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Assessment of a signalized cross intersection optimized by GPS data through V2I connection

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Abstract

The main objective of this work is to analyze the influence of the positioning data errors of connected vehicles in the transmission of information to the controllers of a signalized cross intersection. Taking into account that the arrival of 5G allows the transmission of massive data in an efficient way, this research focuses on comparing the accuracy of the geolocation data of devices that could be found in connected vehicles such as (i) High Accurate GPS devices (negligible positioning errors); (ii) Standard GPS devices (positioning errors greater than one meter); and GPS incorporated in mobile phones (major total positioning errors). For this, three one-hour simulations have been carried out in the VISSIM microsimulation software for the following proposed traffic scenarios: (1) low demand level; (2) approach to congestion of the intersection; and (3) over-saturated intersection. To evaluate and compare the influence of the accuracy of GPS devices in different scenarios, two controllers have been used, which are the queue length of vehicles at the intersection and the number of vehicles that access the intersection at each approach.

Resumen

El objetivo principal de este trabajo es analizar la influencia de los errores de datos de posicionamiento de vehículos conectados en la transmisión de la información a los controladores de una intersección en cruz semaforizada. Teniendo en cuenta que la llegada del 5G permite la transmisión de datos masivos de una manera eficiente, esta investigación se centra en la comparación de la precisión de los datos de geolocalización de dispositivos que podrían hallarse en vehículos conectados como son (i) dispositivos GPS de alta precisión (errores de posicionamiento despreciables); (ii) dispositivos GPS convencionales (errores de posicionamiento mayores que un metro); y (iii) dispositivos GPS incorporados en teléfonos móviles (errores de posicionamiento total mayores). Para ello, se han llevado a cabo tres simulaciones de una hora en el software de microsimulación VISSIM para los siguientes escenarios de tráfico propuestos: (1) bajo nivel de demanda; (2) aproximación a la congestión de la intersección; y (3) intersección sobresaturada. Para evaluar y comparar la influencia de la precisión de los dispositivos GPS bajo los diferentes escenarios se han empleado dos controladores, que son la longitud de cola de vehículos en la intersección y el número de vehículos que acceden a la intersección por cada ramal.

Acknowledgements

I would like to thank Professor Claudio Roncoli and D.Sc. candidate Roozbeh Mohammadi for hosting me and allowing me to carry out my Master Thesis abroad in Aalto University and for their good guidance and help given throughout the achievement of this research. It has been a great and challenging opportunity to overcome myself because I have never worked in an English environment or written and presented a project of these characteristics in English. None of this would have been possible to achieve without them.

I also want to mention Professor David Llopis Castelló and Professor Francisco Javier Camacho Torregrosa for being my home university support, adding their point of view and giving some ideas to improve the work.

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Héctor Del Pino Verona

Contents

List of Figures

List of Tables

Abbreviations and acronyms

2D	2-Dimension
3D	3-Dimension
ADAS	Advanced Driver-Assistance Systems
A-GPS	Assisted Global Positioning System
ALLONS-D	Adaptive Limited Look-ahead Optimization of Network Sinals Control Decentralized
AV(s)	Automated Vehicle(s)
BP	Back-Pressure
CACC	Cooperative Adaptive Cruise Control
CAV(s)	Connected and Automated Vehicle(s)
CORS	Continuously Operating Reference Stations
CV(s)	Connected Vehicle(s)
GA	Genetic Algorithm
GLOSA	Green Light Optimized Speed Advisory
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System Mobile
HCM	Highway Capacity Manual
hEART	European Association for Research in Transportation
HOV	High Occupancy Vehicles
I2I	Infrastructure-to-Infrastructure
IGS	International GNSS System
LOS	Level of Service
LWR	Lighthill-Whitham-Richards
MINLP	Mixed-Integer Nonlinear Program
MP	Max-Pressure
MPC	Max-Pressure Control(ler)
MOVA	Microprocessor Optimised Vehicle Actuation
NEMA	National Electric Manufacturers Association
NRTK	Network Real-Time Kinematic
OPAC	Optimized Policies for Adaptive Control
RAIM	Receiver Autonomous Integrity Monitoring
RAM	Random-Access Memory
ROW	Right-of-Way
RTK	Real-Time Kinematic
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split, Cycle and Offset Optimization Technique
SPS	Standard Positioning System
STM	Signal Timing Manual
SVCC	Signal Vehicle Coupled Control (SVCC)
TRANSYT	Transit Network Study Tool
VST	Vehicle-based Signal Traffic
V2C	Vehicle-to-Cloud
V2D	Vehicle-to-Devices
V2I	Vehicle-to-Infrastructure
V2S	Vehicle-to-Sensor
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

1 Introduction

Intersections, unlike interchanges, have always been a challenge within cities because they are network points where traffic flows are mostly interrupted. It is where all traffic modes which share the same Right-of-Way (ROW) converge and conflicts begin to appear. This usually causes delays in travel times and increases fuel consumption and greenhouse gases emissions.

Indeed, as seen in Figure 1, four-leg intersections have 32 possible conflict points, where 16 are due to crossing, 8 to merging and 8 to diverging. On the other hand, roundabouts are also a good option to avoid those conflicts with only 8 in total, 4 due to diverging and 4 to merging. However, these solutions require bigger surfaces and therefore are more commonly used in suburban or interurban spaces.

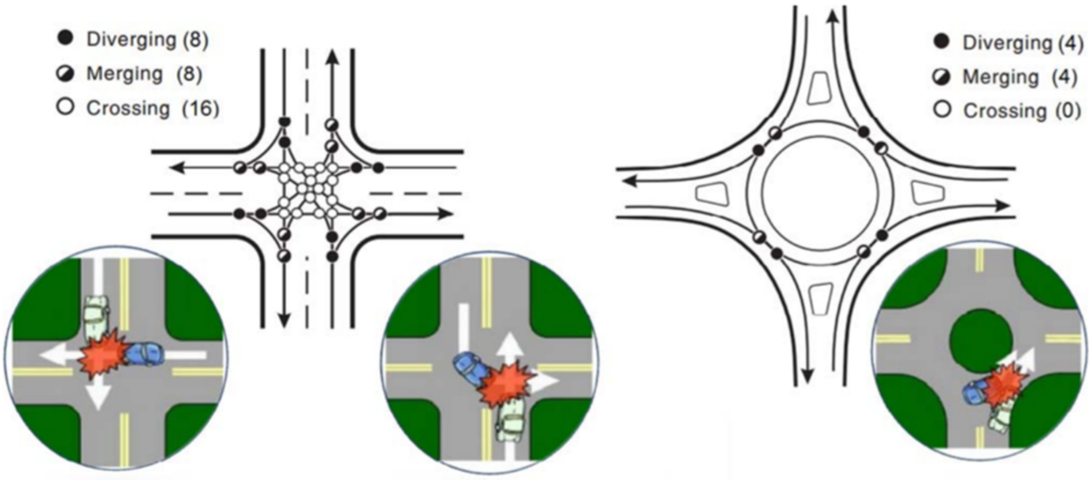

Figure 1: Conflict points in a four-leg intersection versus a roundabout [1]

Once conventional priority rules get overwhelmed by traffic volumes in urban intersections, traffic signals try to solve the conflict issue. Traffic signals controllers have been developed and improved to maximize vehicle throughput, but it has not been until recently when connected vehicles (CVs) have been taken into account for it. In that sense, CVs present an opportunity to give almost instant data to the signal control without relying on infrastructure detectors and following estimations.

Although many efforts have been made in theoretical simulation environments, it has never been considered how errors of the positioning might affect the results of those researches. The goal of this thesis is to discuss and reach a conclusion about whether this is something to be considered in the future or the impact is not that important after all.

1.1 Research objectives

This research started by reviewing a paper called "Sensitivity analysis on information quality for signalized traffic control" presented on a European Association for Research in Transportation (hEART) 2019 symposium. In this paper, disturbances in data for input quantities are measured to get how sensitive it can be for a phase-based predictive controller in under-saturated and saturated conditions. Simulations showed that when errors were increased, the performance of the controller was decreased [2].

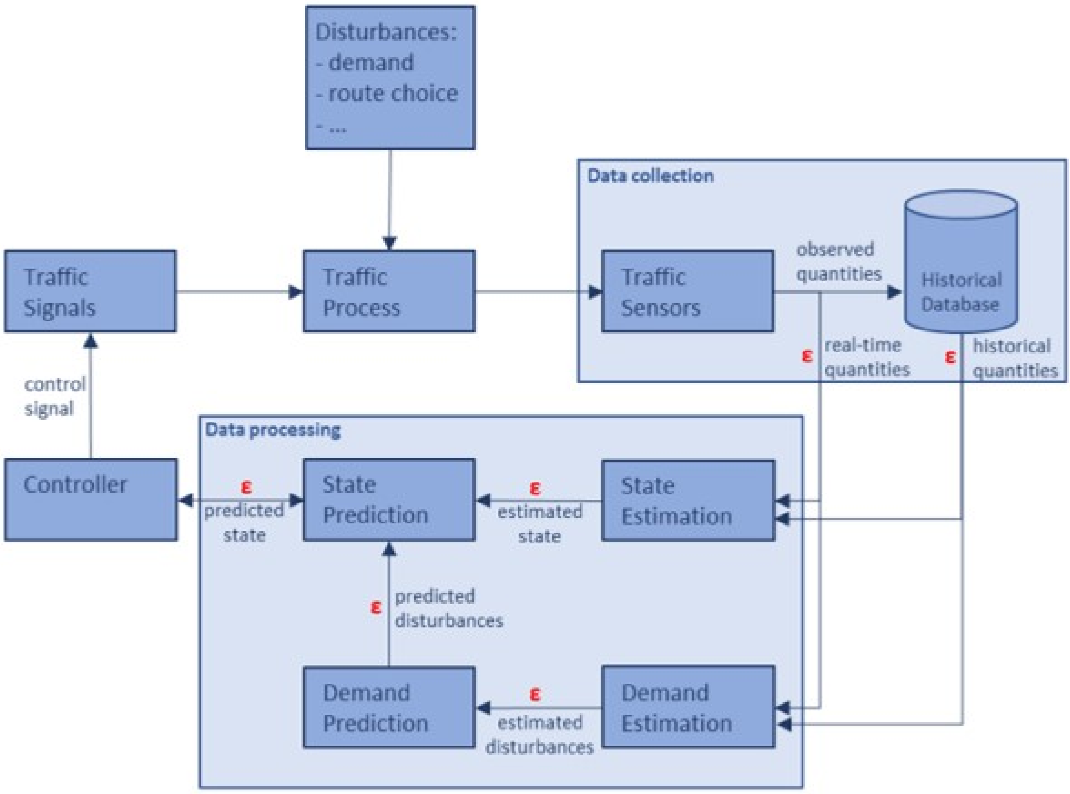

Figure 2: Scheme of the signalized traffic control proposed by the above paper [2]

The idea was moved towards a CV environment since they can potentially bring some benefits such as safety with Advanced Driver-Assistance Systems (ADAS) or efficient driving with best optimal route calculations for fuel consumption and emissions reduction (e.g., avoiding traffic jams, driving through many green lights at a certain speed, ...). In brief, CVs technology can improve throughput and travel time reliability by eliminating the cost and performance limitations of human drivers and increasing the communication between drivers, infrastructure and travelers. However, they may also have some disadvantages which could be privacy and hacking issues, higher prices of acquisition and maintenance, obsolescence or driver-vehicle behavior interactions, which may be expected to change, among others. Besides, they can spread some errors in the position that may affect other vehicles or signal controllers.

