Map matching for intelligent speed adaptation

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Abstract: The availability of Global Navigation Satellite Systems (GNSS) enables sophisticated vehicle guidance and advisory systems such as Intelligent Speed Adaptation (ISA) systems. In ISA systems, it is essential to be able to position vehicles within a road network. Because digital road networks as well as GNSS positioning are often inaccurate, a technique known as map matching is needed that aims to use this inaccurate data for determining a vehicle’s real road-network position. Then, knowing this position, an ISA system can compare speed with the speed limit in effect and take measures against speeding. An on-line map-matching algorithm is presented with an extensive number of weighting parameters that allow better determination of a vehicle’s road network position. The algorithm uses certainty value to express its belief in the correctness of its results. The algorithm was designed and implemented to be used in the large scale ISA project ‘Spar på farten’. Using test data and data collected from project participants, the algorithm’s performance is evaluated. It is shown that the algorithm performs correctly 95% of the time and is capable of handling GNSS positioning errors in a conservative manner.

1 Introduction

The proliferation of mobile computing devices and the increased accuracy of Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS) open new opportunities for traffic telematics applications. Systems to monitor and track the movements of vehicles is one of many such opportunities. Knowledge of a user’s position enables content providers to offer location-based services. Recently, the traffic research community has developed a substantial interest in Intelligent Speed Adaptation (ISA). ISA trial projects take place in many different countries around the world [1–6].

ISA systems use a vehicle’s road network position to extract the speed limit in effect and thus enabling various solutions to prevent drivers from speeding. A digital road network with comprehensive speed limit information and the vehicle’s GPS position are used to determine the vehicle’s road network location. The allowed speed limit is then extracted from the digital road network and compared to the actual driving speed. If speeding occurs, depending on the ISA type, the system takes action, ranging from signalling the speeding to the driver through an information device to physically limiting the speed of the vehicle.

Using an off-the-shelf standard GPS receiver, the positioning error can vary from 5 to 25 m [7, 8]. In urban areas, constructions such as high buildings, ramps and tunnels obscure the line of sight to the satellites, which may result in signal multipaths or even a loss of signal. This increases the positioning error or might lead to a complete blackout where no position is provided. To avoid a total loss of positioning, GPS is sometimes coupled with a dead reckoning (DR) unit that provides vehicle speed and movement direction information. Using sophisticated methods such as Kalman Filter [9, 11], belief theory [10] or fuzzy logic [12], it is possible to fuse GPS and DR information to track the position of user quite accurately, even if the GPS positioning has been unavailable for some time.

ISA systems are real-time systems, meaning that positioning on the road must be done every time a GPS/DR position is received. This is quite challenging, as GPS positions sometimes deviate from the actual vehicle location by more than 50 m [9]. The real-time algorithm that
performs the positioning in the road network is called on-line map matching. This contrasts off-line map matching which is done after a trip is over and all the positions from the start to end point are known. Off-line map matching is more accurate than on-line map matching as more information (i.e. concerning the future movement) is available.

The initial problem of map matching was perhaps first defined by Berstein and Kronhauser [13]. Later followed improved techniques, by White et al. [14], that pay special attention to intersection area. Taylor et al. [15] proposed a novel map matching procedure that uses differential GPS. The proposed road reduction filter algorithm uses differential corrections and height, which leads to improved performance. A complex off-line map matching algorithm was recently developed by Bratkatsoulas et al. [16] that uses the Fréchet distance to map match GPS data samples recorded every 30 s. Quddus et al. [17] provided a categorised summary of different map-matching algorithms and discuss their performance and limitations.

We are not aware of any proposals of a map-matching algorithm for ISA systems. Rather, reports on ISA projects tend to concentrate on the social aspects, performance and acceptability of the overall system. In contrast, we present an on-line map-matching algorithm that has been shown to perform successfully in ISA trials [18]. The algorithm uses sophisticated map matching techniques covering a wide variety of parameters. It adopts a self-evaluation mechanism that uses a unique certainty value that reflects the belief in the correctness of the map matching, that is essential to support smooth and conservative performance of the ISA system.

The performance of the algorithm is studied empirically using a large amount of data collected in various areas in the county of North Jutland, Denmark. These areas include different types of roads, for example, city streets with nearby tall buildings, roads in forests, a tunnel (length: 582 m) and open rural roads with good visibility. This is important to ensure a thorough evaluation of proposed algorithm.

