# Map Matching for Intelligent Speed Adaptation

Tradisauskas, Nerius; Juhl, Jens; Lahrmann, Harry; Jensen, Christian Søndergaard

*Published in:*
Proceedings from the 6th European Congress on Intelligent Transport Systems and Services, Time to Intelligent Move, 18th -20th June 2007 in Aalborg

*Publication date:*
2007

*Document Version*
Publisher's PDF, also known as Version of record

# Map Matching for Intelligent Speed Adaptation

Nerius Tradišauskas[1], Jens Juhl[1], Harry Lahrmann[1], Christian S. Jensen[2]

[1]nerius@plan.aau.dk, jj@land.aau.dk, lahrmann@plan.aau.dk
Department of Planning and Development, Aalborg University, Denmark

[2]csj@cs.aau.dk
Department of Computer Science, Aalborg University, Denmark

## Abstract

The availability of Global Navigation Satellite Systems 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 GPS 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 the vehicle's speed with the speed limit in effect and react appropriately.

This paper presents an on-line map matching algorithm 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 for use 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 algorithm performs correctly $95\%$ of the time and is capable of handling GPS/DR 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 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 systems use a vehicle's road network position to extract the speed limit in effect, thus enabling various solutions to prevent drivers from speeding. A digital road network with comprehensive speed limit information and the GPS position of a vehicle 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 that ranges from signaling the speeding to the driver through an information device to physically limiting the speed of the vehicle. It is very important to identify the correct speed limit, to increase the performance and user acceptance of the ISA system. ISA trial projects take place in many different countries around the world ([1, 2, 11, 12, 13, 18, 20]).

After the selected availability (SA) was switched off in May 2000, GPS position accuracy improved dramatically. Using an off the shelf standard GPS receiver, the error can vary from 5 to 25 meters [5, 8, 19]. In urban areas, constructions such as high buildings, ramps, and tunnels obscure the line of sight to the GPS 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 [10], 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 meters [10]. The real-time algorithm that performs the positioning in the road network is called an on-line map matching algorithm. This contrasts off-line map matching algorithms which are applied 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.

Several proposals exist for on-line map matching. Quddus et al. [14] provide a summary of different on-line and off-line map matching algorithms and describe the disadvantages of each approach. The initial problem of map matching was perhaps first defined by Berstein and Kronhauser [3]. Later followed improved techniques, by White et al. [6], that pay special attention to intersection area. Taylor et al. [15, 16] propose a novel map matching procedure that uses differential GPS. The proposed road reduction filter (RRF) 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. [4] that uses the Fréchet distance to map match GPS data samples recorded every 30 seconds.

We are not aware of any proposals of map matching algorithms 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 [17]. 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.

The paper presents a framework that includes a description of the general map matching steps; it covers certainty calculations for the map matching and execution time constraints; and it defines the speed map used and the ISA requirements for map matching. 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, e.g., city streets with nearby tall buildings, roads in forests, a tunnel (length: 582 meters), and open rural roads with good visibility. This variation is important to ensure a thorough evaluation.

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 structures, and positioning data to locate the position of a moving vehicle in a road network. In this section, key aspects and quality assurance techniques in relation to map matching algorithms for ISA systems are described without defining a particular map matching algorithm.

## 2.1 A General Map Matching Algorithm for ISA Systems

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

1. Startup or identification of the initial polyline in the digital road network.

2. Tracking or identification of subsequent polylines in the digital road network to form the route along which the vehicle is moving.

In first part, the initial map matching is done for the first GPS points received to determine the polyline in the digital road network on which the vehicle is located. The correct outcome of first step is very important, as the algorithms use the link connectivity or road topology to determine the following polylines of the vehicle's movement path.

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

1. Extract the required information from position data received.
2. Select candidate polylines from the digital road network.
3. Use a specific algorithm for determining the most suitable polyline among the 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 preset threshold value from the vehicle position are selected. Another approach is to select the $n$ polylines closest to the vehicle position and temporarily store them as the candidate polylines.

The third step uses specific algorithms and techniques to select the best polyline among the candidates. The most common approach is to use weights. Different weights for different attributes are assigned to the polylines, and the polyline with highest sum of weights is selected. Some algorithms use techniques that reduce the set of candidate polylines. They filter out polylines that are perpendicular to the vehicle movement direction [16] 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 polyline. A more sophisticated approach proposed by Quddus et al. [14] uses the weighted average of two points. This method includes the fusion of the distance traveled since the last map matching and the GPS projection on the link.