As regards the signalized level crossing problem, it has never been studied how errors in data sent by their equipped Global Positioning System (GPS) may have an impact on the throughput of the intersection. Therefore, the main goal of this work is to assess how errors applied in data positioning systems can affect the performance of traffic signal controllers in a cross intersection in a CV environment.

A High Accurate GPS, a common GPS and a mobile GPS have been tested with their respective errors found in the literature in under-saturated, saturated and over-saturated traffic flow conditions with fixed cycle times. The two signal strategies used are a Maximum Pressure Controller (MPC) and a Vehicle-based Signal Traffic (VST) control.

As a consequence of the results and the framework carried out, it will also be possible to decide which controller is more efficient without and considering errors and also determine whether mobile GPS can be feasible to use as a reliable source of input data instead of a car equipped GPS or not. Though the framework of the simulations has been reduced to a very basic and simple state to simplify the problem and the code and to reduce computational times, it has been considered that the outline of the work can be expanded towards a more realistic simulation. Therefore, only one type of car has been considered and neither public transport systems, heavy traffic nor pedestrians have been included. Transmission speed errors have not been considered either.

The main purpose of this research is to find out whether signalized traffic control strategies can properly work with the data that can be provided by CVs or not. Then some of the following questions can also be discussed in Section 6:

1. Which controller has the best performance overall when errors in position are added?

2. How sensitive are the presented signal control strategies to these errors?

3. Would it be possible to rely on GPS that generate such type of errors?

1.2 Structure of the thesis

This document is organized as follows in 7 sections. Section 1 is this introduction of the topic and the purpose of the work, section 2 will present the background and will deepen in previous literature related with the work, section 3 will explain the methodology applied, section 4 will show the simulations setup, section 5 will comment the obtained results, section 6 will contribute some discussion of the results and limitations of the framework and section 7 will conclude with a summary of the work done and future possible research extension. Afterward, references can be found and more detailed results tables will be attached in the appendix section A and section B.

2 Background

2.1 Traffic signal control

Traffic flow has always been an issue and a concern for society since it affects the majority of the population. It is fairly known that traffic causes some social, economic and environmental externalities costs (e.g., construction, maintenance, growing traffic congestion, accidents, pollution, etc) that have always been wanted to be reduced as much as possible.

Intersections are known as the bottlenecks of urban roads because their capacity is mostly equal to one-quarter of the maximum traffic flow that can suit each approach of a standard four-legged intersection [10]. Hence, for safety and operational purposes, traffic needs to be controlled at intersections. This can be done by using priority rules (yields or stops signs, roundabouts, right-before-left, ...) or by implementing traffic lights.

2.1.1 Brief history

Traffic signal lights have existed for almost 150 years when the first mechanical and two-color (red and green) gas-powered semaphore prototype was installed in London in 1868 [11] to solve this mischance. Those signals were operated manually by police officers and therefore they were not very convenient because of the lack of automatic control.

Then, in order to relieve police officers, electromechanical traffic signals were installed first with automatic phase switching and then with coordination with other signals in the USA in 1926 [12]. Finally, it was in the late 1960s when computer-controlled signals were first introduced [13].

The standardization of traffic signals began in the early 1920s [14] and continued until the standardization of the National Electrical Manufacturers Association (NEMA) in 1976 [15].

2.1.2 Basic signal timing methods

Signal controllers are the components of the traffic signal control whose purpose is to interpret the demand at a local intersection and to relate with the rest of nearby controllers [3].

Figure 3: Types of Signal Control [3]

Depending on the type of external input that controllers utilize, some types of signal control are defined as shown in Figure 3. They can be classified not only by how they obtain data but also by how they interpret the input data. Currently, there exist 3 types of traffic control systems:

- Fixed-time.
- Actuated.
- Adaptive.

2.1.3 Coordination

Traffic signals can be coordinated along a corridor to provide a continuous green phase and somehow generate platoons of vehicles at a certain speed [16]. This works either for a fixed time or actuated and adaptive control [3] but in both cases, every signal has the same cycle length [13].

Coordinated methods can be centralized, meaning that their optimization problem is formulated by summing all the objectives of the intersections or defining the same objective, or they can be decentralized or distributed, where it is assumed that the traffic information of the nearby intersections is known as an input data. The latter can reduce computation burden but can be less effective to achieve the expected optimization [6].

2.1.4 Fixed-time control

Fixed-time control strategies were developed between 1920 and 1980 [17]. They use the data collected along the history of the traffic flow to generate static timings for each phase depending on the day or the time of the day. This means they have predetermined plans based on average flow. Their strategy is cyclic because they serve each traffic phase in a particular order [13].

Fixed time plans allow to generate green waves, give some priorities predetermined and bring effective responding to special events that can be previously predicted

[17]. These are the least expensive to implement because they do not have any costs associated with demand detection and thus have lower maintenance costs [3].

However, even if it is assumed that traffic demand does considerably remain akin, this really can relatively and quickly change [18] which is fine for under-saturated conditions but may be inefficient in other cases. Furthermore, they can not respond to unplanned incidents like accidents or road works [17].

One of the most widely used fixed time traffic control is the Traffic Network Study Tool (TRANSYT) [19]. It still has modern use and it assumes that the flow is known and constant for a certain period. Then, it calculates timings offline according to historical measurements to generate optimum plans for each moment of the day during the week. It is used typically for isolated intersections but can also be accommodated to coordinate sequential junctions [17].

2.1.5 Actuated control

Actuated control systems have been developed since the 1970s until present [17]. Actuated control tries to tackle the real-time issue by collecting data from infrastructure detectors (e.g. loop, video, infrared or radar detectors among other) [3]. Detection systems usually collect data upstream of junctions so that vehicles are detected with enough time to react and, that way, traffic signals can get triggered by vehicles present at the junction [17]. After detecting the volume of traffic, it assigns green times according to some predetermined plans that have been stipulated and programmed beforehand [3].

An advanced vehicle actuated controller is the Microprocessor Optimised Vehicle Actuation (MOVA). It takes data from lane-by-lane detectors and controls signal timing to minimize vehicle delays and stops. However, MOVA is not exploiting the full potential because it does not consider surrounding junctions [17].

2.1.6 Adaptive control

On the other hand, although sometimes it is also referred to as actuated, adaptive control proceeds in the same way, but the main difference between both is that it makes use of algorithms to calculate and adjust the parameters for the current conditions [3]. Skipping a phase without vehicles queuing or shorting a green phase if no vehicles are approaching detected are two of the most significant adjustments in actuated controllers [13]. However, currently, the most used adaptive signal control systems rely on data from the infrastructure, causing two main limitations, one is that we can not provide a direct measurement of location, speed or acceleration of vehicles and other is that installation and maintenance cost of detection devices are considerably high [18].

Adaptive control strategies can be sorted into two groups: cyclic and acyclic systems. The difference is that cyclic systems have phases with an established order whereas acyclic do not [13].

For instance, a cyclic strategy is the Sydney Coordinated Adaptive Traffic System (SCATS), developed in the 1970s and implemented in Sydney in 1983, measures the traffic demand from stop-line detectors to assign best cycle length, phase split and offset based on the saturation of an intersection [20]. Another one is the Split, Cycle and Offset Optimization Technique (SCOOT) which has upstream detectors that predict arrivals vehicles and then an optimization in real-time to minimize delays, queue lengths and stops [21].

Acyclic strategies are more recent than the latter. In 1997, the Adaptive Limited Look-ahead Optimization of Network Signals Decentralized (ALLONS-D) was first published. Its objective was to minimize an objective function in a short time horizon of five to fifteen seconds. It requires real-time vehicle arrivals and queue lengths estimated with detectors cite [22]. Another example of acyclic signal control is the Optimized Policies for Adaptive Control (OPAC) developed for non-congested and congested regimes with a limit of three-phase switches over the horizon [23].

Returning to cyclic strategies, one of the most used is the Max-Pressure (MP) or Back-Pressure (BP) policy for the control in signalized intersections. It determines at the beginning of each cycle, which has a fixed length, the green times allocated for each phase based on queue measurements. It is known as a decentralized policy due to calculations only depend on queue lengths adjacent to the intersection, whilst centralized policies consider all intersections [24]. This makes it a simple controller to implement thanks to the lower communication requirements and lower computational burdens [25].

Another thing that characterizes MP is that it is very stable if external arrivals and turn ratios are stationary, even though external arrivals are unknown. Therefore, it can easily adapt to slow changes in demand patterns [24]. Some further experiments have consolidated the theoretical argument of the stabilization of networks [26]. The only variables that are required are turn ratios and saturation flow rates, but these can be estimated [25].

In 2014, the queuing network was stabilized by a BP algorithm through queue length estimations [27]. It was one of the first precedents to open new doors to new developments in the context of wireless communication.

In 2015, one of the first adaptive queue estimations algorithms was presented, since until then, most were applied to pre-timed signals. It was able to estimate queue length without traffic volume, queue length and signal timing as input data both in under-saturated and saturated conditions. However although it works with different penetration ratios, a shortcoming is that it needs to have that information previously [28].

In the same year, two signal BP control were developed but in this case trying to solve the hypothetical wrong assumption of infinite queue length. In this case, the proposed models were outperformed by regular fixed and actuated signal control strategies. This is because usually it is assumed that there do not exist field-like conditions with queues constrained by the intersection capacity [29].

In 2017, some previous work was adapted to current time BP control to consider bounded queues constraints too. Here the issue of congestion propagation was solved by normalizing pressure functions and thus ensure work-conservation [4]. However, this controller only considered queue lengths and not vehicle delays, which could lead to a "last packet problem", where the last packet of flow does not detect new subsequent packet arrivals, remaining the queue very small and persistently giving more priority to the rest of the approaches. In that case, a delayed-based BP is proposed in [30] to deal with this problem and remove excessive delays while keeping stability. One particularity of this controller is that it changes phases without any sequence, which can be harmful to drivers' behavior or may make them change the chosen route [4]. This can be less shocking in fixed-cycle BP control like in [31].