The paper is outlined as follows. Section 2 defines the framework and requirements for map matching in ISA systems. In Section 3 the proposed on-line map-matching algorithm is presented and explained in detail. A thorough analysis of the algorithm is provided in Section 4. Conclusions and possible directions of future work are covered in Section 5.

2 Map matching framework for ISA systems

Various map matching techniques use similar procedures, digital map structure and positioning data to locate moving vehicle position on a road network. In this section, major aspects and quality assurance techniques of map matching algorithms for ISA systems are described without defining a particular map matching algorithm.

2.1 Description of a general map matching algorithm for ISA systems

Map-matching algorithms usually have two phases (some algorithms can skip a step or have an extra step). Some algorithms perform special operations to determine a better match for the first received position data. After the first match is done subsequent data follow the usual map matching pattern. The algorithms can be divided into two basic parts:

1. Startup or identification of initial polyline on the digital road network.
2. Tracking or identification of subsequent polylines of the digital road network to track the vehicle’s route.

In the first part, the initial map matching is done for the first positions received to determine the polyline on a digital road network where the vehicle is located. The correct outcome of the first step is very important, as the algorithms use road topology to determine the following polylines of the vehicle movement path.

Some algorithms simply skip the first step of identification of the initial polyline and use general map matching steps to process the position data:

1. Extract required information from position data received.
2. Select the candidate polylines from the digital road network.
3. Use a specific algorithm determine the most suitable polyline among candidate polylines.
4. Determine the vehicle position on the selected polyline.

In the first step, the information from the GPS/DR unit is extracted and converted to an appropriate format (unified coordinate and metric system consistent with the digital road network).

In the second step, the candidate polylines are selected. Usually the polylines that are within a set threshold value from the vehicle position are selected. An alternative approach is to select the n closest polylines.

The third step uses specific algorithms and techniques to select the best polyline from the given candidate set. The most common approach is to use weights. Different weights for different attributes are assigned to the polylines and the polyline with the highest sum of weights is selected. Some algorithms use techniques to reduce the polyline candidate
set by filtering out polylines that are perpendicular to vehicle movement location [15] or that do not have an intersection with a previously map-matched polyline.

The final step is to determine the vehicle position on the polyline selected during the previous step. The most usual approach is to select the point on the polyline that is closest to the vehicle position. This is done by projecting a point onto the polyline. A more sophisticated approach proposed by Quddus et al. [19] uses the weighted average of two positions. This method includes the fusion of distance travelled since last map matching and GPS projection on the polyline.

### 2.2 Certainty of map matching

ISA system performance highly depends on the scale, accuracy and fullness of the digital road network map, the GPS/DR unit accuracy and the result of the map matching algorithm. The digital road network should contain all the polylines and the polyline information should be up to date with the real world. The GPS/DR unit performance highly depends on the positions of the satellites in the sky and their visibility from the vehicle location. GPS accuracy is expressed in a few attributes available from GPS receiver (SAT – number of satellites visible, HDOP – horizontal dilution of precision, and FOM – figure of merit). If any of these parameters exceeds a certain threshold value, the probability of correct map matching is very low.

The algorithm itself must provide some information on how confident the map matching is. Due to low GPS signal quality, the algorithm should not make a map matching or express the result as an unqualified guess. Sometimes there exists polyline selection problem as there might be more than one polyline with close to the highest weight. In such a case the best candidate should be selected, but the doubt in correctness should be expressed too.

The certainty value could be used to handle outliers. Outliers are position fixes that do not match the pattern of travelling and usually coincide with a sudden change in heading as well as position shift. Greenfeld [20] and Quddus et al. [19] describe steps how to handle outliers in an off-line algorithm.

### 2.3 Constraint on execution time of map matching

The map matching should be done in less than a second (regular interval between two consecutive position fixes using GPS/DR unit) using the limited computational power and memory capacity of the onboard unit (OBU) to provide a position fix for every received GPS/DR point. In many cases, retrieving information from the GPS/DR and the working of the map matching algorithm cause a slight delay; thus, estimation of the user’s real position a few seconds forward on an estimated polyline could be done.