## 2.2 Map Matching Certainty

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

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

The certainty value can be used to handle outliers. Outliers are the position fixes that do not match the pattern of traveling and usually involve sudden changes in heading as well as rapid position shifts. Greenfeld [7] and Quddus et al. [14] describe steps for how to handle outliers in an offline algorithm. The main idea in previously proposed solutions is to postpone the map matching of outliers and only map match them when the next correct polyline has been identified. In an ISA system scenario, this is not possible as on-line map

matching is used. The best possible guess is required at any time.

### 2.3 Execution Time Constraints

The map matching should be done in less than a second, which is the typical duration between two consecutive positions received from a GPS/DR unit. The limited computational power and memory capacity of an on-board unit (OBU) is to be sued to provide a position fix for every received GPS/DR point. In many cases, the retrieval of the data from the GPS/DR unit and the working time of map matching algorithm cause slight delays. Thus, estimation of a vehicle's real position a few seconds ahead on an estimated polyline can be performed.

### 2.4 Speed Maps for ISA Systems

The map matching of a vehicle's position onto a digital road network enables ISA systems to extract the proper speed limit. The speed limit must be stored in a map. The speed limits in the digital road network can be defined in various ways. The speed limits might be defined for each polyline, or they may be given by polygons covering areas with the same speed limit. Speed limits can also have a valid time, as some streets might be closed during the day and open by night, or the speed limits may be lower at night than during the day.

### 2.5 ISA Requirements to Map Matching

A map matching algorithm always returns one polyline and a position on that polyline. For ISA systems, the speed limit associated with a polyline is also provided. In some cases, the map matching can be uncertain due to high GPS/DR positioning error or multiple candidate polylines with weights close to the maximum weight.

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

A conservative map matching algorithm makes a careful and user-beneficial selection of a polyline and speed limit in a situation that is uncertain. Specifically, a conservative map matching algorithm should always select the right polyline (and speed limit) in certain situations, and it should make a user-beneficial polyline (and speed limit) selection in uncertain situations that incurs the lowest loss for the system. Put differently, in these latter situations, it should select the highest possible speed limit.

## 3 Map Matching for "Spar på farten"

The map matching algorithm is developed for the "Spar på farten" [17] ISA project that takes place in the county of North Jutland in Denmark. The project aims to reduce the speeding among young drivers. Drivers get OBU installed in their cars, and if they obey the speed limits, they get a discount on their car insurance. The "Spar på farten" project uses the on-line map matching algorithm to detect the user position on the road and to select the right speed limit.

### 3.1 Setup and General Steps

As an input, the map matching algorithm receives a 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 that sends the vehicle speed value. The polylines are extracted from a speed map of the county of North Jutland. All registered roads (road polylines) of the county have speed values assigned for each allowed movement direction. For the rest of Denmark, only highway information is stored. For all the other land areas in Denmark, the speed limit is set to 80 km/h. For areas outside Denmark, no map matching and ISA control is done. Map matching and other system maintenance functions are performed by an OBU. The OBU has limited computational power (only integer representation, lack of trigonometrical functions) and limited main memory (up to few hundreds of kilobytes). The map matching algorithm

is performed within a second and consists of six steps (see Figure 1).

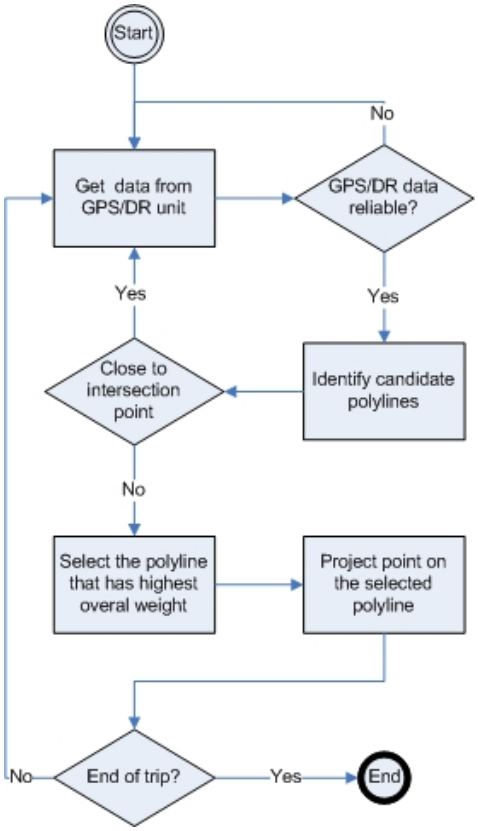
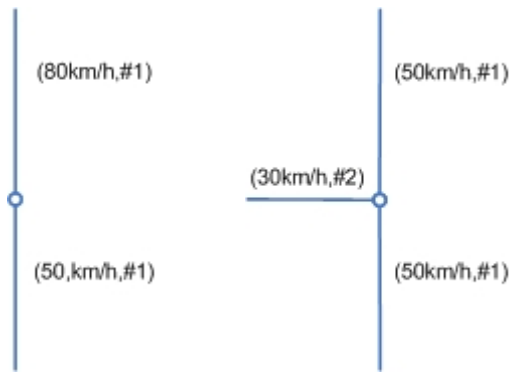