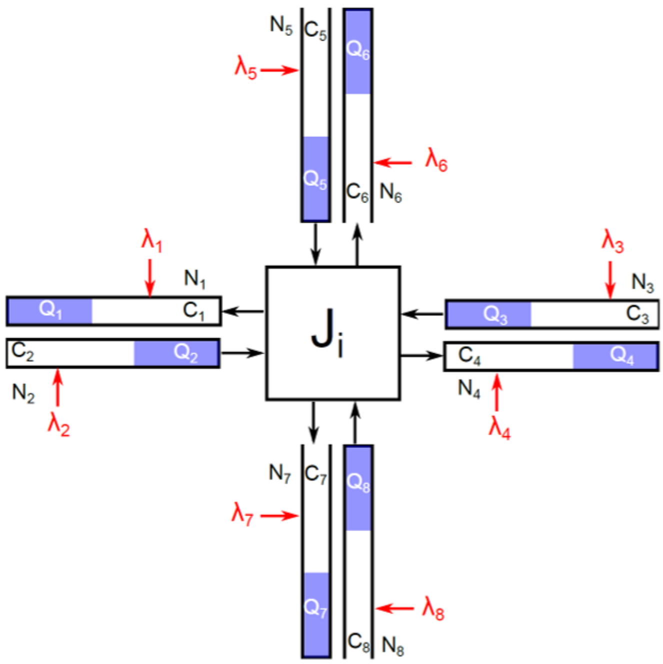

Figure 4: Intersection with a Back Pressure Controller [4]

Some other approaches have been proposed to help traffic signal intersections managing traffic. For instance, some strategies like throughput maximization, queue balancing, negative offset, metering and gating have been studied and utilized to improve the intersection capacity and thus reduce congestion and residual queues [32]–[33]–[34]–[35].

In any case, these control strategies are still restricted to some parameters, such as minimum and maximum green times, even when they adapt to demand changes. Besides, they still rely in fixed sensors, which can only provide data measured at discrete spatial points [36] and afterward they will have to estimate the vehicle's position after passing the detector, queue length and vehicle speeds among others [6]. Hence, there is still a margin to improve the throughput of the traffic operations in a signalized intersection by approaching a better traffic demand [37].

2.1.7 Ring-barrier control

The ring-barrier controller is currently one of the most used methods for defining how a controller organizes phases, even in actuated and adaptive traffic control scenarios [18]. This phasing method from the NEMA separates conflicting movements and sets the phases of the intersection so that compatible phases can time together and conflicts do not happen. It is based on two rings with dual compatible non-conflicting movements separated by two barriers to avoid conflicting movements at the same time (see Figure 5). The barrier is the moment in the cycle when a phase in each ring has ended so that both rings must cross the barrier simultaneously. Usually, these barriers separate major and minor street flows phases [3].

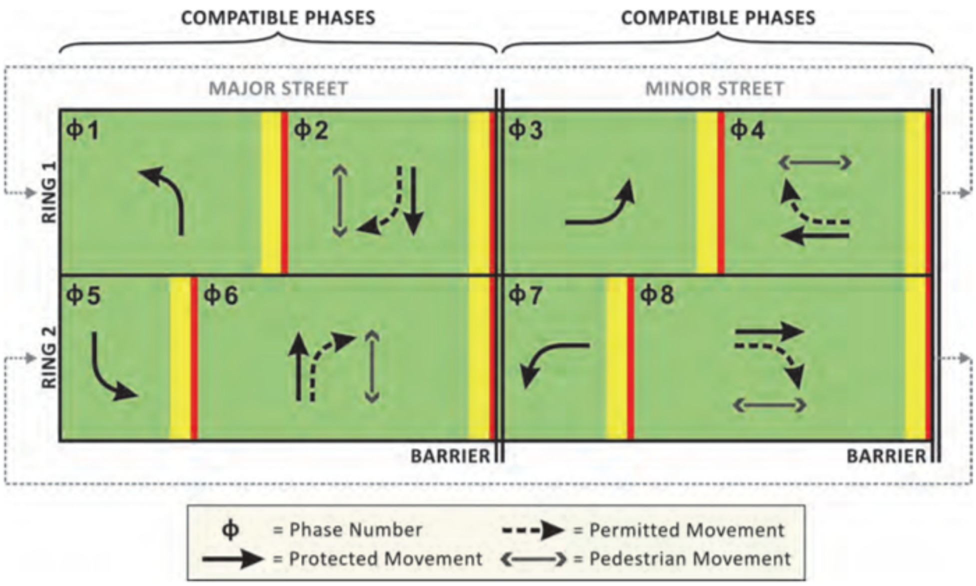

Figure 5: Basic Ring-and-Barrier Diagram [3]

It is considered that dual-ring barrier structure is more commonly used in North America so that although it is the base of the controllers that we are using in this thesis, it would be interesting to model other signal control like stage based controllers, more widely used in Europe [18].

2.2 Connected and Automated Vehicles

In that sense, connected and automated vehicle (CAV) technology is like a breath of fresh air to alleviate traffic congestion through intelligent management of traffic control [38] and to improve road safety via driving assistance and onboard advanced warning systems [39]. Indeed, they can solve the issue of detection and estimation by receiving real-time data instead.

Automated vehicles can react in an almost instantaneously way to any change in the driving environment. Analytical studies have revealed that they can improve throughput, string stability of traffic flow and shockwave formation and propagation [40].

One thing that has permitted the implementation of those modern systems are wireless connections, either vehicle-to-cloud (V2C), vehicle-to-infrastructure (V2I), vehicle-to-sensor on-board (V2S), vehicle-to-vehicle (V2V) or vehicle to handheld devices (V2D), such as smartphones from pedestrians or cyclists, or vice versa. In short, those vehicle-to-everything (V2X) connections are expected to be the next frontier for the automotive revolution. This way, vehicles can get proactive, cooperative and coordinated to improve road safety, smart and green transportation [5].

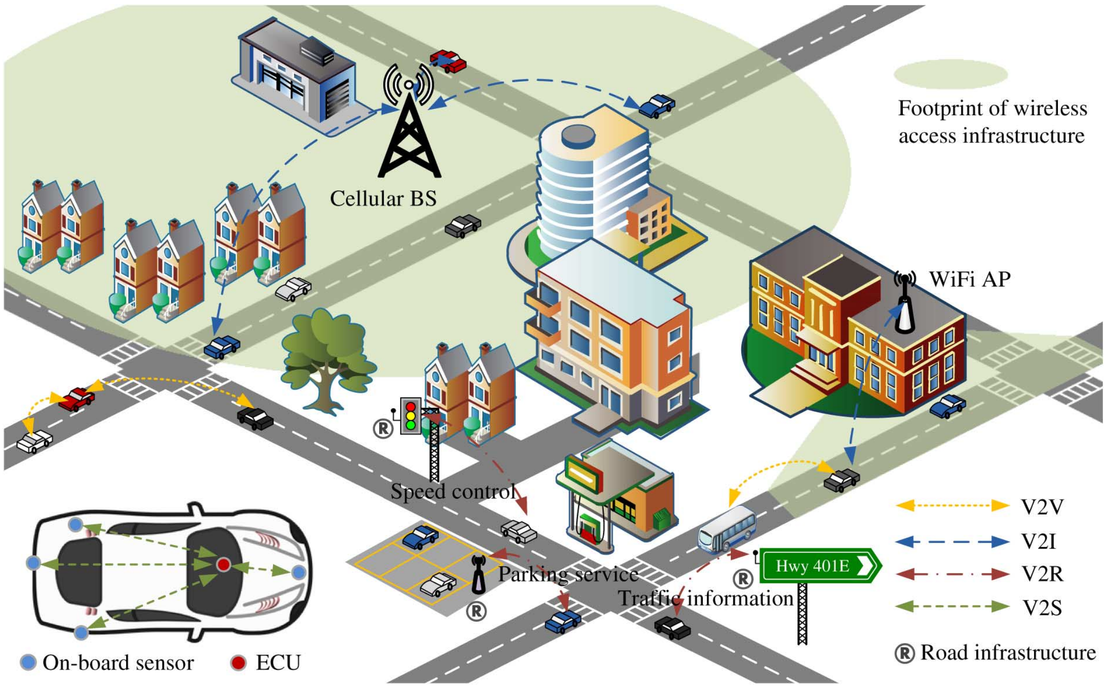

Figure 6: Overview of connected vehicles [5]

This makes an interesting move for signal controllers, which now can easily receive measures that were previously unknown or estimated, such as vehicle speeds, positions, traffic arrival flows, acceleration and deceleration rates, queue lengths, delays, number of users or fuel and energy consumption among others.

Furthermore, it has been demonstrated that intersection capacities can be increased two or three times if vehicles stay organized in platoons with the same speeds and headways when crossing the intersection. However, this is mostly impossible to achieve without the Cooperative Adaptive Cruise Control (CACC) which allows vehicles to move together after being stopped with considerably short headways [41].

Nowadays, the capacity and speed of wireless connections can be increased 10 times from 4G technology speeds up to 10 Gbps with the implementation of 5G networks. Moreover, 5G is able to provide connections to thousands of devices at the same time with lower End to End latency and, unlike 4G, it is not as easy to disrupt by interferences from WiFi signals, buildings, microwaves, etc [42]. According to [43], the maximum End to End latency between two devices for a safe response should be at maximum 100 ms, which is totally feasible with 5G air latency [44]:

- <5 ms End-to-End latency.
- <1 ms Over-the-Air latency.

Therefore, fully automated driving can be achieved strongly depending on 5G communications with extremely low latency and high bandwidth and reliability. Even when infrastructure is damaged, due to natural disasters or other causes, a wireless network could set up connections between vehicles [45], which has a lot of potentials.

Last but not least, using data directly from vehicles can mean a violation of the privacy of individual vehicles and/or users [46] which may involve some issues for transportation researchers as it is a limiting factor for the acquisition or accessing data [6].

2.3 Signal control under CAVs

For CAV-based signalized cross intersections, three common types of controllers depending on the penetration rate and/or V2X connections have been proposed in research, since they do not exist in reality:

- Based on signal and vehicle data where drivers can be notified on how to operate to achieve some objectives (e.g., minimizing travel time, fuel consumption, etc.). As long as vehicles are automated, control performances will be improved since driving operations can be executed automatically [6].
  - Eco-driving guidance
  - Green Light Optimized Speed Advisory (GLOSA)
- Based on CVs data to improve the intersection throughput. Actuated signal control, platoon-based signal control and planning-based signal control can

be categorized within this category. Actuated signal control can optimize the assignation of signal and phases timings for current traffic states without applying any prediction, whereas platoon-based and planning-based will predict future traffic flow states to create optimized timing plans [6].

  - Vehicle-based Traffic Signal Control (lately explained in Section 3.2
  - Max Pressure Control (developed in this research and later explained in Section 3.1)

- In fully automated vehicle (AV) environments, the signal-vehicle connection can optimize vehicle operations and signal timing simultaneously so that better performance can be reached [6].

  - Signal Vehicle Coupled Control (SVCC)

2.3.1 Adaptive traffic signal control under CAVs

As previously seen, CAVs are a key factor for improving intersections throughput. Following, some previous works made from simulation environments are going to be presented, emphasizing the control based on vehicle detection since it is going to be used in this research. Mostly all controllers have been tested on theoretical environments and computational simulations due to the lack of CAVs available in the real world.

