Traffic flow enhancement through guidance for driver based on GPS aided smartphones

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Abstract

Our roads are dealing with an increasing traffic and congestion problem. This problem have historically been solved by adding new roads, however this is an expensive solution. Technical solutions where human contributions to the traffic problem are minimized through automations of vehicles are being researched. However such solutions are still far from an introduction to the market.

This thesis presents a low-cost and broad solution to the traffic congestion problem using smartphones. By creating a smartphone application aided by a GPS-receiver one can produce a system that has the possibility to increase the capacity of the current road network. The develop system uses state optimization technique inspired by the research field of platooning with a two-vehicle look-ahead.

To support the state optimization the use of map matching algorithm based on a point-to-curve-using-heading approach have been implemented along with an estimation based on linear interpolation.

The thesis show that such a system, stated as above, is possible to develop and gave satisfying performance during a field test.

Keywords: Platoon, Vehicle, Smartphone, Map matching, Congestion
Acknowledgements

The work behind this report has been conducted at the Signal Processing department at the School of Electrical Engineering, KTH. I would like to thank Prof. Peter Händel for making this work possible, and also Dr. Isaac Skog who has been my supervisor. Also thanks to Martin Ohlson for the contributions in the real-time android implementation. The work has been really interesting and enjoyable and has given me great opportunities for learning.

- Frej Sojé-Berggren, June 2011
# List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>DR</td>
<td>Dead-Reckoning</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HMI</td>
<td>Human-Machine-Interface</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transport Systems</td>
</tr>
<tr>
<td>IVHS</td>
<td>Intelligent Vehicle Highway System</td>
</tr>
<tr>
<td>MDS</td>
<td>Mass Damper Spring</td>
</tr>
<tr>
<td>MM</td>
<td>Map matching</td>
</tr>
<tr>
<td>THW</td>
<td>Time headway</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle-to-vehicle</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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</tbody>
</table>
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3.1 The elements of the digital road network.
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A4 Flowchart diagram of how the android implemented application decide when to switch mode from Overview/Leader mode to Member mode.
## Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$AB$</td>
<td>Distance between point A and point B.</td>
</tr>
<tr>
<td>$x$</td>
<td>Scalar.</td>
</tr>
<tr>
<td>$\dot{x}$</td>
<td>Time derivative.</td>
</tr>
<tr>
<td>$\ddot{x}$</td>
<td>Second time derivative.</td>
</tr>
<tr>
<td>$\hat{d}$</td>
<td>Estimate of distance.</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>Mapped position.</td>
</tr>
<tr>
<td>$p_i$</td>
<td>Position of vehicle i.</td>
</tr>
<tr>
<td>$p^t$</td>
<td>Position at time t.</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Heading.</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity.</td>
</tr>
<tr>
<td>$h$</td>
<td>Time headway.</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of vehicle.</td>
</tr>
<tr>
<td>$a$</td>
<td>Acceleration.</td>
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1. Introduction

This chapter will present the main objective of the work carried out within this thesis. The specifications and limitations of the work will be outlined and, lastly, previous work related to the thesis will be illuminated.

1.1 Background

Developments within two different areas contribute to the possibility of making this thesis project.

1.1.1 Increased traffic congestions

The current traffic net worldwide is facing an increasing demand and the forecast for the traffic situation in Stockholm shows that congestion will continue to increase in the coming years. This is mainly due to an increased population, a population that will grow 20% to 2030 [1], and also due to economic growth [2]. In Stockholm a controversial bypass highway with a price tag of several billions have been planned. This have been the historical approach to solve the problem of an increasing congestion in road networks.

With increased traffic, the negative effects of human driving will be more obvious. The so called “slinky effect”, caused by oscillations in accelerations and retardation, and other human related drawbacks such as reaction times and driving errors all have a negative effect on traffic flow and thus road network capacity.

More automatic control and less human involvement has been seen as the solution for the traffic congestion problem, this approach can even double the capacity of current road networks. Adaptive Cruise Control (ACC) and platooning are two research fields trying to solve some problems related to traffic congestions. The ACC systems controls the vehicle throttle and brake by sensing the distance to the preceding vehicle and thus removing the delay human driving would cause. However ACC system could still be unstable. The platooning approach is even more automatic and where whole groups of vehicles are controlled automatically and thus optimizing the distances between them and their velocities. These two research fields are however currently far from a broad market introduction and thus the traffic congestion problem is still solved by adding new roads.
1.1.2 The smartphone approach
With the recent developments in the cellphone market, where smartphones have had an intense expansion on the market, one can propose an innovative, cheap and broad solution to the traffic congestion problem. The proposed solution would use technology integrated in smartphones to produce an optimization control signal inspired by platooning and thus provide guidance for a driver.

1.2 Project scope
The objective of the project was to develop a low-cost solution to the increasing traffic congestion problem. This has been done by developing a real-time driver aid device, referred to as the prototype hereafter, which recommends an optimal acceleration for the driver and thus tries to remove the negative traffic effects caused by the human driver such as the slinky effect. The prototype would do this by offering a platooning concept for the user where users e.g. the vehicles, could dock to each other and create groups of vehicles where distances and velocities are, as in the research field of platooning, optimized. To make this application attractive to the users it will be presented as a game where users will get points depending on their driving skills.