Figure 1: Steps of map matching algorithm

Initially, the data is extracted and converted to a common unit of measure.

It is then checked whether the GPS data are reliable. This is done by comparing the GPS speed data with the odometer speed data. The allowed difference should not exceed a 5 km/h threshold. If the speed difference is within the allowed threshold, the angle direction change is checked. The $direction\_change$ is a value representing the difference between the previous and current directions, and it is proportionally connected with the speed: $direction\_change * speed < 1000$. This formula works only if the speed is expressed in km/h and the direction change is an angle in degrees. This equation checks that cars are not making turns with higher than 0.5G force. If a sharp turn is detected and the equation is violated, the GPS positions is most probably an outlier. If any of these checks fail, the algorithm stops the map matching of the current position and returns an error code (via the certainty value). The ISA system is responsible for the graceful handling of situations where map matching is not possible.

In the third step, the candidate polylines are identified. The algorithm selects at most the 12 polylines nearest to the vehicle GPS position. Due to specific the map format, candidate polylines can be no further than 750 meters away. These polylines are used to assign weights, and the one with the biggest overall weight is selected. If no candidate polylines are found within the threshold value, the map matching algorithm returns an error code via the certainty value.




(a) No intersection

(b) Intersection

Figure 2: Polyline join example

The fourth step checks the distance to the intersection point. Usually the end points of a polyline are located as intersections, but in the speed map we use, this is not the case. Some end points represent the start or end of a speed limit on given road (see 2(a)). Thus polyline end points that connect only two polylines with the same street code are not interpreted as intersection points. Only polyline end points that intersect with polylines that have different street codes are considered as intersections (see 2(b)). The street code represents the street real-world street name. If any intersection point is closer than the threshold value $pardistknude$ from a given GPS position, the algorithm stops map matching and returns error code through the certainty value. The threshold value for $pardistknude$ is by default set to 10 meters.

If all the previous steps succeed, the map matching can be done. The algorithm proceeds to analyze the candidate polylines with different criteria,

assigning weights to each. The polyline with the highest final weight value is selected and its matching certainty value is calculated. The bigger the difference between the two polylines with greatest weight and different speed values is, the more certain the map matching result is. The calculation of weights is explained in Sections 3.2–3.9.

The last step of the map matching algorithm is to calculate the point position on the selected polyline. The vehicle position is acquired by simply projecting the point onto the selected polyline. If the point is projected to an extension of a polyline, the closest end point of the polyline is selected.

As the output result, the algorithm returns the map matched position, the certainty value, and the speed limit of the polyline on which the vehicle is driving. The ISA system uses the latest securely map matched speed limit if map matching fails (due to the reasons mentioned above).

### 3.2 Weight for the Proximity to a Point

A polyline is assigned a weight according to its proximity to the GPS point being map matched. It is natural to assume that the closer a polyline is to the point, the higher the assigned value should be. The distance used is that between the GPS point and the point on the polyline that is closest to the GPS position. Weight $W1$ is assigned as follows:

**if** $dist(point, polyline) < parmaxdi$ **then**
  $W1 \leftarrow parcmaxdi + (parmaxdi - dist(point, polyline))/2$
**else if** $dist(point, polyline) < parnuldi$ **then**
  $aa \leftarrow parcmaxdi{*}100/(parmaxdi{-}parnuldi)$
  $kk \leftarrow parcmaxdi - aa * parmaxdi/100$
  $W1 \leftarrow kk + aa * dist(point, polyline)/100$
**else**
  $W1 \leftarrow 0$

**Algorithm 1**: Calculation of weight $W1$

Parameter $parmaxdi$ and $parnuldi$ is set to 10 and 80 meters, respectively. The formula assures that points that are closer than $parmaxdi$ meters get the highest value. If the polyline is between $parmaxdi$ and $parnuldi$ meters away, the weight varies linearly, and zero weight is assigned if the polyline is further than $parnuldi$ meters away from the GPS position.