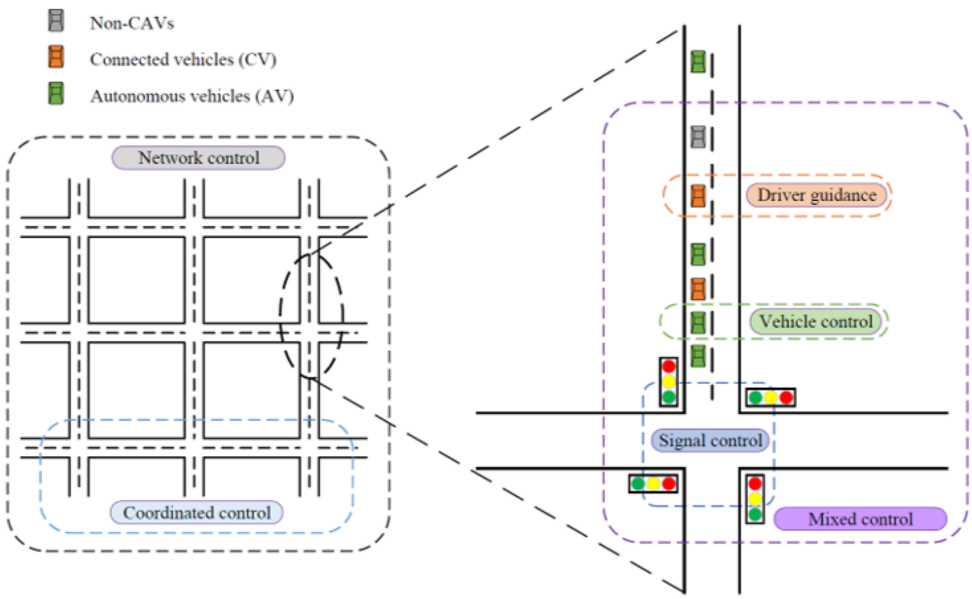

Figure 7: Traffic control in urban environment [6]

In this research, actuated traffic control based on CVs data is going to be used for an isolated intersection. This control is also known as adaptive traffic signal control in literature.

Generally, they try to solve an optimization problem whose states variables usually are performance measures, such as queue length, travel time, fuel consumption, among others. Meanwhile, control variables are the signal phases and timing and input data come from vehicle arrival. Following state equations are then proposed like queuing models, Lighthill-Whitham-Richards (LWR) models and car-following models [6].

In 2007, an actuated traffic control system was proposed based on wireless short-range communications between vehicles. Information was sent within a range of few miles around by V2I and infrastructure-to-infrastructure (I2I) communication to first estimate each approach traffic demand per cycle and then optimize cycle length using Webster's formulation [47]–[3].

Then, several methods were presented such as a scheduling model for a passing sequence in 2009 [48] or the improvement to the conventional red light preemption and green light extension based on short-range wireless obtained traffic data in 2010 [49].

2.3.2 Vehicle-based control

Traffic volumes are considered as the key inputs of signal controllers to reach optimization. In that sense, user and vehicle-based controllers have usually a range detection for getting the number of arrival vehicles or users inside them. One opportunity presented by the user or person based controller is the chance to give priority to the Public Transportation.

An optimization algorithm was presented in 2014 for a simple single-lane, signalized and cross-intersection in an AV environment. It could optimize vehicle trajectories and signal timing simultaneously for a time horizon processing output. It was demonstrated that intersection capacity and throughput were increased. However, the range for collecting data should be at least 2.000 feet to reach expected and favorable results [7].

It was not until 2014 when the first algorithm considering unequipped vehicles appeared in the literature found. In this case, the objective was minimizing the total delay with the information from CVs. This controller considers vehicles within a radius of the intersection, predicts their trajectories and choose the best strategy to reduce the average delay and consequently the number of total stops [37].

An improvement of the latter algorithm was carried out two years later by adding a percentage of AVs to the existent CVs, allowing the central controller to design their trajectories to improve operations. Besides, the algorithm started considering three types of vehicles and a bidirectional V2I connection was implemented. Arrival sequences and trajectories were estimated with kinematic wave theory and Newell's car-following model. Influence of the loss of information in communications was also considered and equated to the lack of CAVs [50].

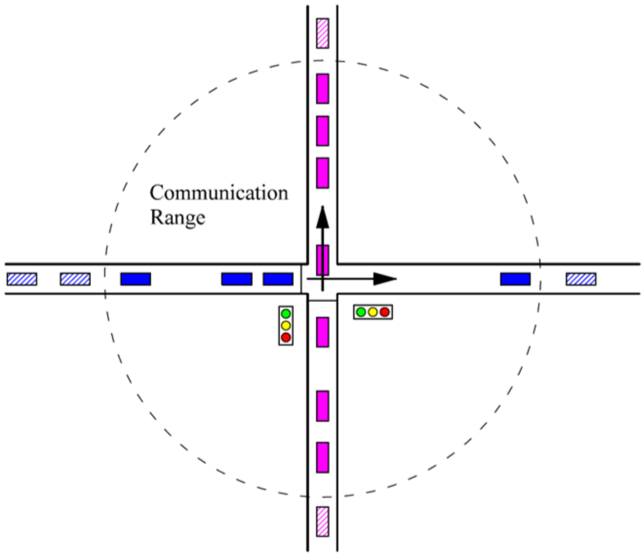

Figure 8: Communication range of a connected signalized single-lane intersection [7]

In 2017, a methodology for estimating traffic volumes from CVs or navigation devices data trajectories was introduced for very low penetration rates (<10%). However, it has not been optimized for short intervals and it was not suitable for over-saturated conditions [51]. A capacity maximization of an intersection was presented the same year with the operation scheme named MCross. This algorithm does not rely on a 100% CAVs environment. This innovative operational traffic control has the peculiarity of maximizing capacity utilizing all the lanes at any time, considering demand fluctuation and collision with on-coming traffic through a dynamic lane assignment [35].

2.3.3 User-based control

Concerning user-based controllers, a person-based signal control was developed in 2013 for an isolated intersection. This controller method accounts for the passenger occupancy of private and transit vehicles and it allows some trade-offs by weighting the passenger depending on the vehicle they are using. In fact, it can provide priority to transit vehicles while having a small delay time increase for vehicles. Nevertheless, it is constrained to under-saturated traffic conditions. [52].

In this thesis, the controller used is based on a user throughput optimization one presented in 2019 [53]. It is the first one found in the literature that takes directly users of vehicles into account for every type of traffic condition. First, the algorithm predicts vehicle arrival times to the intersection and then it splits phase timings according to the exact number of users of each vehicle. It is achieved by an application of a Genetic Algorithm (GA) [54] to tackle the mixed-integer nonlinear program (MINLP) that solves the optimization for numerous possible green time combinations. It was demonstrated that user-throughput outperformed vehicle-based, that public transit priority could be carried out and that it could be a motivation for car sharing, leading to more sustainable mobility [53].

2.4 GPS data error

The Global Navigation Satellite System (GNSS) is a network of satellites emitting microwave signals for location and timing purposes. They are commonly known as GPS, since this is the American standard system, one of the most used and implemented [9]. For this thesis, GNSS and GPS can be utilized indistinctly due to most of the accuracy levels and statistics found are provided by GPS experiences.

GNSS position accuracy depends on 5 factors [55]:

1. Ionospheric errors
2. Tropospheric errors
3. Signal obstruction and multipath
4. Geometric configuration of satellites
5. Other errors

Ionospheric errors are determined by the state of the ionosphere and the change of the propagating wave parameters according to intensive irregularities and/or gradients in electron density [56]. This means that radio noises caused by ionospheric storms can affect and disrupt some communications at a significant level. Some ionospheric models try to eliminate these disruptions [57].

Tropospheric errors are due to the delay of the signals caused while passing throughout the troposphere. Usually, GPS devices have integrated some algorithms that reduce tropospheric impacts [55].

Obstructions like walls or trees can limit the number of visible satellites for devices and can increase signal multipath. Metallic objects, lakes and other reflecting surfaces can affect signals travel times due to reflection. This is closely related to the geometric configuration of the satellites error. It may affect correct measurements since 3D positioning needs at least 4 satellites for not increasing the dilution of precision [55]. That is why in urban environments, GPS accuracy tends to decrease.

Other errors may appear such as satellite clock offset, but they are usually canceled when network corrections are made. These errors are between 0.1 and 10 millimeters and they are normally despised [55].

Errors have been chosen and subsequently implemented from those previous works were the considered GPS types have been used. They only are an estimation and real errors will depend on the factors commented above and also the model and type of GPS. It is important to remind that, for vehicles, the position is simplified to a 2D model and accuracy is not required in the height coordinate [58].

2.4.1 High Accurate GPS

High Accuracy GPS are devices that rely on other stations to get some incredibly high position accuracy. It is not possible to refer to it without naming the Real-Time Kinematic (RTK) positioning system. This is a technique used to enhance the precision of position data obtained from GPS systems [55].

Traditional RTK is based on two components, usually a base and a rover station. Corrections are made in the base station and sent to rover stations via radio. This limits connections to a range of 5 to 10 kilometers. For fixing this issue, Global System Mobile modems are being installed in fixed GNSS stations, providing continuous data transfer thanks to the networks called Continuously Operating Reference Stations (CORS) or Network RTK (NRTK). In this case, networks are provided by 3 or more stable stations that make continuous observations [55]. NRTK needs an algorithm to solve integer ambiguities in static multiple reference receivers in stations whose position is known, in order to form the network [59].

It has been demonstrated that a RTK GPS Networks can reach centimeter-level accuracy, from few millimeters up to 5 centimeters [55]–[60]–[61]–[62]. For instance, a 20-millimeter position accuracy at the 95% confidence level without signal multipath effects (up to 11 millimeters more considering them) is designed in a NRTK in [58].

However, the necessity of installing 3 or more fixed stations in the system makes NRTK GPS a very expensive and costly solution to determine the position, although some new approaches are being emerged like long base RTK with the previously GSM modems commented [55].

2.4.2 Standard GPS with RAIM

The standard GPS accuracy is annually collected by the government of the United States of America. For this research, *"An Analysis of Global Positioning System (GPS) Standard Positioning Service (SPS) Performance for 2018"* [8] served to estimate the errors of a GPS in a vehicle. It has been considered that the vehicles will be equipped with a GPS with a Receiver Autonomous Integrity Monitoring (RAIM), since it is important for safety-critical applications, and that they will use International GNSS System (IGS).

Statistic	Data Editing	Horizontal		Vertical	
		IGS	NGA	IGS	NGA
Mean (m)	RAIM	1.35	1.09	2.24	1.46
	None	3.40	1.10	5.60	1.46
Median (m)	RAIM	1.30	1.09	2.14	1.46
	None	1.35	1.10	2.20	1.46
Maximum (m)	RAIM	8.67	1.27	29.73	1.67
	None	52.18	1.28	83.90	1.68
Std. Dev. (m)	RAIM	0.43	0.03	1.45	0.04
	None	6.09	0.03	9.94	0.04

Figure 9: Daily Average Position Errors for 2018 [8]

2.4.3 Mobile GPS

These are supposed to be the least accurate devices. Nowadays smartphones are equipped with Assisted GPS (A-GPS) which uses mobile networks together with a GPS antenna to increase the speed of position determination [63]. However, it is known that this type of GPS is less accurate than traditional GPS receivers.

It has been proved in [64] that in urban environments horizontal errors oscillate between 7 and 13 meters. This experiment was only made with an iPhone 6 GPS and without considering the standard deviation of the sample. On the other hand, a much more complete study was found with many different devices in [9] as seen in Figure 10, where standard deviations can be found.