1.2.1 Prototype specifications
The prototype should be able to communicate with vehicles nearby and from that calculate a recommended acceleration for the driver. This system would run on a smartphone to thereby increase the availability and offer a low-cost system. The system's input is based on the built-in GPS receiver, these inputs requires some processing to provide acceptable results. Processing will consist of map matching, an approach that projects GPS position onto a digital network. The communication between users will however cause a delay in information which means that the distance to other vehicles constantly need to be estimated.

1.2.2 Prototype capabilities
The prototype should be able to do the following tasks.

- Compute and display a recommended acceleration with the purpose to optimize the states of the vehicle.

- Communicate the vehicle’s states (speed, position and heading) to a server which will distribute the information to target vehicles.
• Be able to map the vehicles position to a road from a digital road map and from this extract and present the current road’s speed limit.

• Be able to display the position of other users on a map.

• Initiate docking to a vehicle group, split from a vehicle group.

To stimulate the users’ interest in the application a scoring system will implemented. The purpose of this scoring system will be to give points to users who

• Use the application.

• Drive in groups; the longer the better.

• Follow the recommended acceleration and thus distance and speed.

1.2.3 Project limitations

While the objective of the project is to develop a full-scale real-time prototype to be used for driver-aid, the project had to be limited in some sense due to the time-constraints. Consequently, the project doesn’t investigate following aspects.

• The human-machine-interface (HMI). Though one could think this would have a major importance since the application convey information to a user in a fairly precarious situation, in traffic. The main focus of driver attention should still, and always, be on the current traffic situation. However, the HMI area of the prototype has not been considered.

• Market need for such a product. The need from a possible market has not been investigated. The thesis has focused on providing a cheap innovative solution for an observed problem.

• No additional sensors. Using other sensors from the smartphone (as the accelerometer and gyroscopes) could have the possibility to enhance the performance of the system, though it would have been more time consuming to develop and implement such a system.

• No use in cities. The prototype has been developed by the assumption that it will not be used in urban canyons. See next section for further details.
1.3 Previous research

An existing substitute to the developed prototype is hard to find, however similarities with other research fields exists.

For example cooperative adaptive cruise control (CACC) which is an extension of the ACC where vehicles communicate to each other and thus tries to remove the instability (slinky effect) which may occur with ACC.

The prototype will mainly be using two different techniques related to the field of vehicle research. These two are the map matching technique and the platooning technique. The following sections will present research within these two fields and also specify similarities and differences some previous research has with the developed prototype.

1.3.1 Map matching

Map matching is a technique to improve the GPS positions when moving on roads. With the knowledge that a vehicle only can travel on a road one can use this assumption to get a more accurate position. An increasing demand for intelligent transport system (ITS) applications and systems such as bus arrival information, route guidance and fleet management have shaped the need for map matching techniques that improves inputs from positioning techniques (such as GPS).

The map matching problem has been studied for at least the two past decades, and several solutions with different complexity have been proposed [3]. The existing proposed solutions within the field can be divided into those using additional sensors (such as odometers and gyros) and those without additional sensors and only relying on a GPS receiver.

With additional sensors one will get an enhanced performance, though with the cost of a more complex algorithm. Presented in [4] is an algorithm based on fuzzy logic which gives high performance. However, this algorithm differs from the chosen approach in this thesis since the algorithm in [4] uses additional sensors as the odometer and a low-cost gyroscope.

Other more advanced map matching algorithms addresses problems with outage of GPS signals or poor positioning which can occur in urban areas where GPS signals are blocked by high-rise buildings (known as urban canyons). Such an algorithm is presented by Cui and Ge in [5] where they use an extended Kalman filter (EKF) and dead-reckoning (DR) to tackle the problem of urban canyons.

However, the developed prototype has been built on the assumption that it wouldn’t be used in high density urban areas. This because it would be hard to form and maintain platoons is such
environments. Thus the problem of blocked GPS signals and the urban canyon difficulties have not been considered. This, however, made the use for a less advanced map matching algorithm, without additional sensors, used in the developed prototype.

More about map matching in general and the algorithm of chose will be thoroughly addressed in chapter 3.

1.3.2 Platooning
Platooning has been a major research field within Intelligent Vehicle Highway Systems (IVHS) for several years. The focus of platooning has been to create automatic vehicles convoys which can drive autonomous without user interference. A review of automatic vehicle convoy control strategies employed in the field of platooning can be found in [6]. Many of the strategies uses lead vehicle information, e.g. information from the first vehicle in group, as in [7] and [8]. Though others like [9], [10] and [11] exists. What these algorithms all have in common are that they are very complex. These algorithms are not suitable for this thesis, mainly because of these criteria.

- The system is not fully automated, a user the driver will be part of the control loop.
- No dedicated Vehicle-to-Vehicle (V2V) communication channel will be used.
- Control signal computations will only use relative distances and velocities from own and other vehicles as input.

1.4 Thesis outline
The remainder of the thesis is structured as follows. The second chapter will start with an introduction and overview of the whole system. The third chapter will thoroughly go through the map matching (MM) concept and the implemented MM algorithm. The fourth chapter will describe the state optimization controller. The fifth chapter will present the results from simulation and real world tests. In the sixth chapter conclusions will be drawn. Finally, the seventh chapter will present future work and possible improvements that can take the system to the next level.
2. The vehicle state guidance system

This chapter will give a detailed overview of the system, its different parts and how they are connected.