### 3.3 Weight for the Continuity of a Polyline

Weight $W2$ is assigned to each polyline for being a continuation of the previously map matched polyline. This weight represents the reasoning that vehicles tend to drive on the same road most of the time. If the polyline has the same road number as the previously map matched polyline, the maximum weight of 30 is added. If the polyline is not an extension of the previous one, but has an end point near the GPS position, a weight of 10 is assigned. Otherwise, zero weight is assigned.

**if** $code(polyline) == code(previous\_polyline)$ **then**
  $W2 \leftarrow 30$
**else if** $dist\_to\_intersection(point, polyline) < 20$ **then**
  $W2 \leftarrow 10$
**else**
  $W2 \leftarrow 0$

**Algorithm 2**: Calculation of weight $W2$

### 3.4 Weight for Speed Limit Change

Weight $W3$ 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: city (all speeds limits that do not exceed 80 km/h) and highway (all speed limits that exceed 90 km/h). This variation was made to give higher weight values for the cars driving on a highway. Weight $W3$ nicely complements weight $W2$, as it assumes that cars are driving on the highway rather than exit from the highway. The odometer speed is selected as the vehicle's speed.

**if** $speedlimit(polyline) == speedlimit(previous\_polyline)$ **then**
  **if** $speedlimit(polyline) > 80$ **then**
    $W3 \leftarrow 20 + 20 * odometer\_speed/80$
  **else**
    $k \leftarrow 20 * odometer\_speed/50$
    **if** $k > 20$ **then** $k \leftarrow 20$
    $W3 \leftarrow 20 + k$
**else**
  $W3 \leftarrow 0$

**Algorithm 3**: Calculation of weight $W3$

### 3.5 Weight for One-Way Streets

Polylines that represent one-way roads have zero speed limit in the direction in which it is prohibited to drive. A conservative approach is taken as there might be an error in the map. This weight also solves the problem of selecting the right polyline on highways. If a polyline is one-way and its direction is against the vehicle movement direction then weight $W4$ is set to $-100$; otherwise, the weight is zero.

**if** $against\_direction(point, polyline)$ **then**
  $W4 \leftarrow -100$
**else**
  $W4 \leftarrow 0$

**Algorithm 4**: Calculation of weight $W4$

### 3.6 Weight for Direction Similarity

Polylines whose bearing is similar to the vehicle movement direction are assigned higher values for weight $W5$. It is well known that GPS position dilution may occur when a vehicle is stationary [14]. To deal with this problem, we check the odometer speed. If the vehicle is stationary (speed is zero) then the direction of previous, non-stationary position is chosen. For highway polylines, a 4 degrees adjustment is made to produce better results at exit ramps.

**if** $odometer\_speed == 0$ **then**
$dir(point) \leftarrow dir(previous\_point)$
**if** $speed(polyline) > 80$ **then**
$dir(point) \leftarrow dir(point) - 4$
$W5 \leftarrow 150 * (90 - abs(mod(dir(point) - dir(polyline), 90)))/90$

**Algorithm 5**: Calculation of weight $W5$

In Algorithm 5 $mod(angle, 90)$ returns an angle in the interval $[0, 90]$.

### 3.7 Weight for Topology

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 in the forward (or backward) vehicle movement direction. If the polylines have no common connection point, a zero weight is added. The presence of a connection between the polylines through one or more intermediate polyline(s) is not taken into account, and the polylines are considered as non connecting. The weight is especially useful at intersection areas, as polylines that intersect with the map matched polyline get higher weights and become more likely to be selected.

**if** $intersect(f, polyline, previous\_polyline)$
**then** $W6f \leftarrow partopologi * ccfactor/100$
**else** $W6f \leftarrow 0$
**if** $intersect(b, polyline, previous\_polyline)$
**then** $W6b \leftarrow partopologi * ccfactor/100$
**else** $W6b \leftarrow 0$
$W6 \leftarrow W6f + W6b$

**Algorithm 6**: Calculation of weight $W6$

The polylines that have a common intersection point have their weight increased by $partopologi * ccfactor/100$ where *partopologi* is a parameter with a value of 150 and *ccfactor* is an average certainty value (defined in detail in Algorithm 9) for the last 5 map matched points. If the map matching is done for the first time, $ccfactor$ is assigned a default value of 5.

