Single Frequency Precise Point Positioning: obtaining a map accurate to lane-level

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***Abstract*— Modern Intelligent Transport Solutions can achieve improvement of the traffic flow at motorways. With lane-specific measurements and lane-specific control more measures are possible. Single Frequency Precise Point Positioning (PPP) is a newly developed technique to get a sub-meter accurate position from the signals of the Global Positioning System (GPS). PPP-GPS allows for sub-meter accurate positioning, in real time, of vehicles on the motorway. In theory, it has been shown that using GPS-PPP probe vehicle data, also the lanes of the motorway can be mapped.**

In this paper this technique is tested in practice and a map of the lanes of a motorway is created. To this end, a vehicle equipped with a PPP-GPS device runs 100 times up and down a specific motorway stretch, for which the PPP-GPS trajectory data are collected. The paper shows a methodology to construct the position of road from the data. Moreover, it shows how the positions and the widths of different lanes can be identified from the data. The results show that the lanes can be successfully identified from the data. With the parametrized lanes, vehicles can be tracked down to a lane with the PPP-GPS device.

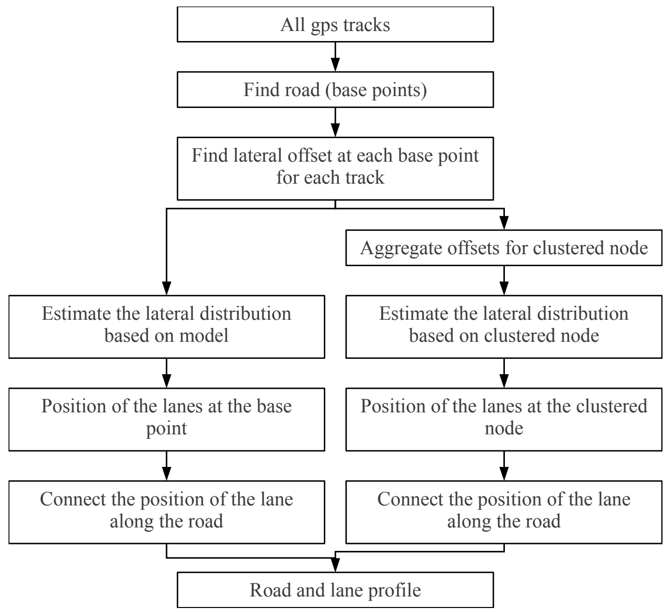

Fig. 1: An overview of the steps taken in the research. In the left branch, the position of the lane is based on measurements for each base point. In the right branch, the lateral passing positions are first combined into clustered nodes for an increased accuracy, and on this larger sample the lane positions are estimated.

I. Introduction

Intelligent Transport Solutions generally work by measuring traffic and applying control measures. Traditionally, measuring and informing traffic happens through road-based systems, but this is changing now towards more in-vehicle systems. One of the requirements for more advanced motorway traffic control is that lane-specific measurements can be made, and vehicles can be provided with a lane-specific control measure. For in-car systems it is hence required that the position is known with an accuracy better than the width of a lane.

Recently, we developed a new technique [1] that improves the accuracy of the positioning based on signals from the Global positioning System (GPS). We showed that this technique was able to determine the position of a car more accurately than the width of a lane. However, in most digital maps today separate lanes are not indicated.

The current paper shows a methodology to create such a map in practice using the PPP-GPS trajectories. Also, the methodology is tested in real life, using 100 trajectories collected by a PPP-GPS equipped vehicle on a multi-lane motorway.

To obtain the digital map with identified lanes, several steps have to be taken. These steps are shown graphically in figure 1. First, PPP-GPS trajectory data in tracks have to be collected. Then, we need to have an exact reference point close to the road, It does not need to be at a specific location (roughly on the road is OK), but it is important that this point is well specified, since we will define other distances from there. These points are called *base points*. Once these base points are determined, for each track the lateral offset of crossing the base point is calculated. Then, the lane positions can be determined by this lateral offset. This is done either at each of these base points (left branch of figure 1), or they can first be combined into larger clustered points, a way to increase the number of observations (the right branch in figure 1, and described in more detail in section VI). This gives the position of the side of the road, in so called *road side points*, and the position of the lanes on a line lateral to the road at the position of the base point (or clustered point). These reference road side points can be connected for all base points (or clustered points), which gives the position of the lanes along the road.