2.1 Overview

The whole system can be illustrated by figure 2.1, where vehicles extract positioning information from GPS satellites and then communicate this information to other vehicles through a server using the network provided by the smartphones.

![Figure 2.1. GPS provides the vehicles states which are communicated to other vehicles through a server.](image)

From a device perspective one can illustrate the system with figure 2.2. As seen in the figure the system consists of the following parts. A GPS-receiver, a map matching process, an estimation process, a state optimization process and inputs from the user. The GPS-chip receives signals from GPS satellites and outputs velocity, heading and position. The map
matching algorithm receives these data and performs the map matching to a position on a
digital road. This mapped position together with the heading and velocity from the GPS
receiver are sent to the server. The server will provide the digital road map needed for the map
matching process and also data uploaded from other vehicles. These data from other vehicles
are needed for the state optimization process. First, however, the distances will be estimated by
the estimation process. Lastly, the other vehicle data provided by the server, the estimated
distance from the estimation, velocity from the GPS receiver and headway from user input are
used to compute a control signal which will be displayed to the driver.

Figure 2.2. The system from the device perspective. $p_{t+1}^i$ is the position of vehicle $i$ at time $t$, $h_i$ is the
headway, $L$ is the length, $v$ is the velocity, $\hat{p}_i$ is the mapped position, $\theta$ is the heading, $\hat{d}$ is the estimated distance
and $a_{rec}$ is the recommended acceleration.

\subsection{2.2 GPS}

This section will present the GPS, an important part of the system since it is the only source of
position information and thus the whole system will be affected by its performance.
2.2.1 Principles of GPS
The GPS is a space-based global positioning system. A receiver on the ground relies on signals from at least four different satellites to estimate its current location. The receiver can from the satellite signals extract information about the distance to and orbital location of each of the received satellites. With this information the receiver can then compute its location through trilateration.

2.2.2 Limitations of GPS
The GPS is however not a perfect system. Several sources of errors exist such as multipath propagation, inconsistencies in the atmosphere etc. Due to this insecurity in the GPS position, a technique is needed to stabilize the positioning output. One such technique is map matching which is widely used and implemented in consumer devices today.

2.3 Map matching
As mentioned in section 1.2.1 MM is a technique used to enhance positioning data. The map matching algorithm gets the position, velocity and heading data from the GPS-receiver-chip and maps this position to a point on a digital road map. A more thoroughly description of the MM concept and the MM algorithm implemented will be given in chapter 3.

2.4 Estimation
Estimation is needed since there will not be any direct communication between devices, instead communication channel used will be the one provided by the smartphone. Thus one can expect a delay that will have significant impact on the system. For example, two vehicles driving at a speed of 90km/h (25m/s) where the communication channel give rise to a delay of 1s, will give a position error of no less than 25 meters. Thus one has to estimate the true position for the system to give acceptable performance.

2.4.1 Estimation method
The purpose of the estimation is to estimate the true distance between vehicles. This is done by linear interpolation. Linear interpolation offers an easy implemented solution and gives good results when the sample frequency is high or when velocities are stable. One could also consider estimating the distance using a more advanced approach, such as a Kalman filter. More advanced approaches have however been disregarded because of satisfactory results from the linear interpolation in the simulation.
2.5 User input
User input is information provided by the user which will be used in the system. This user defined information is length of the vehicle and desired time headway (THW). The THW is the distance to the vehicle in front normalized by the speed of the vehicle. The system will have a three-second THW as default. However the user has the ability to choose between different values to find a value of more liking. This option is provided because different user will have different desire in what they think is a convenient distance to the vehicle in front depending on weather and traffic conditions. The vehicle length is also needed to get a good estimate of the distance between vehicles. More detailed information of this concept is given in section 4.4.

2.6 State optimization signal
The state optimization signal is the recommended acceleration displayed for the driver. It has been calculated to optimize the traffic flow through coordinating distances and velocities. The state optimization signal will get the position and states of the directly preceding vehicle and the vehicle in front of that. An optimization signal is then computed and displayed to the driver. The control signal can be interpreted as the amount of acceleration the driver needs to create using the vehicles engine to be able to keep the desired distance. Chapter 4 will give a deeper description of how the optimization signal will be computed.

2.7 Other system properties
This section will present some properties of the system which makes it attractive to users and how the platooning inspired part of the system works.

2.7.1 Platooning concept
As mentioned, the application will be presented as a platooning game where users get points based on their driving performance. The system communicates with other devices and can thus sense when other vehicles are approaching.

The concept in platooning is to create groups of vehicles where distances and velocities are synchronized. In the developed system this is done through the optimization signal. Users can also dock to an existing platoon or create new platoons with other users. Docking process is started when distance to a vehicle or platoon further ahead is within a given value. During the docking process the user will get the state optimization signal e.g. recommended acceleration information. When the user successfully keeps the user defined THW for a given time the docking have succeeded.
2.7.2 User modes
A user in the system can be in three different modes: single, leader or member. These modes have been chosen because of their significant differences. For example, a user in single mode doesn’t need high frequency server updates, which a user in member or leader mode need. Thus the system can adapt its power consumption depending upon the operation mode of the application; the power consumption optimization extends the battery life time of the smartphone. The system switches the modes for the user depending on the current circumstances. Appendix 9.2 presents the algorithm used to switch between modes in the system.