### 3.8 Weight for Shortest Distance

If the polyline with the shortest distance is not the polyline with the highest weight, a special weight $W7$ is added. The initial value of this weight is 5, and its value is increased by 5 every time the same polyline is closest, but does not have the highest weight. The weight is reset if the closest polyline has changed.

This weight was added to avoid problems with parallel roads. Figure 3 shows a vehicle that is moving from South to North (crosses represent GPS positions and dots represent map matched positions). After an intersection, the algorithm continues to map match the vehicle to road #1 because all the weight calculations favor that road. From point $P_5$, weight $W7$ is added to road #2 and reaches value 20 at point $P_8$, which is sufficient to change the map matching result. This situation is common when a new road is built parallel to an old.

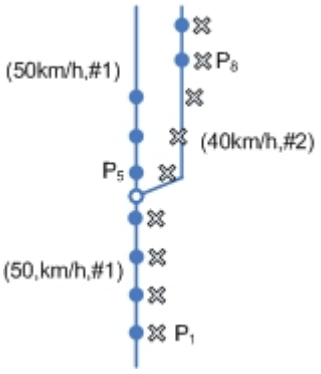



Figure 3: W7 weight example

**if** *closest polyline is not with the highest weight previous shortest polyline = shortest polyline* **then** $W7 \leftarrow W7 + 5$ **else** $W7 \leftarrow 0$

**Algorithm 7**: Calculation of weight $W7$

### 3.9 Total Weight and Certainty Value Calculation

The weights described so far are calculated for each candidate polyline, and a total weight is obtained by adding these up. The polyline with the highest total is selected.

$total\_weight \leftarrow$
$W1 + W2 + W3 + W4 + W5 + W6 + W7$

**Algorithm 8**: Calculation of $total\_weight$

Once the above calculations for polylines are made, the polyline with the highest $total\_weight$ is selected. Then vehicle position on the selected polyline is determined by projecting GPS point to the closest point onto the selected polyline. If the projection is made on the extension of the polyline, then the closest end point is selected.

This algorithm was developed for an ISA system with the objective of extracting the correct speed limit. The certainty of the map matching is estimated by comparing the weights of two polylines. The total weight of the selected polyline (the polyline with the maximum $total\_weight$) is compared with the total weight of the polyline that has the greatest weight value and has a different speed limit. The bigger the difference between these two weights, the more reliable the map matching is. If all candidate polylines have the same speed limit, the certainty value is maximum. The range of the certainty value is $[0, 100]$, where $0$ represents the lowest and $100$ represents the highest certainty. If the certainty value is below the threshold value, set to $25$, the ISA system does not trust the map matching, and no actions for possible speeding are taken.

$certainty \leftarrow (max\_weight -$
$next\_max\_weight) * 100/max\_weight$
**if** $certainty <= 25$ **then**
  Map matching is uncertain.

**Algorithm 9**: Calculation of certainty value

All the constant numbers in our individual weight calculation algorithms are selected to provide the best results for the given speed map of the county of North Jutland. Other maps or more tests with parameter values may lead to a different set of parameters that yield the best performance of the map matching algorithm.

## 4 Empirical Evaluation

This section reports on empirical evaluations of the map matching algorithm. We first analyze the map matching using a known route. We performed visual inspections to check the correctness of the map matching, and we 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 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.

### 4.1 Setting

The digital speed map covers the entire county of North Jutland, which has an area of $6,170$ km$^2$ 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 [9]. 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.