### 2.4 Speed map for ISA systems

Map matching of vehicle position on a digital road network enables ISA systems to extract the proper speed limit. The speed limit must be stored in the map. It might be defined for each polyline or be a polygon covering an area with the same speed limit value. The speed limit can also have a validation time, as some streets in school areas might have different speed limits during the day, or it can be the case that the speed limits of a highway varies across the seasons of the year.

### 2.5 Requirements for navigational performance

The main positioning information used from the GPS unit, and the high availability and accuracy of this information is important for the map matching. The accuracy is highly dependent on the positions of the satellites and direct line of sight to them. It is necessary to see at least three satellites to do the 2D positioning. The more satellites that are visible, the better the GPS positioning can be. In some cases, the satellite signal is lost (e.g. driving in tunnels, city canyons) and thus no positioning information is provided. In these cases, the DR methods (using speed and direction) could be used to position the vehicle and maintain the performance of the ISA system.

### 2.6 Requirements for map matching for ISA systems

The map-matching algorithm always returns one road polyline and a position on the polyline the user is driving on. In ISA systems, the speed limit of a polyline is also provided. In some cases, the map matching can be uncertain because of high GPS/DR positioning error or multiple candidate polylines with the highest sum of weights.

The wrong map matching of small number of GPS/DR positions for ISA system is not a problem as long as the speed limit on the map matched polyline is the same as of the real polyline on which the vehicle is driving. In such a case, the wrong polyline might be chosen by the algorithm, but the correct speed limit is maintained. In an opposite situation, the wrong speed limit is selected causing the irritation and dissatisfaction of the ISA system user. To decrease and possibly avoid such situations, a conservative map-matching algorithm must be implemented.

It is an important task of a conservative map-matching algorithm to select a polylines and speed limit that benefits the user in cases where there is uncertainty. When the correct map matching cannot be guaranteed, some exceptions should be made: the highest speed of the candidate polylines can be selected, or the speed limit is displayed with extra certainty information. In such a case, the system is making an unfavourable decision and loses. The conservative map matching should always select the
right polyline in certain situations or make a user beneficial polyline/speed limit selection maintaining the lowest loss for the system in uncertain situations.

3 Map-matching algorithm for the ‘Spar på farten’ project

The developed algorithm is used for the ‘Spar på farten’ [18] ISA project that takes place in the county of North Jutland in Denmark. The project is aimed to reduce speeding among young drivers. If users obey speed limits, they get a discount on car insurance. The ‘Spar på farten’ project uses the on-line map matching algorithm to detect user position on the road and select the right speed limit.

As an input, the map-matching algorithm receives position fix from a GPS/DR unit every second. The GPS unit is a 12-channel receiver that sends all the information available and the DR unit consists of an odometer and sends vehicle speed values. The polylines are extracted from a speed map of the county of North Jutland. All registered roads (road polylines) of the county of North Jutland have speed values assigned for each allowed movement direction. For the rest of the Denmark only highway information is stored. For all the other areas of Denmark the speed value is set to 80 km/h. For areas outside of Denmark, map matching and speed control are not done. Map matching and other system maintenance functions are made by an OBU that has weak computational power (only integer representation, lack of trigonometrical functions) and a small memory buffer (up to few hundreds of kilobytes).

The map matching algorithm is performed within seconds and consists of six steps (see Fig. 1).

The initial step is extraction of data and conversion to common measure units.

The first step is to check if the GPS data are reliable. This is done by comparing the GPS speed data with the odometer speed data. The allowed difference in speed should not exceed a 5 km/h threshold value. If the speed difference is within the allowed threshold, the direction change is checked. The direction_change is a value representing the difference between previous and current directions and is proportionally connected with the speed: \( \text{direction_change} \times \text{speed} < 1000 \). This formula works only if speed is expressed in km/h and direction change is an angle in degrees. This equation checks that cars are not making turns with higher than 0.5G force. If a sharper turn is detected and the equation is violated, then this is most probably a GPS position outlier. These values were selected using initial tuning of the parameters and perform optimally for regular vehicles and the road network and GPS receiver used. If any of these checks fail, the algorithm returns an error code. The ISA system is responsible for gracefully handling the situation when map matching is not possible. In such cases, the last speed limit is shown in parentheses, and the user is not penalised even if actual speeding occurs.