The structure of the paper is in line with the steps of the research. First, in the next section, we repeat the main ideas of the PPP-GPS technique. Then, section III discusses the

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experiments. Section IV then shows the methodology to find the base line of the road to which the lateral positions can be related. The resulting process including results for the lanes at base points is shown in section V. A more robust way to find lanes, combining different base points into clustered points, is presented in section VI. Section VII shows how the results change if the lane width has to be estimated as well. Finally, section VIII presents the conclusions.

II. Precise Point Positioning: the technique

In this section we introduce the GPS-PPP technique and relate that to existing techniques. This section is based on [2].

A. Existing techniques

In this section we briefly describe the regular existing GPS techniques; for a full overview of existing GPS techniques, see e.g. [3].

1) Regular, stand-alone GPS: In regular GPS positioning, the position is determined using at least 4 satellites, each continuously transmitting time signals. The position of the receiver is found by measuring travel times to these satellites, and solving for the three dimensional receiver position and its clock offset. The positions of the satellites and the satellites' clock offsets have to be known as well. The US Air Force calculates those, and the predicted trajectories of the satellites are sent with the signal of the satellite. Typically, there is an error of several meters in this predicted trajectory, leading to a similar error in the position estimate for the user.

A second source of errors in GPS measurements is the disturbance of the signal in the atmosphere. This can cause variable time delays in the signal traveling to the vehicle. The errors as a result of this delay are larger in the vertical direction than in the horizontal direction. Note that the receiver cannot get signals from satellites which are below the horizon, so satellites are usually situated above the vehicle. A slight error will therefore immediately influence the estimated height, but only modestly change the perceived horizontal position.

All combined, the horizontal position of regular GPS positioning is accurate to approximately 5-10 m, and the vertical precision 10-20 m.

2) Differential GPS: Here, we describe Differential GPS, or D-GPS in its simplest form. More advanced techniques are applied in practice, but the basic idea is the same as explained here. It uses the same GPS signal as in regular GPS. However, the mobile device (i.e., vehicle) is also in contact with a base station nearby. The location of this base station is accurately known already, and hence corrections to the measured ranges can be determined. The difference between known range and measured range is due to atmospheric conditions and due the errors in satellite position and clock. These error sources have a similar impact for all GPS receivers nearby.

The errors in the ranges at the base station are communicated to the mobile device. The mobile device can then compensate for the errors, assuming these are the same as at the base station. The final position accuracy depends on the distance to the GPS base station and the measurement accuracy. In the end, the measurement accuracy is the limiting factor in the eventual position accuracy. This can be down to centimeter-level (using the so called carrier phase cycle ambiguity fixed solution) [3]. For this level of accuracy, high-end, and hence costly, equipment is needed.

Fig. 2: The vehicle equipment used for the test; there are two D-GPS receivers for the ground truth and a PPP-GPS receiver in the middle.

B. Precise Point Positioning

We developed a new technique, Single Frequency Precise Point Positioning (PPP) as an intermediate technique between ordinary stand-alone GPS and classical D-GPS, but at a cost comparable to the stand-alone GPS. Technical details can be found in [1]. The basic idea is as follows. There are several hundreds of permanently operating GPS base stations over the world, for which high-accurate positions ($<$1 cm) are available. At these locations, GPS signals are measured. Based on these measurements, and orbital mechanics, satellite positions are predicted, as well as atmospheric (ionospheric) delay model parameters. This prediction is made for several hours (up to one day) ahead for the whole world. This prediction is essential for *real-time* positioning. Satellites clock error estimates are available in real-time. All this information is made publicly available on the internet. With this information, the GPS measurements can be corrected. A resulting position error is typically in the order of several decimeters. In summary, PPP-GPS can be regarded as a *global* Differential-GPS system.