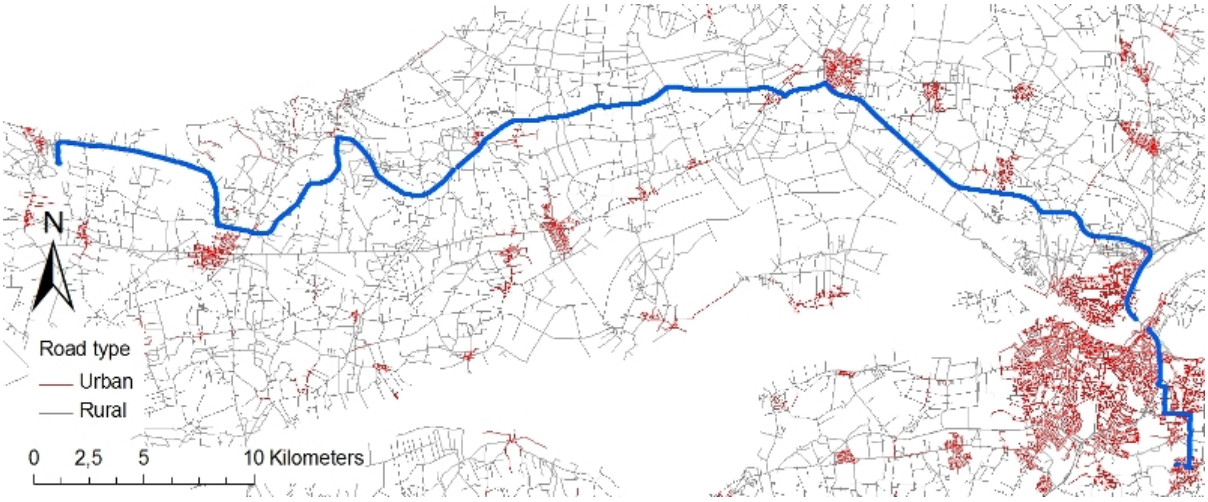



Figure 4: Test trip—the vehicle was driving from West to East.

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 on-board unit. 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.

## 4.2 Analysis of Map Matching Algorithm

The test trip is 72 km long and starts in the Western part of the county and ends in an Eastern suburb of Aalborg (see Figure 4). The trip duration was 76 minutes and took place between 4 p.m. and 6 p.m. on the 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 road the remaining distance.

During the test, the certainty value was high (interval $[26, 100]$) 95.38% of the time. The map matching had low certainty (interval $[0, 25]$) during 0.11% (corresponding to 5 seconds) of the trip. No map matching was performed 4.5% of the trip due to errors (206 seconds). Most of the errors (63.6%) were due to a too high HDOP value. The other main error was a too big difference between the GPS and the odometer speed during fast accelerations and decelerations (31.1%).

## 4.3 Statistical Analysis of ”Spar på farten” Project Data

The data analyzed 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 of 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 Figure 6), the map matching certainty is considered to be insufficient; thus, the ISA system takes no action even if actual speeding occurs. In 4.39% of the total time, no map matching is done at all, which is due to errors.

Figure 7 shows the distribution of the map matching errors. The value $-1$ is returned if no road near the GPS/DR position was found. The value $-11$ is returned when there is a too big difference between the odometer and the GPS speed values. The value $-12$ is returned if the direction change is too big for the given speed. 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