2.7.3 Points system
A user points system has been developed. The purpose of the user points system is stated in section about project capabilities 1.2.1. where following scenarios were decided to give points.

1. Use the application.
2. Drive in groups, the longer the better.
3. Follow the recommended distance and speed.

Therefore three different points frequencies where developed, one for each user mode.

\[ \text{Points}_{\text{single}} = 1 \]  
\[ \text{Points}_{\text{leader}} = 2.6 \times (1 + \frac{\text{members} - 2}{5}) \]  \[ (2.1) \]
\[ \text{Points}_{\text{member}} = 2 \times (1 + \frac{\text{members} - 2}{5}) \times (1.4 - 0.4 \times (\text{position})) \]  \[ (2.2) \]

where \text{members} is the number of members in the group and \text{position} is the normalized error in position. \text{position} ranges from 0, when the distance between vehicles equals the THW, to 1, when the distance between vehicles is 0 or twice THW.
3. Map Matching algorithm

This chapter will explain the concept of map matching, how it works, and why it is needed in the developed system.

Due to the varying limitations of the GPS a common way to improve the accuracy of the system is to combine GPS with map matching algorithms.

3.1 Principles of map matching

With the knowledge that a vehicle only is travelling on a road one can project the GPS position to a position on a digital road network. However this is not a trivial task and many solutions have been proposed during the years. Point-to-point, point-to-curve, curve-to-curve, point-to-curve-including-heading are a few methods that have been proposed. For a brief review of these algorithms one is referred to [12].

Through map matching algorithms one can reconcile noisy and inaccurate GPS positions with an accurate digital road map and hence improve the final location. Map matching algorithms can be divided into two different categories, those who have access to the known traveling route and those who are without additional information and only rely on geometric relationships.

Algorithms with knowledge of the route assume that the vehicle follows the suggested route and matching is thus performed onto segments that belong to that route. Such algorithms also detect large deviations between the GPS position and the predefined route which is interpreted as the vehicle has deviated from the suggested route and a new route will be calculated [13].

Algorithms without additional information have to be more complex to give good performance. It is one of these kinds of algorithms that have been implemented in the developed system.

3.2 Digital road map

The digital road map should be clearly defined since it is the foundation on which MM algorithms are built on. The digital road map consists of several different nodes, which corresponds to geographic coordinates representing locations in the real world. Between these nodes are straight lines which link the nodes together, these links corresponds to roads in the real world. Figure 3.1 illustrates the nodes and links stated above.
Figure 3.1. The elements of the digital road network. Black dots are nodes, links are straight lines between the nodes. Together these model the roads of the real world.

3.3 MM definitions

When reviewing articles and reports in the field of MM one will encounter several different definitions on the consisting parts, mainly parts concerning the digital map. For example, the line between two nodes can be addressed to as links, segments, curves or arcs. This can give rise to some confusion especially when the word segment also can be found to define a set of connecting lines forming a segment of a road. In this thesis, only the word link will be used to describe the line between two nodes. However, in the names of the MM algorithms the word curve will be used since it appears to be standard, i.e. point-to-curve.

3.4 An MM example

One of the easiest MM algorithms is the point-to-curve algorithm. This algorithm calculates the distances to links nearby and then chooses the link with the shortest distance. The GPS position is then projected onto a point belonging to that link.
Figure 3.2. Decision making of the map matching algorithm. \( P_1, P_2 \) and \( P_3 \) are GPS positions to be mapped, the arrows symbolizes possible mapped position and \( A, B, C \) corresponds to the mapped positions made by the algorithm.

One common drawback of such an easy MM algorithm is that it can become rather unstable. Figure 3.3 illustrates the stability problem found in primitive MM algorithms. The definition of an unstable MM algorithm is that such an algorithm jumps between links in a way that would be impossible for a vehicle.

Figure 3.3. Instability problem of a simple map matching algorithm. The mapped position jumps between links in a way that would be impossible for a vehicle, this is the definition of an unstable MM algorithm.
3.5 Purpose of MM in system

The purpose of MM in the develop system is to stabilize and refine the performance. This is needed to be able to give a good experience to the user.

![Figure 3.4. Illustration of how map matching can improve the GPS positions.](image)

Figure 3.4 illustrates GPS positions from two GPS receivers at exact same time. These GPS receivers are of the same hardware and have the same location. However, as illustrated in the figure one can see that they differ in position. The MM algorithm will thus suppress this error, as seen in the figure, which will improve the performance and accordingly the user experience.

3.6 MM artifacts

Even though MM is well-tested and implemented in various devices available on the market today, it has some distinctive drawbacks, mainly through the dependency to the digital road map. An example is that fairly new roads will probably not exist in a digital road map and therefore errors will emerge.
Figure 3.5. Illustration of an error due to an inaccurate digital road map. What can be seen is the GPS position $P$, a digital road map and a new road (dotted line) not yet implemented in the digital road map. If the new road would have been implemented, $P$ would have been projected onto $B$ instead of $A$.

In figure 3.5 one can see the error that emerges when a vehicle travels on a new road (dotted line) which hasn’t been implemented in the digital road map (solid lines). Another drawback can be the resolution of the digital road map. The resolution of a digital road map is defined by its number of nodes. Low number of nodes results in low resolution and thus in a less accurate digital road map.

As stated in [3], the performance of the algorithm relies on the quality of the digital road map. Accordingly, this can lead to different algorithms perform differently depending on the digital road map.