There are commercial D-GPS techniques available, for instance by Omnistar. To the best of the authors knowledge, there are at least two major differences with the technique presented here and the technique used. First of all: most GPS-correction services are regional, whereas the PPP used here is a global approach. Secondly, we use a single frequency GPS receiver (hence cheap, approximately 40 $), whereas the commercial services – as far as the authors are aware – require dual frequency measurements, hence expensive

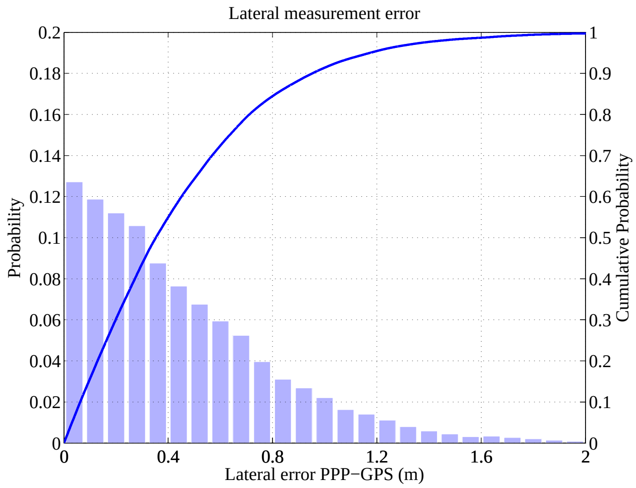


Fig. 3: The histogram and the cumulative distribution of the errors in the PPP-GPS position lateral to the driving direction. The errors are constructed with a D-GPS as reference ground truth.

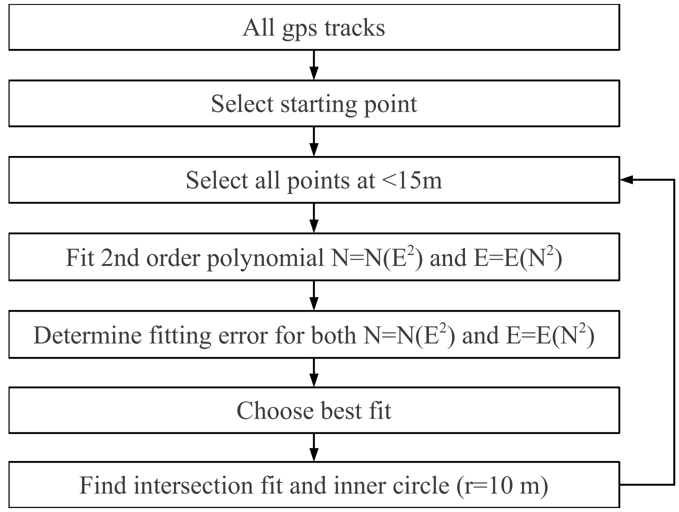


Fig. 4: An overview of the steps taken in the process of defining the road

equipment.

III. Experimental setup

In earlier work we determined that at least 100 passes are required for a single stretch of road to determine the position of the lanes [2]. In order to collect the necessary GPS measurements, a car was equipped with a single frequency u-blox TIM LP receiver connected to a Tri-M Big Brother patch antenna. During a period of approximately two weeks in November 2012 the car was driven the required number of laps on the A13 motorway between exits number 10 (Delft-Zuid) and 11 (Berkel en Rodenrijs). Different time frames were selected during the day, considering the ionosphere and traffic activity as well as the number of visible satellites in the sky. Each lap consists of two parts of approximately 5 km of three lane motorway, and two parts of the underlying road network (intersections, roundabout), which we did not consider in this study. The roadway is fairly flat and there are no high rise buildings along the road, which might disturb the signal. However, the conditions are still considered operational as many overhead signs, street lights, trees and other traffic may cause temporary signal losses and reflected signals.

The collected 10 Hz GPS measurements were combined with precise predicted satellite orbits from the International GNSS Service [4], real-time satellite clock offsets from the Reticle system [5] and predicted ionosphere maps from Center for Orbit Determination in Europe (CODE) [6], and processed with our Single Frequency PPP (SF-PPP) algorithms [1]. Two high-end receivers were also installed on the car to determine an accurate ground truth (at centimeter level) for 54 of the 100 total laps by differential processing with NetPos [7]. These reference tracks were used to assess the accuracy of the PPP-GPS solution.