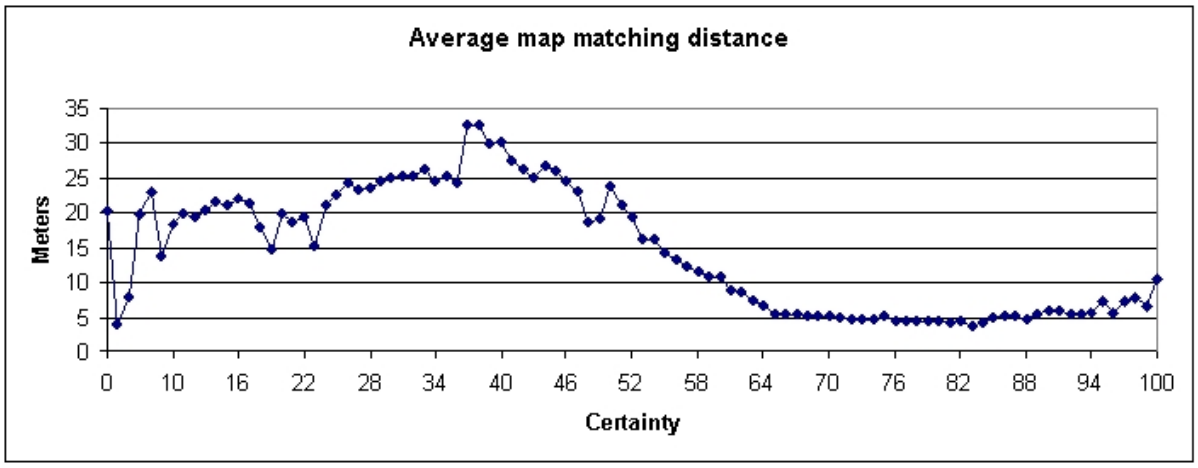



Figure 5: Average map matching distance, %

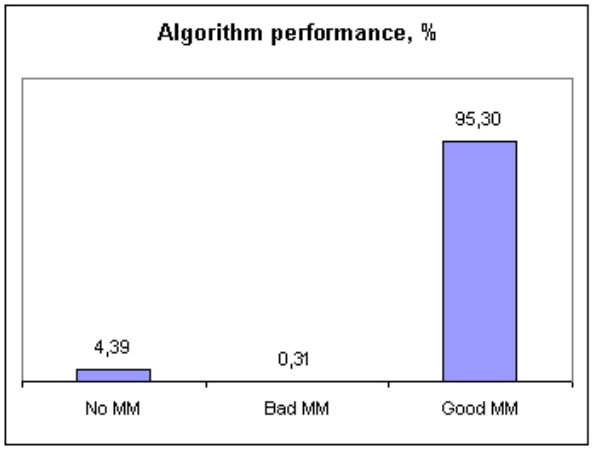



Figure 6: Distribution of certainty value, %

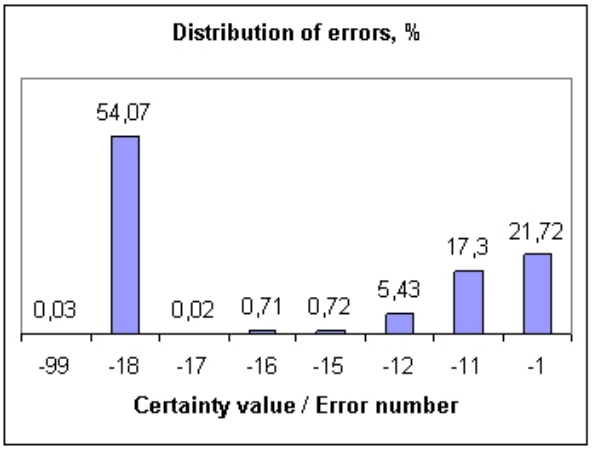



Figure 7: Distribution of map matching errors, %

and proper GPS positioning is unlikely to be possible. Finally, the value $-99$ is returned when the vehicle is driving outside Denmark.

In Figure 7, 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 $-18$). 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 rural road is missing from the map. The too high speed difference between the odometer and the GPS values (error $-11$, $17.30\%$) occurs due to fast acceleration or deceleration. The odometer can show the speed instantly, while the GPS value lags a little. Yet another significant reason for no map matching is the so-called side acceleration (error $-12$, $5.43\%$) due to too high vehicle direction changes at high speeds. These points most probably are GPS outliers and are thus skipped. The last four reasons occur in less than $2\%$ of the cases and are not important.

The maximum distance between the GPS/DR point and the map matched point with low certainty values (interval $[0, 25]$) reaches $150.62$ meters; with high certainty values (interval $[26, 100]$), the distance reaches $154.43$ meters. A high maximum map matching error can be caused by a vehicle driving on a road in a rural area that is covered

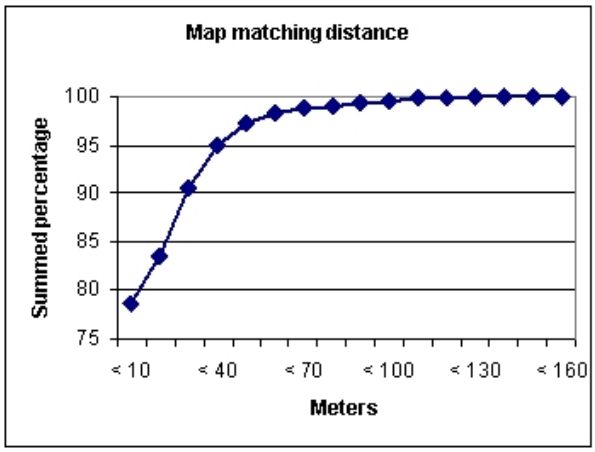



Figure 8: Map matching distance, %

by tall trees and where there are no other roads to map match to. These are extreme cases and appear rarely in the test data.

Figure 5 shows that the average map matching distance is 18.67 meters for low certainty values and only 9 meters for high certainty values. The overall map matching error for all map matchable certainty values (interval $[0, 100]$) is 9.04 meters.

Figure 8 shows the relation between the map matching distance and the percentage of points covered by that percentage. It is seen that 78.70% of all map matched points have a matching distance that is less than 10 meters. It is also seen that 99.02% are map matched within 80 meters. Only less than 1% of extreme cases are map matched between 80 and 160 meters.