Measure of mobile phone GPS receivers (all values in metres)	N	Mean	Std. Deviation	Range	Minimum	Maximum
Horizontal *absolute* accuracy (combined)	638	3.49	3.67	43.96	0.1	44.07
Horizontal *absolute* accuracy (Apple iPhone 4)	40	2.65	1.27	5.37	.78	6.15
Horizontal *absolute* accuracy (Apple iPhone 5)	300	4.19	4.71	43.82	.26	44.07
Horizontal *absolute* accuracy (Samsung)	120	2.75	1.69	10.39	.25	10.65
Horizontal *absolute* accuracy (Sony)	158	2.64	2.06	17.65	.11	17.76
Horizontal *relative* accuracy RMSE (combined)	6026	2.44	3.65	45.23	0	45.23
Horizontal *relative* accuracy RMSE (Apple iPhone 4)	380	1.67	1.31	7.23	.01	7.24
Horizontal *relative* accuracy RMSE (Apple iPhone 5)	2850	3.03	4.78	45.23	0	45.23
Horizontal *relative* accuracy RMSE (Samsung)	1140	1.85	1.70	10.29	0	10.29
Horizontal *relative* accuracy RMSE (Sony)	1466	1.71	2.87	14.68	0	14.68

Figure 10: Statistics of mobile phone GNSS data in [9]

3 Methodology

In previous research, usually, the followed path has always been the one with dashed lines in the scheme presented in Figure 11. In this case, some disturbances in position wanted to be added according to three different types of GPS: high accurate GPS, standard GPS with RAIM and mobile GPS, as seen in Sections 2.4.1, 2.4.2 and 2.4.3. These disturbances in position will then cause errors in speed estimations. Data transmission speed was also considered in the first moment, but finally dismissed thanks to the 5G opportunity, as seen in Section 2.2.

Information with error implemented will be sent to two different types of signal controllers. Once these controllers get the relevant green times, they will allocate them for each phase in the traffic signal.

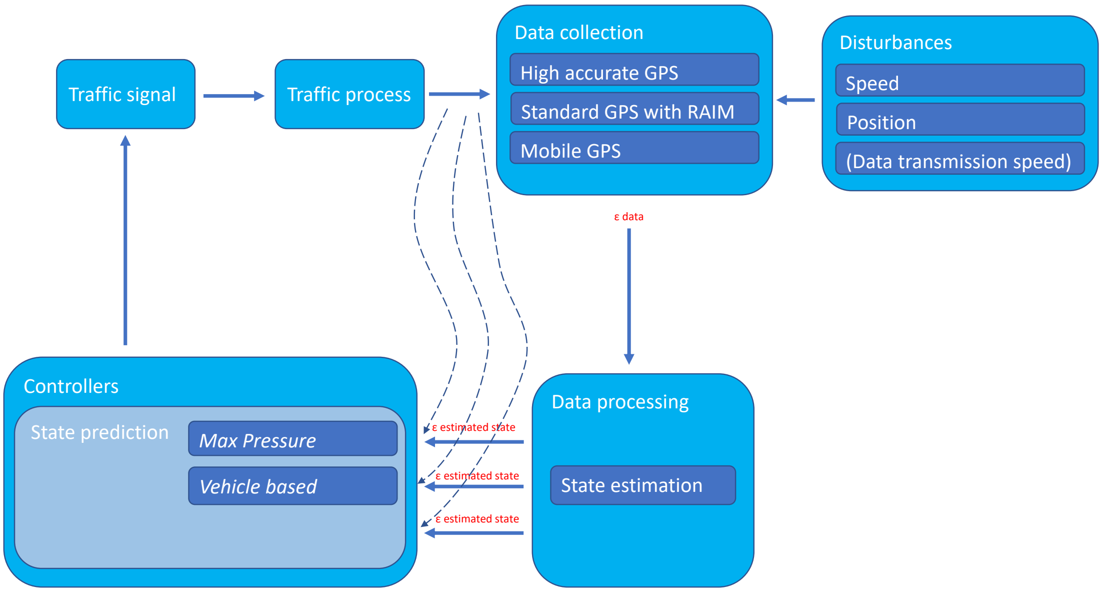

Figure 11: Methodology proposed

Both signal controllers have been simulated in 3 scenarios under a CV environment applying some errors to the vehicle data-position sent. Both of them are fixed-cycle controllers that split and allocate green times for each phase. Since all simulations are run under a full CVs environment, queue length estimation is simply made through the assumption that vehicles with speed close to zero are in the queue. They also both follow the sequence phase of a NEMA ring-and-barrier diagram to organize movements [15].

Finally, average vehicle delay, vehicle throughput and average vehicle stops will be collected from the simulations to be analyzed later on.

3.1 Maximum Pressure Control

The MP control is based on the knowledge of the vehicle queue length as previously seen. First, the algorithm detects if there is a car. If there is, the queue length is determined by collecting the position of the vehicles approaching before each cycle starts and calculating their current speed from it. When the speed is lower than 1 m/s (or 3.6 km/h), then it is considered that it is stopped. It is then added to the queue with its length plus a safety distance of 2 meters. However, the initial estimated length can be updated before discharging if more vehicles join the queue. Formulation of this estimation algorithm is presented as follows:

$$Q_{ij}^{1} = \sum_{n=1}^{N_{ij}} q_{ij}^{n}(l_{ij}^{n} + S) \tag{1}$$

$$q_{ij}^{n} = \begin{cases} 1 & \text{if } v_{ij}^{n} = 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Where:
Q_{ij}^{1}: estimated initial queue length in assigned lane for phase i in ring j (m);
i: signal phase index (i=1,2,..,I);
j: ring index (j=1,2,..,J);
n: vehicle index (n=1,2,..,N_{ij});
l_{ij}^{n}: length of vehicle n in phase i of ring j (m);
S: safety distance between stopped vehicles (m);
q_{ij}^{n}: binary parameters indicating the vehicles is in queue or not;

Once queues are saved for each phase, the ones in complementary phases are summed. To get the split times, formulas 3, 4, 5 and 6 are used, where g_i is the green time and C the cycle length, both in seconds. As it may be seen, a 10 seconds minimum green time is added to the equations, in order to get an average minimum green time between 5 and 15 seconds, which is the frame usually used according to [3].

$$g_1 = \frac{(q_1 + q_5) \cdot (C - 40)}{\sum_{i=1}^{8} q_i} + 10 \tag{3}$$

$$g_2 = \frac{(q_2 + q_6) \cdot (C - 40)}{\sum_{i=1}^{8} q_i} + 10 \tag{4}$$

$$g_3 = \frac{(q_3 + q_7) \cdot (C - 40)}{\sum_{i=1}^{8} q_i} + 10 \tag{5}$$

$$g_4 = \frac{(q_4 + q_8) \cdot (C - 40)}{\sum_{i=1}^{8} q_i} + 10 \tag{6}$$

This process is then repeated before every cycle starts again.

3.1.1 MPC Algorithm

Table 1: MPC Algorithm

Step 1	Vehicle position detection at the begining of each cycle
Step 2	Error implementation in position
Step 3	Speed calculation according to positions with errors
Step 4	Estimation of queue length in each lane (vehicle length + safety distance)
Step 5	Green time splitting proportionally to each queue
Step 6	Green time allocation to each phase

3.2 Vehicle-based Signal Traffic Control

This controller is completely based on the user-based signal control developed in [53], but in this case, vehicles have been considered instead of people. Vehicle-based Signal Traffic (VST) control uses a strategy which calculates the stop-bar passage time for each vehicle approaching the intersection within all of the area simulated, which has a radio of 1 km.

Its objective is to predict which vehicles can pass through the intersection in allocated green times. First, it estimates initial queue length in each approach, like in equations 1 and 2, and then vehicles arrivals to the intersection, based on whether a vehicle joins or not the queue.

All of the arrival conditions to the intersection have been ensured in 3 main cases and 6 sub-cases. Based on each case characteristics, some different formulations are proposed for stop-bar passage time estimation.

The first criterion for this classification is estimated with some kinematic wave theory principles whether the vehicles will join the existing queue or not. To satisfy car-following principles, minimum time headway is contemplated in the formulation of [53]. The stop-bar passage time prediction considers from the closest detected vehicle to the stop-bar until the furthest. The different cases are presented as follows.

- **Case 1: No initial queue** ($Q_{ij}^1 = 0$)

  There is no initial queue in the assigned lane for phase i of ring j. Firstly, arrival time with the current speed between the vehicle position and stop-bar is calculated. Then, the arrival condition is determined by comparing arrival time and signal timing. The mathematical formulation is presented as:

$$\alpha_{ij}^n = \begin{cases} 1, & \text{if } t_{ij}^n < c_{ij} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

$$t_{ij}^n = d_{ij}^n / v_{ij}^n \tag{8}$$

$$c_{ij} = \sum_{k=1}^{i-1} g_k + (i-1)Y, \tag{9}$$

Where:
α_{ij}^n: binary variable indicating the vehicles arrive to stop-bar before green time or during time;
t_{ij}^n: travel time between initial position of vehicle n to stop-bar in assigned lane for phase i of ring j (s);
d_{ij}^n: initial distance between head of vehicle n and stop-bar in assigned lane for phase i of ring j (m);
c_{ij}: time from starting of cycle to starting of phase i in ring j (s);
g_{ij}: green time of phase i in ring j (s);
Y: amber and all red time duration (s);

Depending on the resulting variable α_{ij}^n, this case can be further classified into two sub-cases.

- *Case 1.1: Arrival to stop-bar before green time starts ($Q_{ij}^1 = 0$ and $\alpha_{ij}^n = 1$)*

  In this sub-case, vehicles should stop before the stop-bar at a safety distance until green time starts. In order to calculate the time difference between the start of a green phase and the start of a vehicle movement, backward recovery shock-wave speed (v_s) is used, while assuming a constant headway. The calculation is then expressed as follows:

$$v_s = \left(\frac{H_t}{S} - \frac{1}{v_q}\right)^{-1} \tag{10}$$

$$T_{ij}^n = c_i + S\left(\frac{1}{v_q} + \frac{1}{v_s}\right) \tag{11}$$

$$Q_{ij}^{n+1} = Q_{ij}^n + l_{ij}^n + S \tag{12}$$

  where:
  v_q: vehicles speed in moving queue (m/s);
  v_d: desired speed of vehicles (m/s);
  v_s: backward recovery shock-wave speed (m/s);
  H_t: time headway between vehicles and time gap between starting of green and stop-bar passage of first vehicle (s);
  T_{ij}^n: time between starting of cycle and when vehicle n in phase i of ring j, passes the stop-bar(s).