The dominant error sources in SF PPP are the pseudo range measurement noise, multipath delays (caused by reflected signals), residual errors in the ionosphere model, and residual errors in the satellite orbit and clock products. The estimated reference position is far less sensitive to these errors since the much better equipment reduces the measurement noise and impact of reflected signals, and the relative set-up largely reduces the impact of ionosphere delays as well as orbit and clock errors. Furthermore, in relative set-up the accurate carrier phase measurements dominate the positioning (since the carrier phase ambiguities can be fixed) reducing the effects of pseudo range measurement errors and multipath delays [8], [9]. Therefore, the reference (ground truth) positions are have a much higher (cm-level) accuracy than the SF-PPP positions and can be used to assess the errors in the latter.

Figure 3 shows the results of this assessment by means of the cumulative distribution of the horizontal errors lateral to the driving direction. The figure shows that this error was smaller than 0.71 meter for 80% and smaller than 1.2 meters for 95% of the measurement epochs, consistent with the expected accuracy from our SF-PPP solution [1].

IV. Finding a base road position

The collected points are part of trajectories of vehicles driving at a road. For this study, we assume it is known at which road the vehicles drive. Various map matching procedures are available to distinguish this (e.g., [10]). This section explains how a base position of the road can be found, a rough outline at which the lane positions can be related. No extensive tests on the best algorithms have been performed: the procedure described here shows a working solution, which met the requirements.

Since the road does not necessarily follow a function N(E) (north position as function of the east position) or E(N), fitting a polynomial function to the entire road is not possible. Instead, we split the road in separate parts for which we determine the average position by estimating a local polynomial.

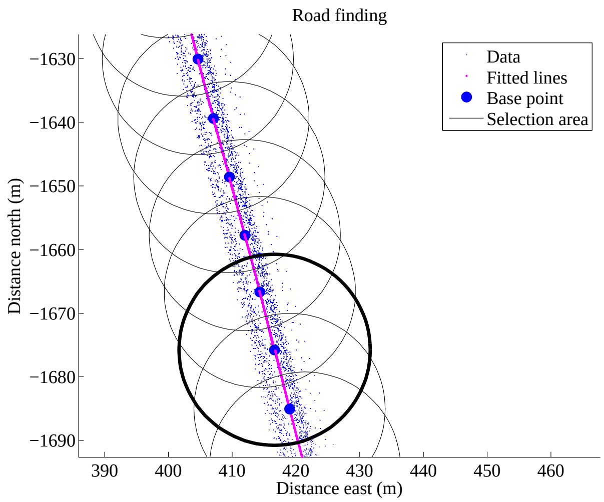


Fig. 5: The measured data points and the results of the process of finding the road points.

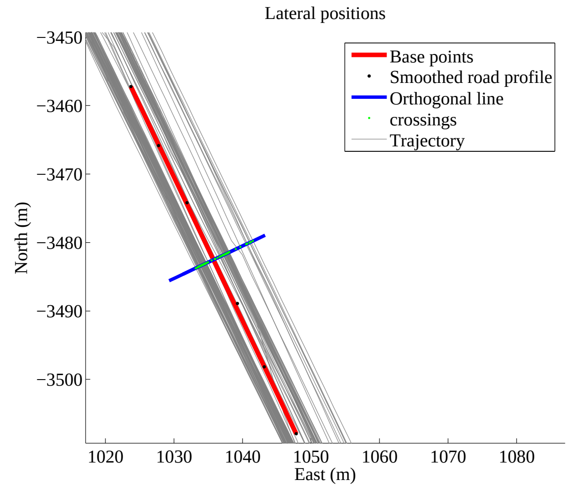


Fig. 6: The lateral positions are calculated by reconstructing where each of the trajectories crosses a line orthogonal to the (average) road direction

The exact steps are described below. The whole process is also shown in figure 4.