## 5 Conclusions and Directions for Future Research

This paper defines 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. 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 speed limit is correct. In case of low certainty, the ISA system takes no action to prevent speeding. The use of the certainty value also allows 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 testing its parameters. The tweaked parameters are adopted for the road network of the county of North Jutland. Starting summer of 2006, the deployment of the ”Spar på farten” project began, and we currently have 50 participants. The volume of GPS position data allows thorough statistical evaluation and delivers new insights into the algorithm's performance and the performance of the overall ISA system. Performance analyses show that the algorithm performs correctly 95% of time with an average map matching distance of just a bit above 9 meters.

Based on data from the ”Spar på farten” project, we have identified areas where the algorithm can be improved. As part of 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. However, in some cases, map matching can be improved using odometer speed and traveled distance. Small hardware enhancements like the use of turn signal information would provide additional knowledge in situations near intersections and highway exits.

## References

[1] Limiteur s'Adaptant la VItessse Autorise (LAVIA). `http://heberge.lcpc.fr/lavia/GB/indexGB.html`.

[2] Swedish Road Administration. Intelligent Speed Adaptation project. `http://www.isa.vv.se/index.en.htm`.

[3] D. Bernstein and A. Kornhauser. An introduction to map matching for personal navigation assistants. *New Jersey TIDE Center*, 1996. `http://www.njtide.org/reports/mapmatchintro.pdf`.

[4] Sotiris Brakatsoulas, Dieter Pfoser, Randall Salas, and Carola Wenk. On map-matching vehicle tracking data. In *VLDB*, pages 853–864, 2005.

[5] Martin Brandi, Ole Runge Madsen, Nikolaj Møller Nielsen, and Jesper Runge Madsen. INFATI Test af GPS-nøjagtighed og digitale kort med hastighedesgrænser. Technical report, Aalborg University, Denmark, 2001. http://www.trg.dk/projekter/infati/notat4.pdf.

[6] C.E.White, D.Bernstein, and A.L.Kornhauser. Some map matching algorithms for personal navigation assistants. *Transportation Research Part C*, 2000.

[7] Joshua S. Greenfeld. Matching GPS observations to locations on a digital map. *81th Annual Meeting of the Transportation Research Board*, 2002.

[8] Paul Heide. INFATI Hardware og Software. Technical report, Aalborg University, Denmark, 2001. http://www.trg.dk/projekter/infati/notat2.pdf.

[9] Jens Juhl, Poul Heide, Harry Lahrmann, and Sonne Ian Berg. ”Spar på farten” . Technical report, Aalborg University, Denmark, 2006.

[10] L.Zhao, W.Y.Ochieng, M.A.Quddus, and R.B.Noland. An Extended Kalman Filter Algorithm for Integrating GPS and Low Cost Dead Reckoning System Data for Vehicle Performance and Emmision Monitoring. *The Journal of Navigation*, 2003.

[11] Monash University Accident Research Centre. In-vehicle ITS and Young Novice Driver Safety. http://www.monash.edu.au/muarc/projects/its.html.

[12] Monash University Accident Research Centre. Intelligent Speed Adaptation and Heavy Vehicles. http://www.monash.edu.au/muarc/projects/its.html.

[13] Harri Peltola, Juha Tapio, and Riikka Rajamki. Intelligent Speed Adaptation (ISA) - recording ISA in Finland. http://www.rws-avv.nl/prosper/ISA_NVF2004_Peltola.pdf.

[14] M. Quddus, W. Ochieng, L. Zhao, and R. Noland. A general map matching algorithm for transport telematics applications. *GPS Solutions Journal, 7(3)*, pages 157–167, 2003.

[15] G. Taylor and G. Blewitt. Virtual differential GPS & road reduction filtering by map matching. In *ION'99*, 1999.

[16] G. Taylor, G. Blewitt, D. Steup, S. Corbett, and A. Car. Road Reduction Filtering for GPS-GIS Navigation, 2001.

[17] Aalborg Universitet, Nordjyllands Amt, and Topdanmark. ”Spar på farten” . http://www.sparpaafarten.dk.

[18] University of Leeds and the Motor Industry Research Association (MIRA). Intelligent Speed Adaptation. http://www.its.leeds.ac.uk/projects/isa/.

[19] US DoD. Global positioning system standard positioning service performance standard. October 2001.

[20] Alex van Loon and Lies Duynstee. Intelligent Speed Adaptation (ISA): A Successful Test in the Netherlands. http://www.rws-avv.nl/pls/portal30/docs/911.PDF.