error is thus clearly larger than the errors found in the current situation. Probably this is due to the fact that the London trials covered more city roads and the fact that London has much more areas with tall buildings such that the canyon effects will be much larger than in the Dutch situation.

There is a important difference between the proposed KMP scenarios and the London Congestion Charging scenario. In the London scenario one pays when crossing the boundary of the city center. There are then high demands for the position accuracy in order to determine accurately enough if the border has been passed or not. The Dutch scenarios charge per km driven, an error at a certain point does not strongly influence the charging for a complete month.

Harvey Applebe [9] describes also possible use of GNSS systems for road charging schemes; he questions if GNSS systems are accurate enough for this. The GPS-position accuracies he mentioned ("a 99% confidence level of 30 m can be expected from the better GPS-receivers") are in line with the GPS-receiver used for the current investigation. Unfortunately he mainly focus on the accuracy of positions, not on the accuracies of distance measurements. The current investigation do confirm the statements of Applebe that auxiliary techniques are needed: A solution for the period to TTFF is needed and map-matching is required to determine the road-class.

In ref. [10] Siemens "challenges the view of certain industry opinion formers who favor Dedicated Short-Range Communications (DSCR) over GPS and who claim that satellite positioning technology is not yet capable of supporting a road pricing regime". In [10] the advantages of GPS are clearly described. It also states that if needed some beacons could be used at certain, highly complex locations. The current investigation confirms the arguments of Siemens; moreover in the Dutch situation and the proposed KMP scenarios, there seems not to be any need for additional beacons. Ref. [10] also mention some test results as an example of a lorry that drove 1140 km. The distance error measured was 0.8% overall and for most sub-trajectories (varying between 20 and 300 km in length) the error was below 1%, although two trajectories gave a larger error: one of 64 km with an error of 7.4 % and one of 25 km with an error of 5.4%. The trajectory of 64 km went through London-City. These figures fits very well with the more extensive and detailed findings of the current investigation.

In [11] Bern Grush comments the Siemens paper and question if the reported accuracy is enough for distance charging schemes. Also in the current investigation it is shown that short distance on road class 50 km/h might have errors in the order of 9% per km. But it also shows that on the average the accuracies are far better and even significantly below 1%. Grush questions if it will be acceptable to the public if for short trips the error might be this high (even when the average over longer trips is accurate enough). This is, however, not a technical issue, but a legal issue and an issue for proper definitions of the ‘rules’ of the charging and the communication to the public. E.g. a fixed discount per month of one euro could prevent discussions around this problem..

8. Conclusions and recommendations

8.1. Conclusions

The main conclusion of the current study are:

- With the commercial-of-the-shelf GPS receiver used in the analyzed data set distances can be measured sufficiently accurate to meet the KMP requirements provided that:
  - An average is taken over longer distances (in the order of more than 30 km)
  - Positions are used after the moment of the first valid fix (TTFF)
- Averaged over a typical mileage (1350 km/month) and the typical trip distribution in the data set used, the deviation of the GPS-distance is 0.4 +/- 0.06% (0.16% at the 99% confidence level). This means that distances measured via GPS should be corrected by 0.4% to reflects the true distance. (A correction per road class would give a slightly more accurate result)
- The current GPS-system is accurate enough already for the parts of the trip after TTFF. In addition, further improvements of GPS accuracy and Galileo are expected.
- The availability of the GPS-system in the data set used is 87 +/- 2 %. For the average of all Dutch vehicles the availability may be smaller, if on the average Dutch drivers makes shorter trips than the drivers that produced the used data set. This availability is clearly insufficient. This figure is pessimistic because a large part was caused by the slow start of the logging system. Still, TTFF is the main bottleneck for using GNSS systems for distance charging and a solution is necessary.
- Exceptional cases are not considered here, but need to be considered in a later stage due to the large standard deviations at low mileage.
- Map-matching is needed when different tariffs are used at different locations. Straightforward map-matching is possible, but more advance map-matching is recommended. Map-matching needs only to be done in the vicinity of tariff borders. Defining narrow corridors in urban areas better can be avoided at all.

8.2. Recommendations for each of the KMP scenarios

Based on the results of the current study Table 13 gives recommendations for each of the KMP scenarios, under the following assumptions:

- Private roads are charged identically as the bulk of the public road.
- The specified requirement (99%/1%) relates to the average of the invoices per month over all vehicles
- Exceptional cases are thus not taken into account individually.
- Map-matching (if done) is done in the OBU in the vehicle.
- The OBU has a mobile phone communication link (UMTS,…).

Nr.	Short description of scenario	Recommendation	Consequences
I	Flat fee	Use GNSS with a assisted or	Extra communication costs.

		differential mode, such that TTFF is as short as possible and the position accuracies are improved. Use the mobile phone system for the communication.	Slight increase in complexity of the software on-board.
I.A	Flat fee plus tolls	As I, plus advanced map-matching around the toll locations. It is not necessary to have the whole digital map of NL on-board, only parts around the toll location is sufficient (this must include parallel roads, etc.). The part need to be large enough to accurately determine that the location has been passed. Using a larger segment also prevents effects of local jamming around such an location.	As I, plus development of an advanced, local map-matching. Extra software to communicate the locations to the OBU and to do the local map-matching.
II	Uniform peak off-peak	As I.	As I.
III	Peak tariff on congested segments	As I, plus advanced map-matching around the segments with a different tariff when this segments are mainly at the motorways. In case of the Rotterdam example a map-matching with the full map the area is needed.	As I, plus development of an advanced, local map-matching. Extra software to communicate the locations to the OBU and to do the local map-matching. In case of Rotterdam a complete detailed map is needed for that area.
III.A	III plus apportionment	As I plus – if necessary – local advanced map-matching, depending on the border of the region. If around the border roads with different tariffs are close together, local advanced map-matching is recommended there.	As I. If the border are chosen carefully, no local map-matching is needed.
III.B	III.A plus tolls	As I.A.	As I.A.
IV	Urban – interurban	As III.A.	As III.A.