In the second step, the candidate polylines are identified. The algorithm selects at most the 12 nearest polylines from the vehicle GPS position. These polylines are used to assign weights, and the one with the highest sum of weights is selected. If no candidate polylines are found within the threshold value, the map matching algorithm stops map matching and returns an error code.

In the third step, the algorithm checks the distance to the intersection point. Usually the end points of a polyline are considered as intersections, but in speed map we are using this is not the case. Some end points represent the end or start of the speed limit validity on given road. Polyline end points that intersect with other polylines that have other street code are considered as an intersection. Street code represents the street naming in the real world. If any intersection point is closer than the pardistknude threshold value from a given GPS position the algorithm stops working and returns an error code. The threshold value for pardistknude is set to 10 m.

If all the previous steps succeed, the map matching can be done. The algorithm proceeds, analysing candidate polylines with different criteria and assigning weights to each. The polyline with the highest sum of weights value is selected and its matching certainty value is calculated. The larger the difference between the two greatest weight polylines with different speed limit values, the more certain the map.

![Figure 1 Steps of map matching algorithm](image)
Algorithm 1: Calculation of weight $W$

The polyline is assigned a weight $W_1$ for the proximity to a point. It is natural to assume that the closer the polyline is to the point the higher the assigned value should be. The distance to the point on the polyline that is closest to the GPS position is calculated. The weight $W_1$ can vary from 0 to 105. Weight $W_1$ is assigned as follows:

$$W_1 = \begin{cases} 
\frac{\text{parmaxdi}}{2} + (\text{parmaxdi} - \text{dist}(\text{point},\text{polyline}))/2 & \text{if dist}(\text{point},\text{polyline}) < \text{parmaxdi} \\
\frac{\text{parnuldi}}{2} + (\text{parnuldi} - \text{aa})*\text{dist}(\text{point},\text{polyline})/100 & \text{else}
\end{cases}$$

Values $\text{parmaxdi}$ and $\text{parnuldi}$ are parameters and are set to 10 and 80 m, respectively, $\text{parmaxdi}$ is 100. The formula assures that positions that are closer than $\text{parmaxdi}$ get the highest value. If the polyline is between $\text{parmaxdi}$ and $\text{parnuldi}$ then the weight varies linearly, and zero weight is assigned if the polyline is further than $\text{parnuldi}$ distance away from the GPS position.

Algorithm 2: Calculation of weight $W_2$

The weight $W_2$ is assigned to each polyline for being a continuation of the previously map matched polyline. This weight represents the reasoning that users tend to drive on the same road most of the time. It also helps to keep map matching to the same polyline. If the polyline has the same road number as the previously map matched polyline, a maximum weight of 30 is added. If the polyline is not an extension of the previous one, but has an end point near the user position, then the weight of value 10 is assigned. Otherwise zero weight is assigned.

**Algorithm 2:** Calculation of weight $W_2$

$$\begin{align*}
\text{if code}(\text{polyline}) &= \text{code}(\text{previous polyline}) \text{ then} \\
W_2 &= 30 \\
\text{elseif dist to intersection}(\text{point},\text{polyline}) &< 20 \text{ then} \\
W_2 &= 10 \\
\text{else} \quad W_2 &= 0
\end{align*}$$

Algorithm 3: Calculation of weight $W_3$

The weight $W_3$ is assigned to polylines according to their speed limit value. A polyline that has the same speed limit value as the previously map matched polyline gets a non-zero weight value. The weight is calculated differently for two speed groups: urban (all speeds limits that are lower or equal to 80 km/h) and rural (all speed limits are greater or equal to 90 km/h). This variation was made to give higher weight value for the cars driving on rural roads and highways. The weight nicely complements the $W_2$ weight, as it assumes that cars are driving on the highway rather than on an exit from the highway. The odometer speed is selected as the vehicle speed. The weight $W_3$ can vary from 0 to 60.