3.7 The MM algorithm

The vehicle exists in a geographic coordinate system provided by the GPS receiver where latitude and longitude, degrees given in decimal form, determines the position. However the map matching algorithm needs a local metric coordinate system to compute the distances to nearby segments. Hence the coordinates given from the GPS receiver must be transformed before map matching algorithm can perform its calculations.
In figure 3.6 is the GPS position (P) and a link with two end nodes (A and B) are illustrated. These locations are all given in a geographic coordinate system represented by a longitude and latitude coordinate. The transformation equation used to obtain the distance between two locations given in the geographic coordinate system is known as the inverse method in Vincenty’s formulae. It is an iterative method and is accurate to within 0.5mm. For more about Vincenty’s formulae one is referred to [14]. By using Vincenty’s formulae to calculate the distances AB, AP and BP, one can through simple geometric calculations stated by equations 3.1 to 3.3, get the minimum distance (d) from the GPS position (P) to this particular link (AB).

\[
\alpha = \arccos((AB^2 + AP^2 - BP^2)/(2 \times AB \times AP)) \tag{3.1}
\]

\[
\beta = \arccos((AB^2 + BP^2 - AP^2)/(2 \times AB \times BP)) \tag{3.2}
\]

\[
d = AP \times \sin(\alpha) \tag{3.3}
\]

However, from figure 3.7 one can see that the simple geometric calculations does not account for scenarios where the angles β or α is larger than π/2 which will give rise to an error of the minimum distance to that specific link. By observing figure 3.7 one can conclude that the correct minimum distance in this example would be the same as distance BP in such a case.
3.8 The improved MM algorithm

The improved MM algorithm in this thesis uses a fusion of the MM algorithms heading-to-curve with point-to-curve which gives an algorithm where both heading and distance to link is considered when finding the best fitting link. This approach is called point-to-curve-including-heading. The algorithm also uses topology information by looking at the connecting links and uses velocity, provided by the GPS, to test important conditions.

The structure of the algorithm is as follows.

1. The distance to nearby links is calculated as stated in section 3.7.
2. The heading of the link will be compared to the heading from GPS receiver.
3. Each link will be given score depending on the distance and heading differences.
4. The link with best score will be used, and the GPS position will be projected onto that one.

One important condition have been mentioned, where $\beta$ or $\alpha$ were to be larger than $\pi/2$. Another condition is mapping to a link with large difference in heading compared to heading from GPS receiver. This will only allowed if velocity is below a given threshold. Purpose of this condition is to suppress false matches to intersecting links. The following sections will go into detail in the parts 2-4 in the implemented MM algorithm.
3.8.1 Point-to-curve-including-heading

Part 2 of the implemented algorithm compares the heading from the GPS receiver to the heading of the link. Figure 3.8 shows an example of three GPS positions ($P_1$ to $P_3$) that have been mapped to a digital road map.

![Diagram showing GPS positions mapped to a digital road map.](image)

*Figure 3.8. Positions mapped to links using point-to-curve-including-heading. Notice that $P_3$ isn’t mapped to the closest link.*

A minimum difference between heading of the link and heading of the vehicle (from GPS receiver) is desired. If the link is direct connected to the current link, i.e. if the link shares a common node with the current link the heading of the link is known and the difference in heading is thus

$$\Delta \theta = \theta_{\text{GPS}} - \theta_{\text{link}}$$  \hspace{1cm} (3.4)

However, when the link is not directly connected to the current link the heading of the link can be in two directions which have to be accounted for. This is done by using the smaller of the two computed differences. What can be seen in figure 3.8 is that position $P_3$ not have been mapped to the closest link. However at low velocities the GPS heading is not reliable and thus greater heading differences would be allowed.

3.8.2 Link score

Part 3 of the algorithm computes the link score by weighting the difference in heading and distance with weighting constants.
where $D$ is the distance to the link, $\Delta \theta$ is the difference in heading between the vehicle and link, $w_d$ is the weighting factor for distance and $w_{\theta}$ is the weighting factor for heading. Finally, the link with the lowest score will then be chosen. The weighting constants are obtained from statistical analysis from field test data.
4. The State Optimization Signal

This chapter will look into the state optimization signal displayed for the user. The chapter will describe its principles, how it works and how it is connected to the estimation.

4.1 Introduction of state optimization

The implemented state optimization signal has been inspired by the ongoing research within automatic platooning. Platooning and automatic control is a major research field within the Intelligent Vehicle Highway System (IVHS) where one objective is to increase the capacity of the current road network.

The control strategy within the field of automated longitudinal vehicle control can be divided into an upper and a lower control. The upper control makes the decision of what kind of acceleration is desired whereas the lower control then tries to fulfill this demand through adjustments of engine thrust or to use braking.

The upper controller in the developed prototype will be constructed by a Mass-Damper-Spring (MDS) system model with a two-vehicle-look-ahead approach. The lower control will be represented by the human driver who is assumed to try to follow the control signal from the upper controller at best effort.

4.2 The chosen control strategy

The control strategy implemented in the system uses the MDS inspired by [15]. The strategy uses a so called two vehicle look-ahead control strategy where a vehicle will obtain information from both the direct preceding vehicle and the vehicle in front of that, see figure 4.1 for an illustration of the two-vehicle look-ahead approach.
This strategy was chosen because its non-complex computations; it only needs information about speed and position of the two directly preceding vehicles to compute the control signal.