Table 13. Recommendations for each of the KMP scenarios.

In summary:

GNSS can meet the requirements, but a solution for the TTFF-problem is needed as well as an advanced map-matching at those locations where different tariffs meet (including the virtual toll locations)

8.3. Additional options and recommendations

In Table 14 some additional options relevant for KMP are given together with the recommendations on how to handle them (including the consequences).

Nr.	Option	Recommendation	Consequences
1.	Different fees for private and public roads	In areas where public and private roads are close together (e.g. less than 50 m), local advanced map-matching is needed	Communication of those local areas to the vehicle and some extra software complexity.
2.	Catering for exceptional cases and individual situations.	They need to be identified and best would be to cater for them in the charging rules, for instance by giving a discount for vehicles driving few kilometers per month.	Identification of those cases. Extra charging rules.
3.	Central map-matching in stead of map-matching in the vehicle	To transmit all positions to a central facility, where the map-matching is done. The OBU can then be much simpler. Central map-matching can be more advanced then on-board and can be steadily improved. Consequently map-matching and changing tariffs will be more flexible. Privacy needs to be taken into account.	Much simpler OBU. No digital map data to the vehicles. There will be communication costs of transferring the positions to the center (estimated at 10 Mbyte per vehicle per year), but no large map updates are needed. Privacy issues.

Table 14. Recommendations on further options for KMP.

Option 3 in Table 14 is very advantage since it allows the most accurate map-matching techniques, which can also be further developed over time and it allows a very flexible handling of the changes in the locations with a different tariff. Assisted operation (to reduce TTFF) remains needed in the vehicle.

Privacy is the main issue here. There are, however, advanced techniques that can handle this.

9. Identify remaining areas of uncertainty and risks

9.1. Uncertainties and risks

The remaining areas of uncertainty and risks with respect to the current research assignment are:

- It is not completely clear what the effect will be of the large uncertainties for short distances on various groups of drivers.
- Exceptional cases need to be exploited further, so measures can be thought of in advance (example: roads in wooded areas)
- There may be large differences in trip characteristics between drivers, that may effect the overall effect.
- It needs to be clear what the minimum TTFF is that persistently can be reached with for instance AGPS. It needs to be ensured that this time acceptable, also in a legal context.
- It should be investigated if advanced map-matching can improve the distance measurements over plain measurements.
- Fraud and enforcement are important issues, but in the current investigation only slightly touched upon

9.2. Topics for further investigations

The current analysis is done in a rather short time, meeting the planning requirements of the KMP process. As indicated in previous sections, there are several areas where further investigations are desirable/needed. Recommendations for further investigations are:

- Detailed analysis of exceptional cases. A detailed risk analysis should be done to identify which exceptional cases can be expected and what would that mean for the KMP scenarios.
- Investigate and test measures such as A-GPS and DGPS to determine how much they really can reduce the TTFF.
- Investigate the possible improvements by a better, off-line map-matcher. It is necessary to develop and test and advance map-matcher in order to determine how that can improve the distance measurements before TTFF and the distance measurements of short trips.
- Detailed analysis of fraud possibilities. Many possibilities of fraud are possible. Investigations are needed to identify them as much as possible and to define corresponding counter-measures and/or enforcement measures.
- Analysis of all 5 months of data. The current analysis used only 1 out of 5 months of data. It is recommended to analyze also the other 5 months. This will provide insight in the consistency (give the other months the same results) and will enable to look for exceptional cases.
- Set-up a test-fleet of about 200 cars for the coming years. Considering the importance (and magnitude) of KMP it is highly recommended to set-up now a test-fleet of 200 ‘normal’ drivers that represent the Dutch population properly. The vehicles of those

drivers should be equipped with GPS/GSM equipment and a connection to the CAN-bus. Possibly extra equipment could be included also. The vehicles should be followed continuously and the data analyzed. This will yield much insight in the GPS-accuracy, but also insight in exceptional situations.

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ANNEXES

Annex 1. Correction factors CAN-distances.

Correction factors for each of the 19 vehicles in the GPS data set. Car-id ranging from3 to 31 are the identifiers of the different vehicles in Full Traffic. A number larger then 1 means that the uncorrected CAN-distance is larger than the corresponding GPS-distances.

CAN-distance/GPS-distanc

Average of CAN Calib ave		
CAN calib	carId	Total
1	3	1,0065
	4	1,0075
	6	1,0029
	7	1,0037
	8	1,0039
	9	1,0118
	12	1,0032
	13	1,0072
	14	0,9995
	15	1,0036
	19	1,0091
	21	1,0052
	22	1,0035
	23	1,0043
	24	1,0005
	26	1,0037
	27	1,0055
	29	1,0076
	31	1,0055
Grand Total		1,0048

Annex 2. Specifications of the GPS-receiver used in the analyzed data set

GPS-receiver: Holux GM-210

Acquisition time:
- Cold start: less than 45 seconds
- Warm start: less than 38 seconds
- Hot start: less than 8 seconds

Update rate:
- 1 second

Accuracy:
- Position: 5 – 25 m CEP.
- Velocity: 0.1 m/s.
- Time: +/- 1 us.

Operational limits:
- Velocity: 515 m/s.
- Acceleration: +/- 4G.