– *Case 1.2 vehicle arrives at the stop-bar during green time ($Q_{ij} = 0$ and $\alpha_{ij}^n = 0$)*

In this circumstance, the vehicle arrives at the stop-bar during the green time and is expected to pass the intersection without stopping. It means that queue length will not increase and remain zero. Stop-bar passage time is then calculated as:

$$T_{ij}^n = t_{ij}^n \tag{13}$$

$$Q_{ij}^{n+1} = Q_{ij}^n. \tag{14}$$

- **Case 2: There is initial queue at the intersection and vehicle is part of queue** ($Q_{ij} > 0$ **and** $q_{ij}^n = 1$)

In this situation, the vehicle can be part of the queue during the green time. The first car in the queue is considered similar to case 1.1. Stop-bar passage time for the next vehicle is calculated based on the front vehicle passage time, while the queue length does not change in this case. The mathematical formulation will be the following:

$$T_{ij}^n = \begin{cases} c_{ij} + S\left(\frac{1}{v_q} + \frac{1}{v_s}\right), & \text{if } n = 1 \\ T_{ij}^{n-1} + \left(S + L_{i-1j}^n\right)\left(\frac{1}{v_q} + \frac{1}{v_s}\right), & \text{if } n > 1 \end{cases} \tag{15}$$

$$Q_{ij}^{n+1} = Q_{ij}^n. \tag{16}$$

- **Case 3: There is initial queue at the intersection and vehicle approaches to intersection** ($Q_{ij} > 0$ **and** $q_{ij}^n = 0$)

In this case, vehicles move towards the intersection while there already exits a queue before the stop-bar. It can be classified into three sub-cases depending on whether the vehicle can reach the queue before clearance or not. First, arrival time between the vehicle position and the end of the queue is calculated, always considering a safety distance. Then, vehicle travel time and queue clearance time are compared to determine vehicle arriving type. The first level of classification establishes whether the vehicle will join the queue before discharging or not, as follows:

$$\beta_{ij}^n = \begin{cases} 1, & \text{if } \gamma_{ij}^n < \theta_{ij}^n \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

$$\gamma_{ij}^n = \frac{d_{ij}^n - (Q_{ij}^n + S)}{v_d} \tag{18}$$

$$\theta_{ij}^{n} = c_{ij} + \frac{Q_{ij}^{n}}{v_s} \tag{19}$$

Where:
β_{ij}^{n}: binary parameter indicating the vehicles will join queue before discharging or not;
γ_{ij}^{n}: travel time between initial position to tail of queue for vehicle n in assigned lane to phase i of ring j (s);
θ_{ij}^{n}: time interval from starting of cycle to when backward recovery shock-wave arrives to tail of queue (s).

If it is shown that the vehicle joins the queue, the second level of classification is activated to show whether the vehicle will join the queue during discharge or pass the stop-bar after queue clearance, as follows:

$$D_{ij}^{n} = d_{ij}^{n} - v_{ij}^{n}\frac{Q_{ij}^{n}}{v_s} \tag{20}$$

$$\mu_{ij}^{n} = \frac{D_{ij}^{n} - Q_{ij}^{n}}{v_{ij}^{n} - v_q} \tag{21}$$

$$\delta_{ij}^{n} = \frac{Q_{ij}^{n}}{v_q} \tag{22}$$

$$\phi_{ij}^{n} = \begin{cases} 1, & \text{if } \delta_{ij}^{n} > \mu_{ij}^{n} \\ 0, & \text{otherwise,} \end{cases} \tag{23}$$

Where:
D_{ij}^{n}: updated position of vehicle n in assigned lane to phase i in ring j, when backward recovery shock-wave arrives to the tail of queue;
μ_{ij}^{n}: travel time from updated position of vehicle n to tail of moving queue (s);
δ_{ij}^{n}: time interval from when the backward recovery shock-wave arrives to tail of queue and when the tail of queue passes the stop-bar (s);
ϕ_{ij}^{n}: binary variable indicating that the vehicle will join queue while discharging or passes the stop-bar after queue.

Depending on the variables β_{ij}^{n} and ϕ_{ij}^{n}, we further distinguish into the following sub-cases.

- *Case 3.1: vehicle arrives to tail of queue before queue starts to discharge ($Q_{ij} > 0$, $q_{ij}^{n} = 0$, $\beta_{ij}^{n} = 1$)*

As the vehicle joins the queue, stop-bar passage time is calculated based on the front vehicle calculated time, backward recovery shock-wave and queue discharging speed. Queue length is then updated. The formulation is the following:

$$T_{ij}^{n} = T_{ij}^{n-1} + (S + L_{i-1j}^{n})\left(\frac{1}{v_q} + \frac{1}{v_s}\right) \tag{24}$$

$$Q_{ij}^{n+1} = Q_{ij}^{n} + l_{ij}^{n} + S. \tag{25}$$

– *Case 3.2: vehicle arrives to tail of queue during queue discharging ($Q_{ij} > 0$, $q_{ij}^n = 0$, $\beta_{ij}^n = 0$, $\phi_{ij}^n = 1$)*

In this case, the vehicle joins the queue but with the particularity that the queue is moving. Therefore, backward recovery shock-wave speed is not included in the calculation:

$$T_{ij}^{n} = T_{ij}^{n-1} + \frac{S + L_{i-1j}^{n}}{v_q} \tag{26}$$

$$Q_{ij}^{n+1} = Q_{ij}^{n}. \tag{27}$$

– *Case 3.3: vehicle cannot reach to tail of queue before or during discharge ($Q_{ij} > 0$, $q_{ij}^n = 0$, $\beta_{ij}^n = 0$, $\phi_{ij}^n = 0$)*

In this last case, vehicle n does not join the queue and passes the stop-bar after the queue is completely discharged. Queue length does not change in this case.

$$T_{ij}^{n} = \frac{d_{ij}^{n}}{v_d} \tag{28}$$

$$Q_{ij}^{n+1} = Q_{ij}^{n}. \tag{29}$$

The collected stop-bar passage time for each vehicle is then compared to its corresponding green time so that it is determined whether that vehicle can be served in the cycle time or not. The comparison is made as follows:

$$G_i = \sum_{i=1}^{i} g_i + (i-1)Y \tag{30}$$

$$p_{ij}^{n} = \begin{cases} 1, & \text{if } T_{ij}^{n} < G_i \\ 0, & \text{otherwise,} \end{cases} \tag{31}$$

Where:
G_i: end of green time for phase i (s);

p_{ij}^n: binary parameter indicating if vehicle n is served in current cycle or not;

The final objective function is to maximize the vehicle throughput in a fixed-time cycle and fixed-phase sequence.

$$\max \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{n=1}^{N_{ij}} p_{ij}^n v_{ij}^n \tag{32}$$

Subject to:

$$\sum_{i=1}^{I} g_i + (I-1)Y = C \tag{33}$$

$$g_i > g_{i,\min} \quad \forall i \tag{34}$$

$$g_i < g_{i,\max} \quad \forall i \tag{35}$$

Where:
C: cycle time (s);
v_{ij}^n: number of vehicles in assigned lane to phase i of ring j;
$g_{i,\min}$: minimum green time of phase i (s);
$g_{i,\max}$: maximum green time of phase i (s).

Since we are dealing with a complex problem of optimization, to solve this Mixed-Integer Nonlinear Program (MINLP) algorithm, whose solution is within a region comprised by multiple combinations of green times, a Genetic Algorithm (GA) is used due to unacceptable calculation times by conventional methods.

GA is a search technique used in computing to find true or approximate solutions to optimization and search problems by applying the principles of the survival of the fittest.

For VST, it runs 10 times with separate random instances for each of the random seeds. It generates random populations, green times in this case, and then evaluates the objective function, which is the maximization of the vehicle throughput, by applying the principles of selection, crossover and mutation to check if the termination criteria are satisfied.

GA parameters used are the following:

- Population size = 40;
- Generation number = 50;
- Crossover probability = 1;
- Mutation probability = 0.5;

3.2.1 VST Algorithm

Table 2: VST Algorithm

Step 1	Vehicle position detection at the begining of each cycle
Step 2	Error implementation in position
Step 3	Speed calculation according to positions with errors
Step 4	Arrival time to passage stop-bar estimation
Step 5	Identification of case type (1.1, 1.2, 2, 3.1, 3.2 o 3.3)
Step 6	Application of the GA according to each case (maximization of throughput)
Step 7	Result of the best fitting green time obtained in GA
Step 8	Optimal green times allocation to each phase

3.3 GPS data error

3.3.1 Implementation

Errors in GPS are introduced in the *MATLAB* [65] code for each controller. Since each vehicle position is detected every second, errors have been applied in a previous position and the position after one second, as shown in equation 37.

GPS errors are always within a maximum radius, which means that average error can occur in every direction around the device. In the concern of this thesis, it is assumed that vehicles are always in the lanes where they approach the intersection. Thus, it is not important where the GPS locates the vehicle, but its projection in the road lane.

For solving this problem, a polar coordinate system has been used to project the GPS error to the road. It is then implemented by simplifying each approach as a two-dimension coordinate system. In that situation, projection is obtained by multiplying the value of the distance by the cosines of the angle formed with the axis of the road.

Both, the distance and the angle are generated randomly by the software. The angle in radians must be between 0 and π (first 2 quadrants or 180 degrees in Cartesian coordinates). Therefore, to obtain it, a random number is generated by a function between 0 and 1 and then multiplied by π (see equation 37). Concerning the distance, it is obtained from a normal distribution with a mean equal to the mean error in meters and standard deviation found in literature as seen in sections 2.4.1, 2.4.2 and 2.4.3 and summarized in Table 3.

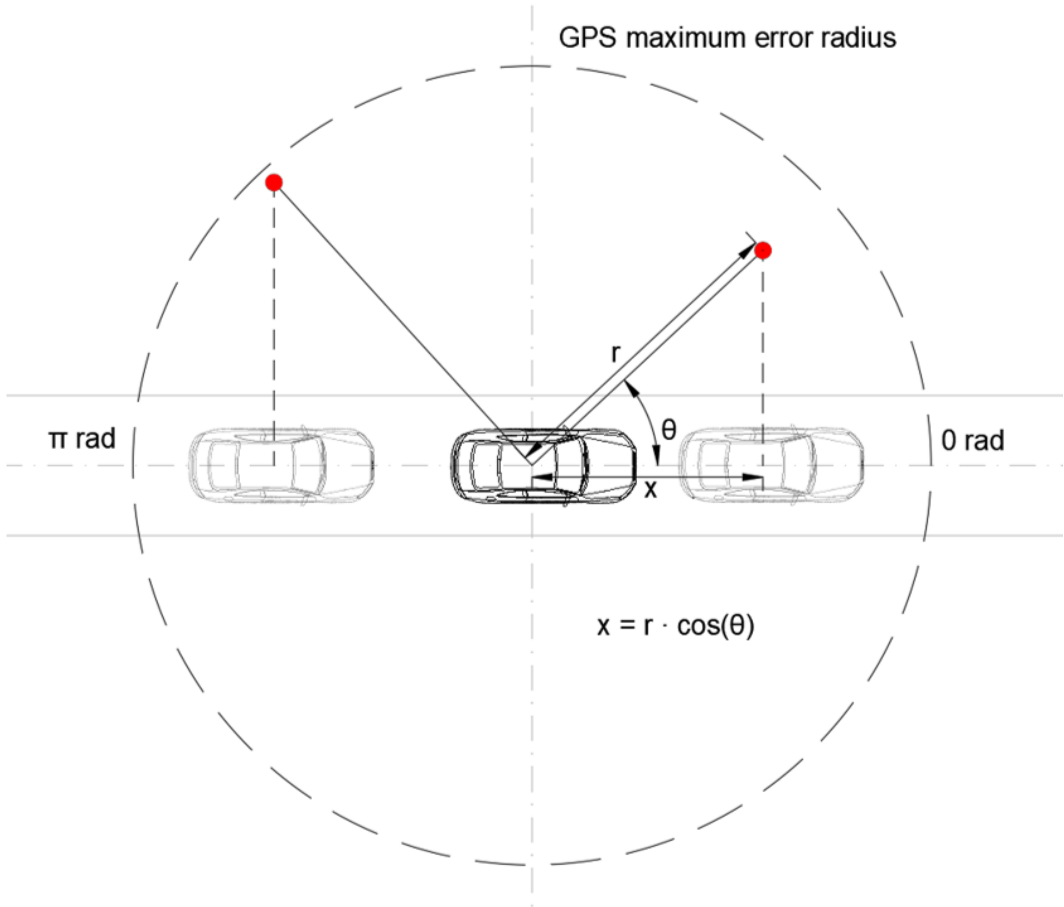

Figure 12: GPS errors from polar coordinate to Cartesian coordinate system

The difference between two normally distributed variables makes their final mean the subtraction of their previous means and their final standard deviations the sum of their previous standard deviations [66].