1) Manually, we take a starting point at the beginning of the road.
2) Select all points within the proximity of this base point. In this study, we take a radius of 15 meters, which is related to the width of the roadway (all lanes should be in).
3) Fit a second order polynomial $N = N(E^2)$ function through all these points. The error of the fit is defined as the difference between the measured north coordinate and the estimated north coordinate via the function.
4) Fit a second order polynomial $E = E(N^2)$ function through all these points. The error of the fit is defined as the difference between the measured east coordinate and the estimated east coordinate via the function.
5) From both fits, $N = N(E^2)$ and $E = E(N^2)$, choose the best fit
6) The fit takes into account all measurement in its surroundings, and thus gives a better value than the initial estimate for the middle of the road. Therefore, we change the North coordinate of the base point to the value of the fitted function at the East coordinate of the base point. (East respectively North coordinate for the function $E = E(N^2)$)
7) Calculate the intersection of this fit with a inner circle (10 m radius). This forms the starting point for the next iteration.
8) If the road is not yet complete, return to step 2.

The result of the fitting procedure can be seen in figure 5. Manual inspection shows these points follow the road closely, and they form a good basis to find the lanes within the road.

V. Fitting lanes at base points

For all base points, the positions of the lanes lateral to the roadway is determined. We first have to find the lateral position of the tracks crossing a line orthogonal to the roadway; this is described in section V-A. Then, the position of the lanes has to be found. The methodology for this is described in section V-B. Section V-C presents the results.

A. Lateral crossing

The optimization procedure requires that the lateral positions of the vehicle at a cross section are known. To obtain these for a particular base point i, the following steps are taken

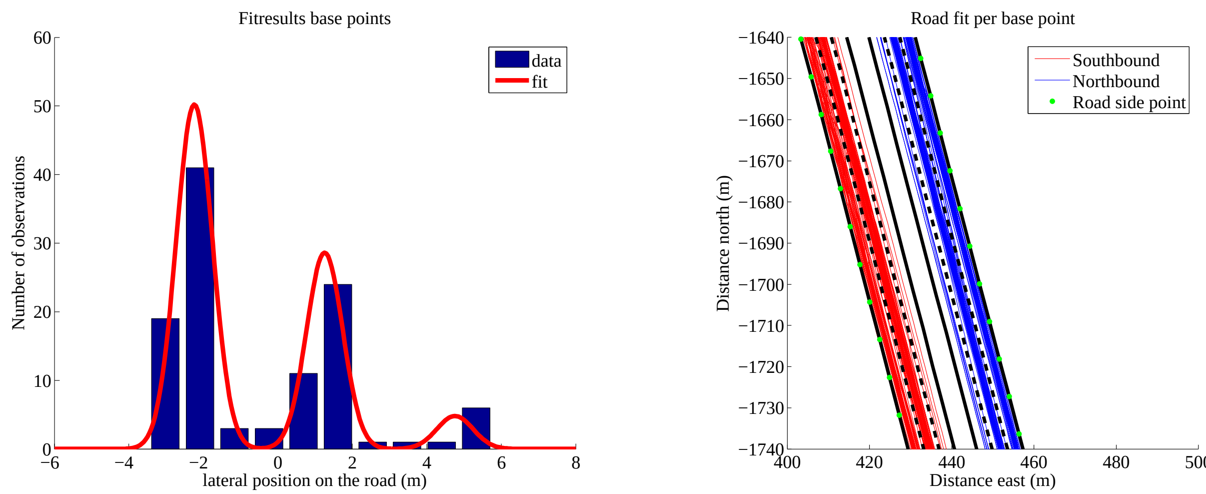
1) Connect the base points $i-3$ and $i+3$.
2) Determine the direction of the road segment, taken linearly between these two points.
3) Construct line orthogonal to the direction of the road, through the base point.
4) Determine where each of the GPS tracks crosses this orthogonal line; this gives a set of lateral offsets.

By taking not the direct neighbouring points, but the third point before and after, the road direction is "averaged". This gives a more robust direction of the road. This process is shown graphically in figure 6.