**Algorithm 3:** Calculation of weight $W_3$

$$\begin{align*}
\text{if speed limit}(\text{polyline}) &= \text{speed limit}(\text{previously matched polyline}) \text{ then} \\
W_3 &= 30 + 20 * \text{odometer speed}/80 \\
\text{else} \\
W_3 &= 0
\end{align*}$$
where \( k = 20 \times \frac{\text{odometer\_speed}}{50} \)

**if** \( k > 20 \) **then** \( k = 20 \)

\[ W3 = 20 + k \]

**else**

\[ W3 = 0 \]

### 3.4 Weight for one-way streets

Polyline that represent the one-way road have zero speed limit for the direction that it is prohibited to drive. A conservative approach is considered for one-way streets as there might exist an error in the map. This weight also helps to correctly identify the correct polyline on the highway. If a polyline is a one-way and its direction is against the vehicle movement direction, then the weight \( W4 \) is set to be \(-100\) (the total weight is decreased by 100); otherwise, the weight is set to zero.

**Algorithm 4:** Calculation of weight \( W4 \)

**if** against\_direction(point, polyline) **then**

\[ W4 = -100 \]

**else**

\[ W4 = 0 \]

### 3.5 Weight for direction similarity

Polyline whose bearing is similar to the vehicle movement direction are assigned a higher weight \( W5 \) value. There exists a well-known problem of GPS position dilution when the vehicle is stationary [19]. To deal with this problem, we check the odometer speed and if the vehicle is stationary (the speed is zero) then the direction of the last non-stationary position is chosen. The weight \( W5 \) can vary from 0 to 150.

**Algorithm 5:** Calculation of weight \( W5 \)

**if** \( \text{odometer\_speed} = 0 \) **then** \( \text{dir}(\text{point}) = \text{dir}(\text{previous\_point}) \)

**if** \( \text{speed}(\text{polyline}) > 80 \) **then** \( \text{dir}(\text{point}) = \text{dir}(\text{point}) - 4 \)

\[ W5 = 150 \times (90 - \text{abs}(\text{mod}(\text{dir}(\text{point}) - \text{dir}(\text{polyline}), 90))/90)) \]

### 3.6 Weight for topology

The weight \( W6 \) for topology consists of two parts: forward and backward polyline connection similarities. The weight is added to polylines that have the same intersection point as the previously map-matched polyline end point forward (or backward) to the vehicle movement direction. If the polyline has no common connection point, then zero weight is added. If there is a connection between the polylines through intermediate polyline(s), it is not taken into account, and the polylines are considered as disconnected. The weight is especially useful at an intersection area, as polylines that intersect with the map-matched polyline get higher weight and become more likely to be selected. The weight \( W6 \) can vary from 0 to 300 (\( 2 \times 150 \)). The weight is different from the weight for the continuity of a polyline, which gives weight to only one polyline having the same road number at an intersection area.

**Algorithm 6:** Calculation of weight \( W6 \)

**if** intersect(foward, polyline, previous\_polyline) **then**

\[ W_{6f} = \text{par topology} \times \text{ccfactor}/100 \]

**else**

\[ W_{6f} = 0 \]

**if** intersect(back, polyline, previous\_polyline) **then** \( W_{6b} = \text{par topology} \times \text{ccfactor}/100 \)

**else**

\[ W_6 = W_{6f} + W_{6b} \]

The polylines that have a common intersection point have their weight increased by \( \text{par topology} \times \text{ccfactor}/100 \) where \( \text{par topology} \) is a parameter with the value of 150 and \( \text{ccfactor} \) is an average certainty value for the last five map-matched positions. If the map matching is done for the first time, \( \text{ccfactor} \) is assigned default value of 5.

### 3.7 Weight for the shortest distance

If the polyline with the shortest distance is not the polyline with the highest weight, then special weight \( W7 \) is added. The initial value of weight is 5, and is increased by 5 every time the same polyline is closest but not with the highest sum of weights. The weight is reset if the closest polyline has changed. This weight was added to avoid problems with parallel connected roads where weight for continuity might dominate and keep on map matching to a wrong polyline.

**Algorithm 7:** Calculation of weight \( W7 \)

**if** closest\_polyline is not with the highest\_sum of weights and previous\_closest\_polyline = closest\_polyline **then**

\[ W7 = W7 + 5 \]

**else**

\[ W7 = 0 \]
3.8 Total weight calculation

The weights are calculated for each candidate polyline and a total weight is obtained by summing all the weights:

\[ \text{total weight} = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 \]

The polyline with the highest total weight is selected and the vehicle position on the selected polyline is determined by projecting the GPS point to the closest point on the selected polyline.