4.3 The MDS two-vehicle look-ahead system

The MDS with the two-vehicle look-ahead approach gives the model illustrated by figure 4.2. In the figure $k_{p1}, k_{p2}, k_{v1}, k_{v2}$ are the coefficients for the spring respectively damper. $x_i(t)$ is the position of vehicle $i$ at time $t$.

From the illustrated MDS model in figure 4.2 one can extract the following equation.

\[ 0 = m_i \ddot{x}_i + (k_{v1} + k_{v2}) \dot{x}_i + \left( k_{p1} + k_{p2} \right) x_i - k_{p1} x_{i-1} - k_{v1} \dot{x}_{i-1} - k_{p2} x_{i-2} - k_{v2} \dot{x}_{i-2} \]  

\[ (4.1) \]

Since the force $F = m_i \ddot{x}_i$ of the vehicle will be determined by the driver one can set $m_i = 1$ and thus only get the desired acceleration as control signal

\[ \ddot{x}_i = (x_{i-1} - x_i)k_{p1} + (x_{i-2} - x_i)k_{p2} + (\dot{x}_{i-1} - \dot{x}_i)k_{v1} + (\dot{x}_{i-2} - \dot{x}_i)k_{v2}. \]

\[ (4.2) \]

However, if also to consider the desired distance to preceding vehicle which is equal to the THW following equation will be obtained
\[ \ddot{x}_i = (x_{i-1} - x_i - h_i \dot{x}_i)k_{p1} + (x_{i-2} - x_i - h_{i-1} \dot{x}_{i-1} - h_i \dot{x}_i)k_{p2} + (\dot{x}_{i-1} - \dot{x}_i)k_{v1} + (\dot{x}_{i-2} - \dot{x}_i)k_{v2} \] (4.3)

where \( h_i \) is the THW of vehicle i. Taking the Laplace transform of equation 4.3 and rearranging the equation gives

\[ X_i = \frac{x_{i-1} - h_i \dot{x}_i}{s(h_i \dot{x}_i + k_{p1} + k_{p2})} + \frac{x_{i-2} - h_{i-1} \dot{x}_{i-1} - h_i \dot{x}_i}{s(h_i \dot{x}_i + k_{p1} + k_{p2})} \] (4.4)

If then the following condition is fulfilled

\[ \frac{k_{p1}}{k_{v1} + k_{p2}h_i} = \frac{k_{p2}}{k_{v2}} = \frac{k_{p1} + k_{p2}}{h_i} \] (4.5)

the equation can be further simplified to

\[ X_i = \frac{x_{i-1} + x_{i-2}}{s(h_i \dot{x}_i + k_{p1} + k_{p2})} \] (4.6)

which is stable since \( h_i, k_{p1} \) and \( k_{p2} \) are all positive.

If only two vehicles exists in the group the two-vehicle look-ahead approach is impossible and therefore equation 4.6 becomes

\[ X_i = \frac{x_{i-1}k_{v}}{s + kh_i} \] (4.7)

which is the one-vehicle look-ahead approach where

\[ \frac{k_{p2}}{k_{v2}} = k_{v} = \frac{1}{h_i} \] (4.8)

### 4.3.1 Setting the coefficients

For a fast response in the MDS system the \( k_{p2} \) coefficient should be as high as possible [15]. However from equation 4.5 following limit can be concluded

\[ k_{p2} \leq \frac{1}{h_i^2 + h_i h_{i-1}} \] (4.10)

Thus \( k_{p2} \) is set to maximize the limit given in 4.10. The other coefficients can then be extracted from equation 4.5 which gives following equations.

\[ k_{v2} = k_{p2}h_i \] (4.11)
For the one-vehicle look-ahead scenario the coefficient are obtained through equation 4.8.

4.4 Estimation

Used in equation 4.3 is the distance between vehicles. However, because of the delay caused by the communication channel these distances need to be estimated.

To be able to get a good output from the estimation one need to define what is to be estimated. Since the purpose of the system is to give guidance to a driver, the assumption have been made that the GPS receiver is located in the front of the vehicle as seen in figure 4.3. The distance between two vehicles is however from the preceding vehicles rear end and the front of the following vehicle. Accordingly system has to estimate where the preceding vehicle ends and the following begins based on the position of the device.

![Figure 4.3. Model of the distance between vehicles.](image)

Since the length of a vehicle can vary from vehicle to vehicle the system needs user input. The user will be able to choose between some different common lengths or types of vehicle. This will however not provide a perfect solution and hence give rise to an error between the estimated distance between vehicles and true distance as illustrated by figure 4.3. From the figure the following equations can be extracted.

\[
distance_{receivers} = \rho + \gamma + \delta \quad (4.14)
\]

Length of leading vehicle is

\[
Length_{leading} = \sigma + \rho \quad (4.15)
\]
and true distance is

\[ \text{distance}_{\text{vehicles}} = \gamma \]  \hfill (4.16)

Approximated length of leading vehicle is given by user and assumed to be

\[ \hat{\text{Length}}_{\text{leading}} = \text{Length}_{\text{leading}} + \epsilon \]  \hfill (4.17)

where \( \epsilon \) is the error between the true length of the vehicle and the approximation made by user input. Approximated distance between vehicles is thus

\[
\hat{y} = \rho + \gamma + \delta - \hat{\text{Length}}_{\text{leading}} \\
= \gamma + \delta - \sigma - \epsilon
\]  \hfill (4.18)

The estimated distance using linear interpolation will then be given by equation 4.19

\[ \hat{d} = d + v_{i-1} \times \Delta t \]  \hfill (4.19)

where \( d \) is the distance between vehicles computed using Vincenty’s formulae and \( \Delta t \) is the difference in timestamps provided with the GPS positions. \( \hat{d} \) is the estimation used in equation 4.3.
5. Results and analysis

This chapter will present results verifying the performance of the different parts of the developed prototype.