B. Optimization of distribution

From the lateral crossing points obtained by the methodology described above we estimate the position of the lanes. Note that a priori the number of lanes is unknown. We hence estimate the lane positions for roads with different number of lanes, and then select the best fitting result.

The first step is to make a histogram of the lateral crossing points. The points are distributed in b bins of equal width, in which b is the (rounded) square root of the number of observations. We take the square root of this number as



(a) Fitting for one base point

(b) Lanes on the map

Fig. 7: Finding the lanes: lanes based on the base points

trade-off between the number of bins and the number of observations per bin, which both are preferably high.

Then, this is compared with a reference function. In this reference function, the lateral passing point of the vehicle in a specific lane is assumed to be drawn from a normal distribution function with a certain width σ. The total distribution function of the lateral passing points of all vehicles is the sum of the normal distribution functions for each lane, weighted by the relative share of the flow in that specific lane (the lane flow distribution). This function has the parameter σ, the offset of the first lane, and the lane flow distribution, which adds $N-1$ parameters (the lane flow distribution adds up to one). The mid points of distributions per lane are a lane width apart from each other; this lane width is either put into the function (section V-C and VI) or found in the optimization (section VII). From the reference function, the probability mass in each of the bins of the histogram can be calculated.

The goodness of fit of the reference function is determined by the root mean square of the errors, i.e. the differences between the measured relative number of observations (histogram) and the predicted number of observations (reference function) in each bin. Now, the parameters in the reference function are adapted such that this error is minimized.

This optimization gives the lateral position of each of the lanes for each of the base points. The points for the same lanes can be connected from base point to base point to construct the lateral road profile.

This methodology is similar to [2], but we optimize on the differences in the histogram of the lateral positions, rather than minimizing the KolmogorovSmirnov distance. In practice, it turned out that this methodology is more robust.

C. *Results*

Figure 7(a) shows the histogram of the lateral offset and the fit through the points. As figure 7(b) shows, the estimated road path follows the measured trajectories quite accurately. However, the fitting procedure is not robust and for several base points no optimal solution is found.

At the beginning of the section, the test vehicle had to drive from the on-ramp onto the main road, and at the end, the test vehicle had to leave the section at an off-ramp. Hence, the trajectories are not well spread over the lanes, and the estimation procedure does not work correctly. It should be noted that this is not a weakness of the methodology, but more of the experimental set-up (one vehicle, always taking the same on-ramp and off-ramp).

VI. Increasing the Robustness: Clustering

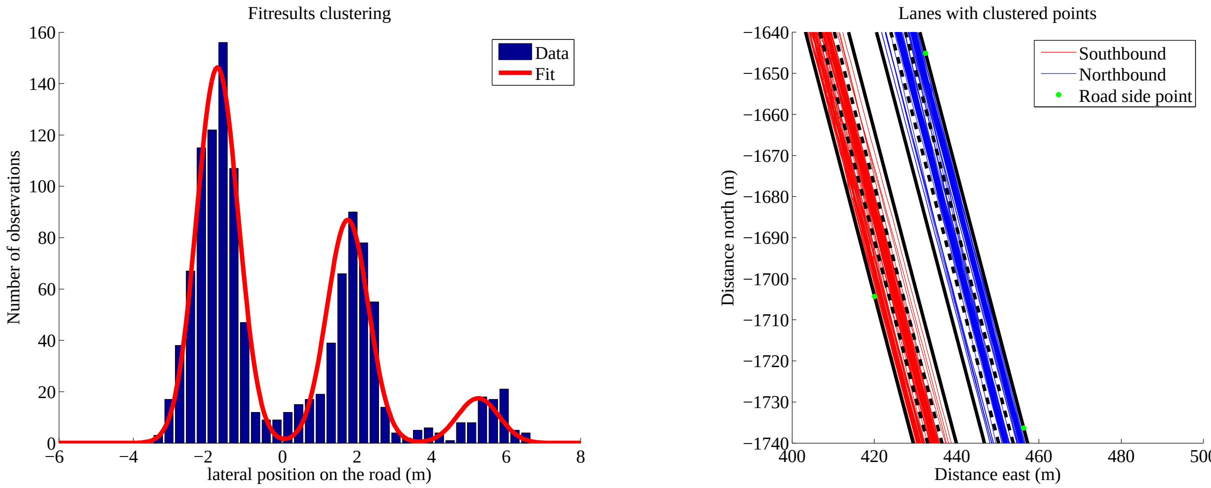
The method can be improved for low numbers of trajectories. To this end, we introduce in this section a method which increases the number of observations, and hence improves the robustness of the optimization technique. First, the methodology is introduced and in section VI-B results are presented.