$$\mu_{x-y} = \mu_x - \mu_y \;\; ; \;\; \sigma^2_{x-y} = \sigma^2_x + \sigma^2_y \tag{36}$$

By subtracting two equal random normal distributions, it is expected that at a certain point tending to infinity, the final mean turns 0. In that case, a resulting normal distribution is expected to have the similar amount of errors both to the positive and to the negative side of the axis, avoiding the issue of not considering cars being further from the intersection but only closer to it, which will cause some bias in the error instead.

The final equation applied to the positions of each vehicle is the following:

$$V = D_{t+1} + \cos(\pi \cdot x) \cdot N - (D_t + \cos(\pi \cdot x) \cdot N) \tag{37}$$

Where:
x = random number $\in \; \mathbb{R}\,[0,1]$;
$N \sim \mathcal{N}(\mu, \, \sigma^2)$;

3.3.2 Errors summary

The final errors implemented in each simulation are presented in the below summary Table 3 as a mean in meters and as a standard deviation of the normal distribution of the sample for each type of GPS.

Table 3: GPS errors applied

Errors (m)					
High Accurate GPS		**Standard GPS with RAIM**		**Mobile GPS**	
Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
0	0	1.35	0.43	3.49	3.67

4 Simulations setup

Cases studied were conducted from the *MATLAB* [65] code with the microsimulation software *VISSIM* [67] on its 64-bit version 11.00-10. In total, 18 simulations were made. Each simulation has consisted of 20 unique random seeds of vehicle traffic flow to consider the vehicle's arrival pattern as stochastic. Those seeds are based on a previously input volume depending on the scenario. Each simulation consisted in a warm-up time of 600 seconds (10 minutes) and a total time of 3600 seconds (1 hour) of cycles run so that in total 40, 30 or 24 cycles were carried out depending on the cycle length.

The equipment used for carrying the simulations has been 3 computers with Windows 10 64-bit operating system software. Their processors are Intel(R) Xeon(R) CPU E3-1230 v5 and have a clock speed up to 3.40 GHz. They have 16 GB of installed memory RAM.

The intersection is designed as a simple four-leg one with two lanes on each approach (see Figure 13). Each approach measures 1 kilometer and each exit 500 meters. Every left lane has the purpose to turn left, whereas the right lanes are supposed to keep going straight forward.

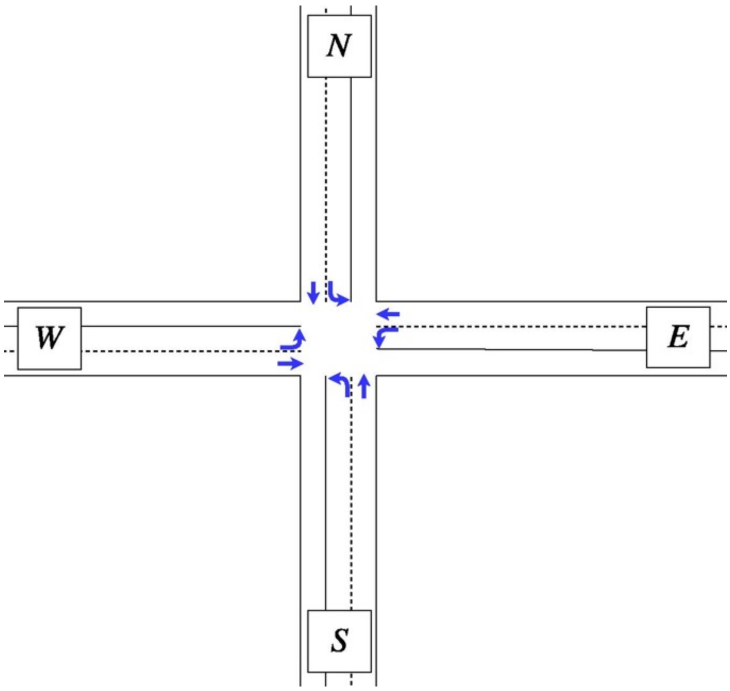

Figure 13: Intersection proposed

The desired speed v_d and the queue discharging speed v_q are set to 60 km/h and 30 km/h, respectively. Minimum safety distance between vehicles is set to 2 meters and minimum time headway is considered 2 seconds. In both controllers, a minimum green time of 10 seconds is considered for each phase, as previously seen, and yellow changes and red clearances times are 6 seconds for each cycle.

4.1 Assumptions

Some following assumptions have been considered for vehicles and driving behaviour for all scenarios:

1. The penetration rate is known and it is 100% of CVs.
2. Therefore, position, speed, vehicle length and other possible considered vehicle data has been provided in a fully connected environment without any delay or outage.
3. Overtaking and lane changing are not allowed, meaning each phase will receive the same amount of vehicles that arrive in each lane in the boundaries of the intersection.
4. All vehicles are the same type of private car, which means they move at the same speed and with the same constant safety distance. Thus, the desired speed for all vehicles is constant and identical.
5. Vehicles speed in stopped queues is equal to zero, whilst vehicles speed operating out of them is above 3.6 km/h.
6. Cars do not turn to the right at the intersection.

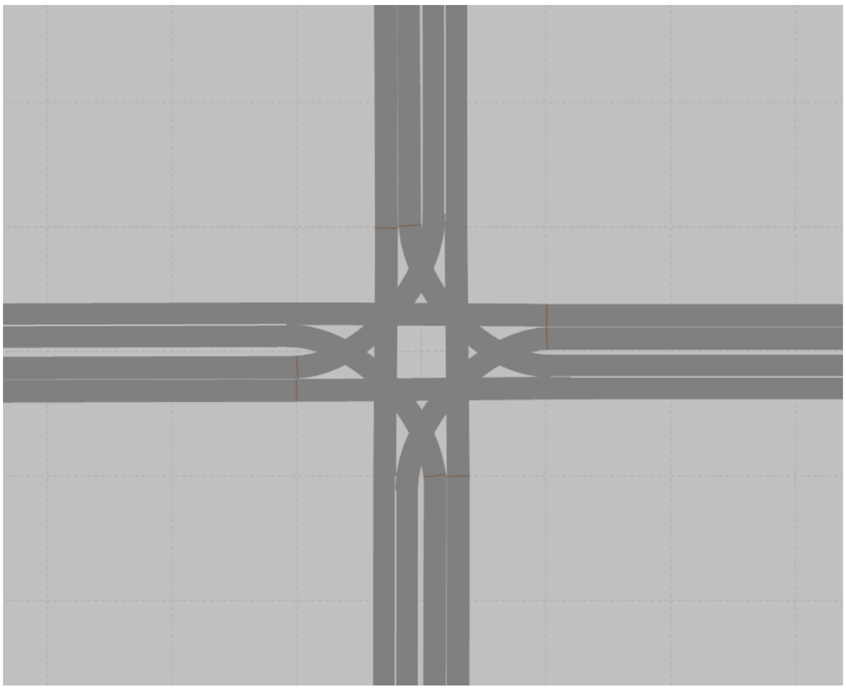

Figure 14: Zoom in intersection proposed

4.2 Scenarios

Scenarios chosen wanted to collect the influence under every type of traffic condition. That is why it was considered important to have an under-saturated condition, saturated condition and over-saturated condition.

Since the controllers are fixed-cycle time, cycle lengths are determined according to the most used in standard real-life situations and previous research (90, 120 and 150 seconds). They are complemented with their corresponding maximum theoretical capacity according to conventional methods of the Signal Timing Manual (STM) and the Highway Capacity Manual (HCM) [3]-[10]. These values can be a bit conservative since they consider a headway of 2.5 seconds per vehicle, which is a bit high for the urban environment. However, they have been the reference numbers for generating different traffic conditions.

Table 4: Scenarios cycle lengths and maximum intersection capacities [3]-[10]

Scenarios	1	2	3
Cycle length (s)	90	120	150
Maximum conventional capacity (veh/h/lane)	1089	1167	1900

Concerning traffic distribution, to add a touch of realism, it has been adopted the road with North and South bounds as the major road and then the road with East and West bounds as the minor road. So that if vehicles going through the major road are considered as 1, traffic flow turning left from the major road and going through in minor road will be equivalent to the half and vehicles turning left in the minor street will be equal to a quarter of the main flow in major road.

Table 5: Scenarios traffic conditions

Scenarios		1	2	3
Traffic condition		*under-saturated*	*saturated*	*over-saturated*
Approach	**Phase**	**Traffic flow (veh/h/lane)**		
S-W	1	100	130	240
N-S	2	200	260	480
W-N	3	50	65	120
E-W	4	100	130	240
N-E	5	100	130	240
S-N	6	200	260	480
E-S	7	50	65	120
W-E	8	100	130	240
TOTAL		900	1170	2160

5 Results

Results are collected from the simulations for each phase. It turns out that simulations for MP control took between 2 and 4 hours, while simulations for VST took between 8 and 10 hours approximately in total. The data collected is the following:

- Average vehicle delays.
- Total vehicle throughput.
- Average vehicle stops.

All the results found in this section are in absolute numbers and can be used as a reference together with bars graphs for better visualization. For analysis purposes, the different results are going to be treated speaking in terms of the relative percentage difference between all the simulations taking as a reference the best number for each case (lowest one for delays and stops and highest for throughput) for each scenario.