5.1 Map-matching

The performance of the MM algorithm is measured by counting the number of matches onto false links. This is done by manual analysis of recorded data. A minimum of false matches is preferred. The figure 5.1 illustrates the performance of the implemented MM algorithm and figure 5.2 the performance of a simple MM algorithm.

![Figure 5.1. The mapping of real GPS positions using the implemented MM algorithm](image)
What can be seen in the figures above is the improved performance of the implemented MM algorithm which uses heading and distance to choose the correct link. During a two hour long field test the following result, in table 5.3, was collected.

<table>
<thead>
<tr>
<th>Sample set</th>
<th>Total matches</th>
<th>False matches</th>
<th>Percentage correct matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1. Large road, flat landscape.</td>
<td>220</td>
<td>2</td>
<td>99%</td>
</tr>
<tr>
<td>S2. Large highway and a large road</td>
<td>995</td>
<td>90</td>
<td>91%</td>
</tr>
<tr>
<td>surrounded by buildings.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3. Large highway.</td>
<td>426</td>
<td>15</td>
<td>96.4%</td>
</tr>
<tr>
<td>S4. Large highway.</td>
<td>681</td>
<td>36</td>
<td>94.7%</td>
</tr>
<tr>
<td>S5. Large highway</td>
<td>667</td>
<td>63</td>
<td>90.6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2334</strong></td>
<td><strong>206</strong></td>
<td><strong>91.2%</strong></td>
</tr>
</tbody>
</table>

Table 5.3. Performance of the MM algorithm during a field test.

The sample set S1 has been recorded on a large road with open sky. The false matches can largely be attributed to low velocity driving which gave poor outputs from the GPS receiver. Sample set S2 was recorded part on a large highway, part in large road surrounded by buildings. Almost all false matches were made on the large road where GPS gave poorer performance due to the buildings. The false matches at the large highway of S2 occurred at highway exits where the MM algorithm had a hard time deciding between links because of the small differences distance and heading of these. Sample set S3, S4 and S5 were recorded on a
highway and should give good results, however in S3 there were a group of samples after exiting the highway that accumulated a lot of false matches.

According to [3] the percentage of correct link matches ranges from 86 to 99. However, if one is only to consider map matching algorithms using data from only GPS receiver, two papers have performance above 90, [16] at 91.7% and [17] at 96%. However, through finer tuning of the implemented map matching algorithm it is believed for it to also reach such results.

5.2 State optimization signal

To verify the performance of the state optimization signal the MDS control strategy using two-vehicle look-ahead have been simulated in MATLAB. Figures 5.4 and 5.5 illustrate the results from this simulation. Figure 5.4 illustrate the velocity of the vehicles at different times and figure 5.5 are the relative distances to preceding vehicle for each vehicle. In the simulation the stability of the system where tested when lead car accelerated two times and then had a sudden brake, for example trying to avoid a collision with an animal.

![Figure 5.4. Velocity-time diagram of vehicles with the MDS control](image-url)
One can see that no oscillations occur and that the relative distance never goes below zero which would have represented a collision. This validates that the stability is kept. However, the simulation assumes that recommended accelerations are followed perfectly. This will not be the case in real world where the driver is a part of the control loop and thus can create instability by not following the recommend acceleration.

5.3 Communication channel
An important effect of the communication channel on the developed system is the delay. A large delay will have greater impact on the overall system since the uncertainty in the estimation will increase with time. The real-time implementation shows that the communication channel gives a delay around 500ms but spikes going over 2000ms are common. These spikes may cause poor performance of the estimation, especially at unsteady states and thus have a negative effect on the user perceived experience of the prototype.

5.4 Overall prototype performance
The developed prototype had no problem running on the test device, see appendix 9.1 for specifications. The prototype was tested with two vehicles during a field test. During this field test, vehicles were able to dock and build platooning groups. The system could sense when a vehicle left the platoon and take action thereafter. The overall experience from this field test was that the prototype gave best performance at stable states and not to low velocities, 30km/h and above.
An interesting observation was that the prototype never recommended the driver to decrease the acceleration, for example when approaching the preceding vehicle at a traffic light. The conclusion from this is that the human driver keeps a safer distance to the vehicles than what is recommended by the system.
6. Conclusions

This chapter will present the conclusions that can be drawn from the work done and presented throughout this paper.

The prototype developed in this thesis has used techniques from different fields of research. A MM algorithm has been implemented to improve and stabilize the vehicle positioning from GPS. The enhanced positioning is then used in the state optimization signal which has been inspired by the research field of platooning. The implemented state optimization uses a MDS with two-vehicle look-ahead approach.

Also since the system uses the smartphone-provided communication channel a delay will arise which needs to be considered. This problem has been dealt with through the estimation using linear interpolation.