A. *Methodology*

The lateral offsets are found for each of the base points are calculated as explained in section V-A. All these offsets are combined into one series of lateral offsets. Note that we combine the offsets of *different* base points.

The main requirement for this methodology to work is that the position measurements relative to the respective base points are independent. That means that (1) the measurement error is independent, (2) the position of the lanes is the same for all base points included into the clustered point and (3) the lateral position of the points is not correlated. Note that even if the road itself is curved, requirement 2 is not violated, as long as the base points follow the road profile. With a low number of trajectories at a high sampling rate, requirement 3 is violated (one vehicle chooses one lateral position through the road stretch, so no lanes are visible).

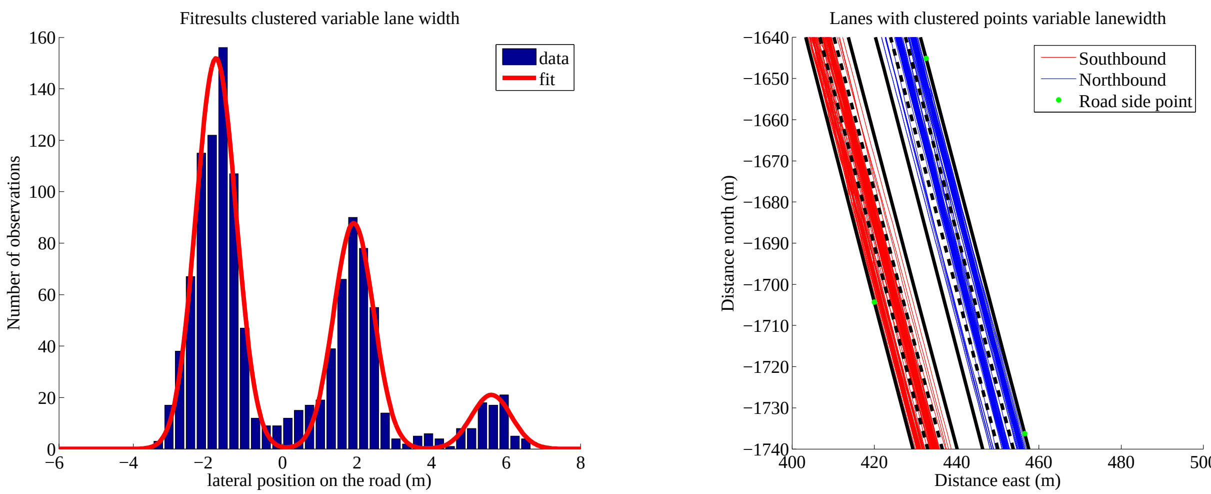
We choose to combine the lateral offsets of ten nodes and assign these to the middle base point, which we will call a



(a) Fitting for one clustered point

(b) Lanes on the map

Fig. 8: Finding the lanes: lanes based on the clustered points



(a) Fitting for one clustered point

(b) Lanes on the map

Fig. 9: Finding the lanes: lanes based on the clustered points with a variable lane width

clustered point; with the chosen distances between the points, this equals approximately 100 m.

B. Results

The results of this methodology are show in figure 8. From the histogram in figure 8(a), it is clear that the lanes can be determined much more robust. In fact, the lanes can easily be seen in the distribution of the lateral position. The fitting is hence much more robust, leading to a road profile as show in figure 8(b).