This map-matching algorithm was developed for an ISA system with the main objective being to extract a correct speed limit. The certainty of the map matching is determined by comparing the weights of two polylines. The weight of the selected polyline (the polyline with maximal total weight) is compared with the polyline that has the greatest total weight value with a different speed limit than the selected one. The greater the difference between these two weights, the more reliable the map matching is. If all the candidate polylines have the same speed limit, the certainty value is maximal. The value of certainty varies from 0 to 100, where 0 represents low and 100 represents high certainty. If the certainty value is equal to or below the threshold value set to 25 (interval [0 . . 25]), then the map matching is uncertain and the ISA system does not take actions for possible speeding. Negative certainty values are used to express the insufficient or unreliable data.

4 Evaluation of map-matching algorithm

This section reports on empirical evaluations of the map-matching algorithm. We first analyse the map matching using a known route and report failures using statistical analysis. Second, we use data received from vehicles participating in the 'Spar på farten' project. This data covers much of the county of North Jutland. In both parts, the data used is real, and the map matching was performed while the vehicles involved were driving using the project equipment. As the algorithm was specifically developed for an ISA system, the most important criterion is the correct speed extraction from the digital road network. The correctness of the map matching was verified using visual inspection – manually checking if the map matching is made to a correct link on the road network.

The digitalised speed map covers the entire county of North Jutland, which has an area of 6170 km² and approximately 22 000 km of private and public roads. A total of 80% of these roads are rural roads and have a speed limit of 80 km/h [21]. In addition to these roads, also the national and county roads outside the county are contained in the map if they have a speed limit that exceeds 80 km/h. The ‘Spar på farten’ project is thus one of the first ISA-projects that deals with a larger rural area.

The ‘Spar på farten’ project uses a 12-channel, single frequency GPS receiver and a vehicle odometer as the DR unit. GPS/DR unit information is received every second, and map matching is done using an OBU. The current speed information is displayed on a screen in the vehicle. If the map matching is uncertain or there are errors, the most recent speed limit is displayed in parentheses, and the ISA system takes no action in case of speeding.

Map-matching errors occur due to high positioning inaccuracy or map errors. The certainty value is used to report errors. The value –1 is returned if no road near the GPS/DR position is found. The value –11 is returned when there is a too large a difference between the odometer and the GPS speed values. The value –12 is returned if the direction change is too fast for the given speed (handling of GPS position outlier). The value –15 is returned when there are too few satellites to get a position. The value –16 is returned if the first positions are blocked by a tunnel, a garage or other outdoor objects. The value –17 is returned when the GPS speed exceeds 220 km/h. The value –18 is returned when the HDOP value is greater than 5 and proper GPS positioning is
unlikely to be possible. Finally, the value \(-99\) is returned when vehicle is driving outside the territory of Denmark.

### 4.1 Analysis of map-matching algorithm

In Fig. 2, the test trip can be seen. The trip is 72 km long and starts in the western part of the county and ends in an eastern suburb of Aalborg. The trip duration was 76 min and took place between 4 p.m. and 6 p.m. on July 2, 2006. The average HDOP value is about 1.70, and the average number of satellites visible is 6.84. The test vehicle was driving on rural roads 90% of the distance and was driving on urban roads the remaining distance.

During the test, map matching was certain 95.39% of the time (see Fig. 3a). The map matching was uncertain during 0.11% (corresponding to 5 s) of the trip. No map matching was performed during 4.5% of the trip due to errors (206 s). Most of the errors (error \(-18\), 63.6%) were due to a too high HDOP value (see Fig. 3b). Another source of errors is too large a difference between the GPS and the odometer speed during fast accelerations and decelerations (error \(-11\), 31.1%). A relatively small amount of positions had a too sudden direction change at a given speed and were considered as GPS/DR positioning outliers (error \(-12\), 2.43%). Also, a small amount of errors occurred due to an insufficient number of visible satellites (error \(-16\), 0.97% and error \(-15\), 1.94%). Errors with codes \(-1\), \(-17\) and \(-99\) are absent in the test drive.