The developed prototype can sense when other vehicles are approaching and take action thereafter. Dock or split to/from a group of vehicles and merge two groups of vehicles are possible scenarios that can be deployed.

It has been proven that a vehicle state guidance system for driver using GPS aided smartphones can be developed and give satisfying performance during a field test, e.g. the prototype gave information about the recommended acceleration in which users experienced as reasonable. Though, further research is needed to conclude if the developed system truly can increase traffic flow.
7. Future work

This chapter will present some different techniques that have the possibility to improve the overall system performance and thereby the developed prototype.

7.1 Dedicated communication
One of the problems stated in the report is the delay caused by the communication channel. A possible approach to solve this problem is to use the integrated WLAN found in most smartphones to create a direct channel between devices in neighboring vehicles. This could significantly decrease the delay and thus remove the need for estimation in the system.

7.2 Local radio to improve positioning
Today it is common to use WLAN signals to position devices. By measuring the signal strength of the WLAN connection between vehicles one may get additional information that could be used to estimate the distance between devices and thus enhance the position estimates of vehicles.

7.3 Additional sensors
A common approach to improve the MM algorithm is to use additional sensors. As seen in [4] one could use an odometer which gives additional information about the traveled distance. Such additional information could be used in a Kalman filter to give better positioning performance. Also gyroscopes or accelerometers, which often are built-in in smartphones, could be used as such additional information.

7.4 Improved estimation
The estimation implemented in the system gives best performance at steady states. At unsteady states, e.g. during acceleration or retardation of other vehicles the estimation will give less accurate results. Thus an improved estimation would be preferred in future improvements of the system.

7.5 HMI
An important task that hasn’t been investigated during this thesis is the HMI perspective. This is of major importance if the system would become more than just a prototype.
8. Bibliography


9. Appendix

9.1 Hardware

The hardware used to run the system is an HTC android smartphone with the following specifications:

- Model name: Desire
- Screen:
  - Size: 3.7 inches
  - Resolution: 480x800 pixels
- OS: Android 2.2
- Communication: UMTS with HSDPA 7.2mbit/s and HDSUPA 2mbit/s, EDGE, GPRS, GSM (QUAD)
- CPU: 1Ghz Single-Core Qualcomm Scorpion
- GPU: Adreno 200 (AMD z430)
- RAM: 576 MB
9.2 Mode states switches

The figure A1 shows the different application working modes and how these are connected, e.g. how transitions between the modes can occur.

The three main modes which the application can work in are single (represented by S in figure A1), member (M) and leader (L). Except for the main modes, also four transitions mode have been illustrated. These are the unconfirmed member (UM), unconfirmed leader (UL), unconfirmed leader and unconfirmed member (ULUM), leader but unconfirmed member (LUM). Figure A1 also shows which modes require high frequency updates from server and
GPS to give good performance. Table A2 shows the scenarios representing the transitions between the different modes illustrated in figure A1.

<table>
<thead>
<tr>
<th>Transitions</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Member splits from group with no vehicle behind.</td>
</tr>
<tr>
<td>b</td>
<td>Single vehicle start docking process to single vehicle or group of vehicles.</td>
</tr>
<tr>
<td>c</td>
<td>Vehicle fails with the docking process and has no vehicle behind.</td>
</tr>
<tr>
<td>d</td>
<td>A following vehicle fails with the docking process.</td>
</tr>
<tr>
<td>e</td>
<td>A following vehicle begins a docking process.</td>
</tr>
<tr>
<td>f</td>
<td>A leading vehicles split from group.</td>
</tr>
<tr>
<td>g</td>
<td>When in docking process get a following vehicle that begins docking process.</td>
</tr>
<tr>
<td>h</td>
<td>When a following vehicle is in docking process and own docking process to preceding vehicle begins.</td>
</tr>
<tr>
<td>i</td>
<td>When in docking process with an following vehicle which fails with its docking process.</td>
</tr>
<tr>
<td>j</td>
<td>When a following vehicle in docking process and then fails with own docking process.</td>
</tr>
<tr>
<td>k</td>
<td>When docking process succeeds.</td>
</tr>
<tr>
<td>l</td>
<td>When a following vehicle in docking process and succeeds with own docking process.</td>
</tr>
<tr>
<td>m</td>
<td>When in docking process and following vehicle succeeds with its docking process.</td>
</tr>
<tr>
<td>n</td>
<td>When the following vehicle succeeds with its docking process.</td>
</tr>
<tr>
<td>o</td>
<td>When as a leader fails with own docking process.</td>
</tr>
<tr>
<td>p</td>
<td>When as a leader succeeds with own docking process.</td>
</tr>
<tr>
<td>q</td>
<td>When as a leader begins docking process.</td>
</tr>
<tr>
<td>r</td>
<td>When as a member splits from group but have confirmed vehicle behind.</td>
</tr>
<tr>
<td>s</td>
<td>When as a member splits from group but have a following vehicle in docking process behind.</td>
</tr>
</tbody>
</table>

Table A2: The table shows what kind of scenarios the different transitions from figure A1 corresponds to.
Figures A3 and A4 shows the flowchart diagrams of the implemented algorithms that control the transitions between modes.

Figure A3. Flowchart diagram of how the android implemented application decide when to switch mode from Member mode to Leader or Single mode.
Figure A4. Flowchart diagram of how the android implemented application decide when to switch mode from Single/Leader mode to Member mode.