This shows that it is possible to create lane map with 100 measurements. Using the technique of clustered nodes, the number of measurement points can artificially be further increased for a higher reliability. The requirement that the lateral positions at different base points are not correlated holds reasonably well for 100 trajectories: there is a reasonable amount of spread over the lanes. For a lower number of measurements, this spread will reduce, and the quality of the fit will reduce.

VII. Clustered points and variable lane width

The situation with the clustered base points gives a clear profile for the lateral distribution of passing points. Therefore, we try to fit the distribution function without the lane width being know We do assume all lanes still have the same width. That means for a three lane road, five parameters have to be found: the offset of the first lane, the width of the distribution (σ), the lane width and for two lanes the fraction of the flow travelling in that lane (the fraction of flow in the third lane can be determined by the fraction of flow in the other two lanes).

The results of this fitting procedure are shown in figure 9(a). The result is similar in quality result if the lane width

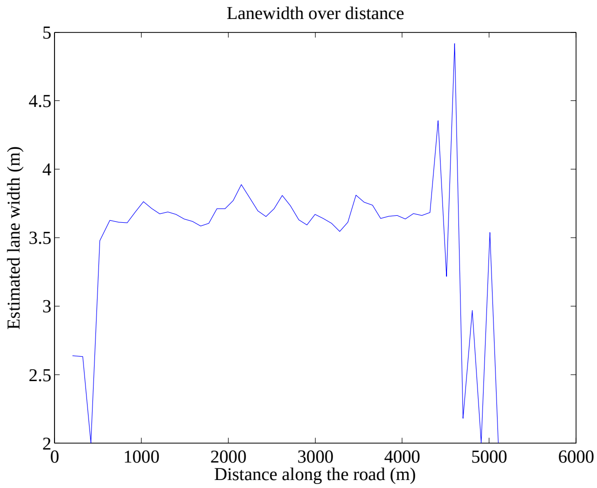


Fig. 10: Estimated lane widths as function of distance (northbound). Again, in the first 500m and after 4500m of distance, the test vehicle does not travel in the designated lanes, but is merging into, or out of the main road, so trajectories are not distributed over the lanes.

has been put in exogenously. The optimization procedure does also lead to a quite correct lane width estimation.

Figure 9(b) shows that the procedure works quite well in following the road. Since the limitation of the methodology using clustered requires the road profile to be the same for all base points in clustered into one clustered point, this holds also for the lane width. However, a slight variation in the lane width will not be too problematic, since it can be captured in the intrinsic lateral error of the drivers and the device (σ). Moreover, even if a lane width changes abruptly, drivers will need space to adapt, so averaging over approximately 50 meters, as done here, will most likely also work for stretches with different lane widths.

Again, in the first 500m or after 4500m distance, the test vehicle does not travel in the travel lanes, but is merging into of out of the main road. Because the distribution of the measurements over the lanes is lacking, the estimation procedure fails, and hence the estimated lane width is wrong. The estimated lane width along the northbound road stretch is shown in figure 10. The lane widths which deviate too much from the expected values are excluded from the data set.

VIII. Conclusions and outlook

In this paper, we introduced a methodology to determine the lane map on a multi-lane motorway using the Precise Point Positioning GPS technique. It has been shown to work, i.e. the lanes can be extracted from real-world data. For application in practice it is needed that vehicle trajectories collected with the PPP-GPS technique are determined. For this technique, a simple GPS chip suffices, of the cost and quality currently used in the automotive industry. Using these trajectories, a lane-specific map can be created. With this map, the position of vehicles equipped with a PPP-GPS device can be measured and matched with the lane-map at lane-level accuracy. This technique can be used to get lane-specific traffic information, or to perform lane-specific traffic management. In order to use the GPS-PPP map, a low bandwidth connection to the vehicles is necessary, in order to provide the system with the positions of the satellites, the clock errors and the atmospheric conditions. Moreover, for lane-specific management, it is required that the vehicles communicate their own measured position in real-time (order: tens of seconds) with a central server.

Finally, the current tests showed that the system and the methodology work for flat roads and open surroundings. The sensitivity of the PPP-GPS measurements to the different physical environments (hills, urban environments) is topic for further research.

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