### 4.2 Statistical analysis of the ‘Spar på farten’ project data

The data analysed in this section is log data from the ‘Spar på farten’ project that has data from 50 participants that are located in the county of North Jutland. The dataset considered consists of nearly 10 million GPS positions from the period from August 1 to December 1, 2006.

The algorithm exhibits high performance and works well 95.30% of the time. The rest of the time (see Fig. 4a), the map matching certainty is considered to be insufficient. In 4.39% of the total time, no map matching is done at all, which is due to errors.

Fig. 4b shows the distribution of the map matching errors. It is seen that the main reason for no map matching is a too weak GPS signal, which is expressed as a high HDOP value (error \(-18\), 54.07%). This can happen when driving between tall buildings in cities or on rural roads with nearby tall trees.
Another reason for no map matching is the inability to find a nearby road (error $-1$, 21.72%). This can occur when the HDOP value is high or when a road is missing in the map or when the user is driving outside the area of the county of North Jutland. The too high a difference between the odometer and the GPS values (error $-11$, 17.30%) occurs due to fast acceleration or deceleration, especially at an intersection area. The odometer can show the speed instantly, whereas the GPS value lags a little. Another significant reason for no map matching is the so-called side acceleration (error $-12$, 5.43%) due to too high difference in vehicle direction change at high speeds. These positions most probably are GPS outliers and are thus skipped. The last four errors occur in less than 2% of the cases and are insignificant.

The maximum distance between the GPS/DR point and the map matched point with uncertain map matching reaches 150.62 m; with certain map matching the distance reaches 154.43 m. A higher error can be caused by a vehicle driving on a road in a rural area that is covered by tall trees and where there are no other roads to map match to. These are extreme cases and occur rarely in the data.

Fig. 5 shows the average distance between the GPS position and the map-matched point on the road network. The average map matching distance is 9.04 m. The average map matching distance is 18.67 m for uncertain map matching and only 9 m for certain map matching. The increase in map matching distance with higher certainty values (interval [95..100]) might be due to the fact that most of the polylines are with the same speed limit and only few polylines exist with very small total_weight and different speed limit.

Fig. 6 shows the relation between the map-matching distance and the percentage of positions covered by that distance. It is seen from the graph that almost 79% of all map matched positions have a matching distance that is less than 10 m. It is also seen that 99% of all positions are map matched within 80 m. And only less than 1% of extreme cases are map matched between 80 and 160 m.

For all map matchable certainty values, the average HDOP value is 1.46 with an average standard deviation of 0.65. For uncertain map matching, the average HDOP value is 1.46 and for certain map matching the average HDOP value is 1.45. The HDOP value with high certainty value is a little bit better, but has no significant impact on the overall map-matching result. The average HDOP value is quite stable and varies insignificantly (standard deviation $-0.035$) for different certainty values.

5 Conclusions and directions for future research

In this paper, we define an on-line map-matching algorithm designed and implemented especially for ISA systems and currently being used in a large scale trial – the ‘Spar på farten’ project [18]. The algorithm works on hardware with limited CPU and memory resources and yet performs within strict time constraints. The algorithm provides the best possible map matching. It extracts speed information for a map-matched polyline and calculates a value that captures how certain the algorithm is that the extracted speed limit is correct. In the case of low certainty, the ISA system takes no action to prevent speeding. The certainty value also allows us to deal with loss of the satellite signal and to handle GPS position outliers. The algorithm is designed to provide conservative, user beneficial speed limit selection when the certainty value is low.

Initial tests were performed on individual vehicles while developing the algorithm and fine tuning its parameters. The tweaked parameters are adopted for the road topology of the county of North Jutland. In summer of 2006, the deployment of the ‘Spar på farten’ project began, and we currently have more than 100 participants. The volume of the GPS position data allows thorough statistical evaluation and delivers new insights into the algorithm’s performance and the effect of the ISA system. Performance analyses show that the algorithm performs correctly 95% of the time with an average map-matching distance of just a bit above 9 m.

Based on data from the ‘Spar på farten’ project, we have identified areas where the algorithm can be improved. As part of our future work, we will continue the analysis of data and map-matching quality, and we will adjust the map-matching parameters. We also aim to enhance the self-evaluation capability of the algorithm. Currently, no map matching is done when the GPS signal has errors, but in some cases, map matching can be improved using dead reckoning.
6 Acknowledgment

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7 References