5.1 Scenario 1

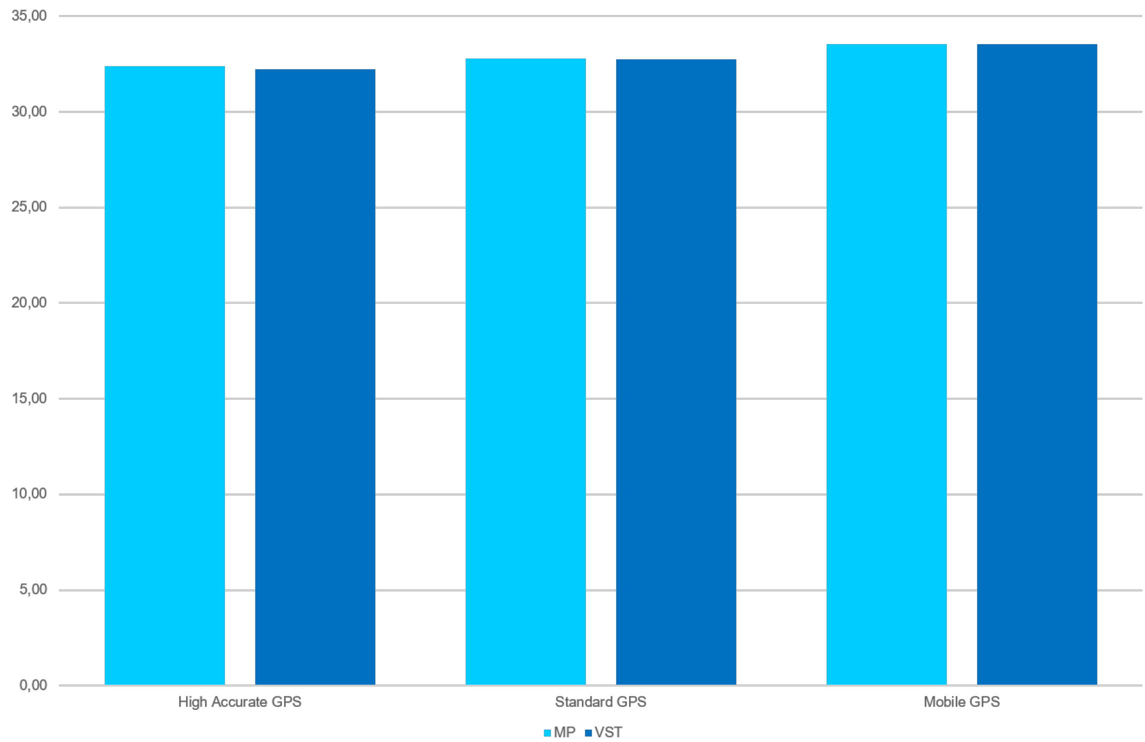

Figure 15: Vehicle delay in Scenario 1 (s)

– Vehicle delay increases from a 0.52% to a 4.07% for MPC and from a 1.65% to a 4.08% for VST.

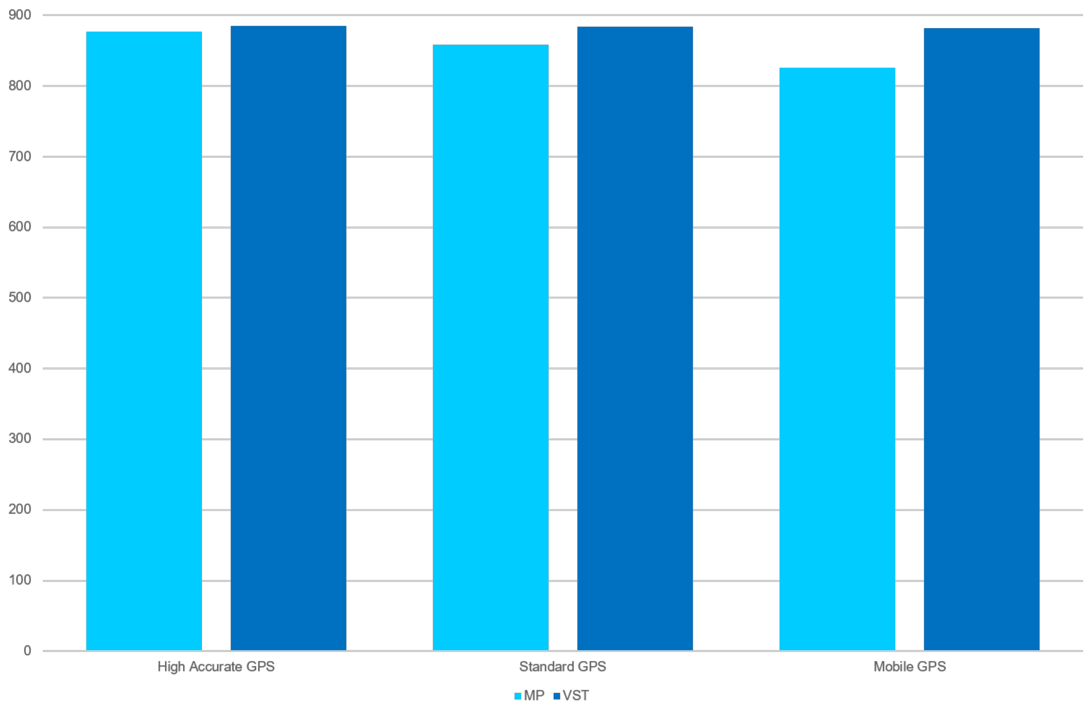

Figure 16: Vehicle throughput in Scenario 1

– Vehicle throughput decreases from a 0.95% to a 6.80% for MPC and from a 0.16% to a 0.41% for VST.

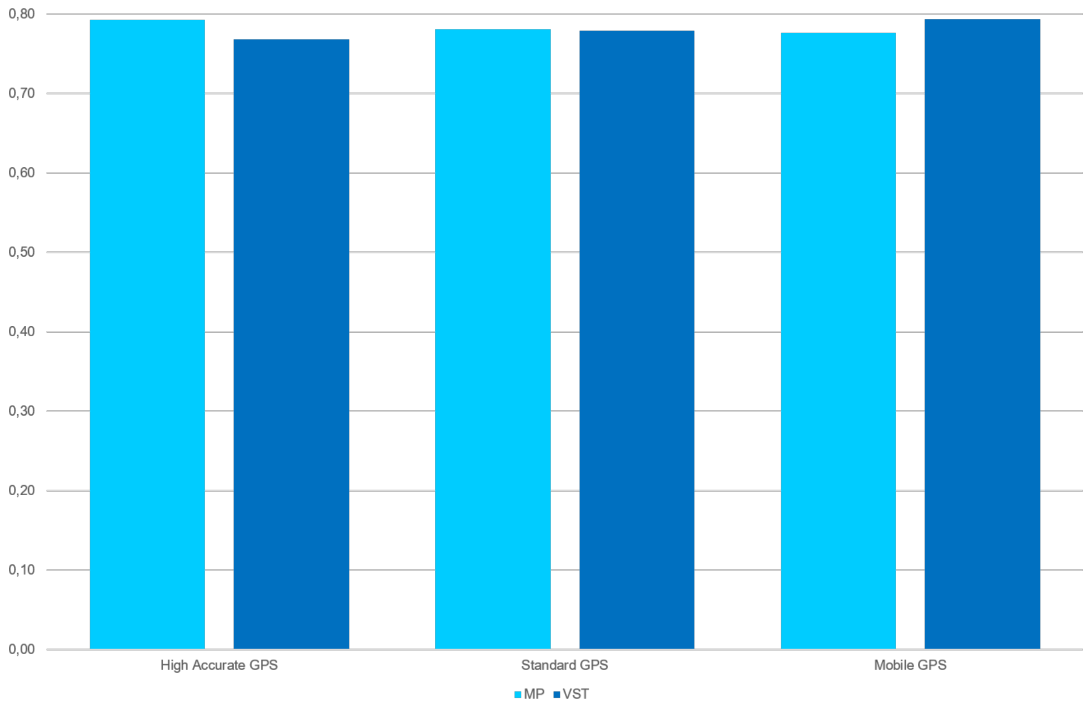

Figure 17: Vehicle stops in Scenario 1

– Vehicle stops increase from a 1% to a 3.10% for MPC and from a 1.43% to a 3.23% for VST.

Scenario 1, with under-saturated conditions, has very similar results for both controllers. It seems that when errors are added average vehicle delays, total vehicle throughput and average vehicle stops changes are mostly imperceptible in the whole intersection. In this case, VST gets better results for the High Accurate GPS. However, the other two GPS perform similarly for delays and stops. It is the vehicle throughput which is more affected with the MPC, whereas VST has similar results for every type of GPS. In all of the cases, the theoretical *Level of Service* (LOS) defined by the HCM [10] remains the same as *"C"*.

5.2 Scenario 2

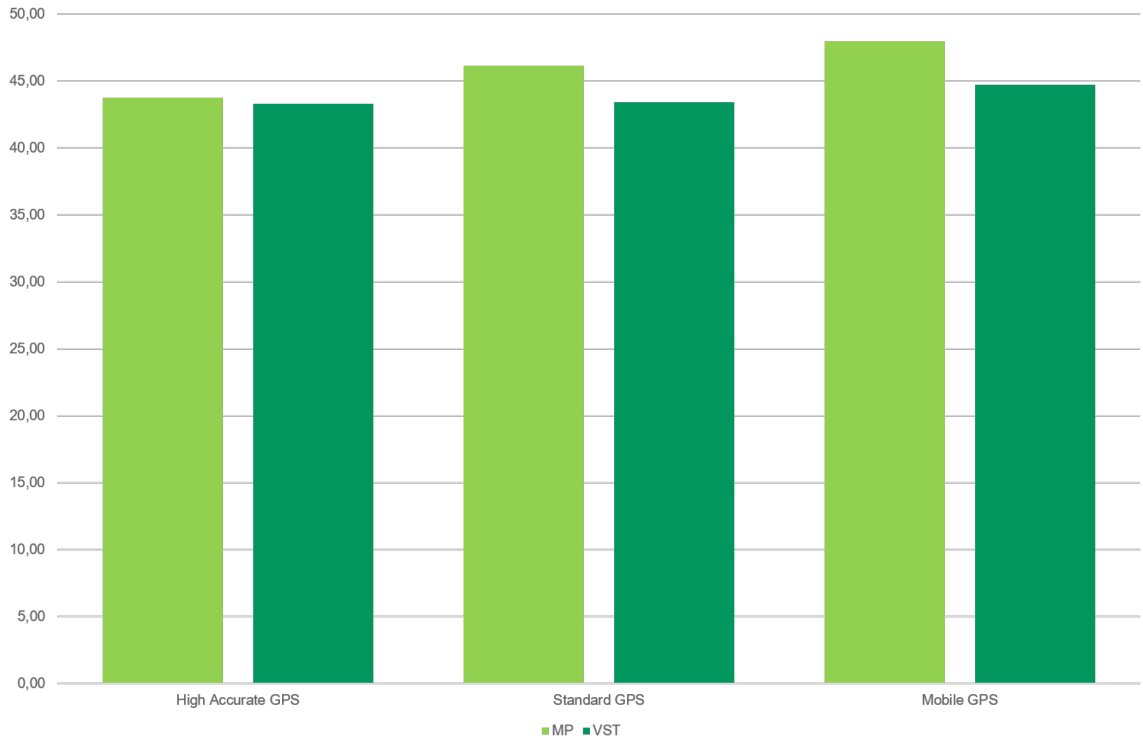

Figure 18: Vehicle delay in Scenario 2 (s)

– Vehicle delay increases from a 1% to a 10.08% for MPC and from a 0.2% to a 3.23% for VST.

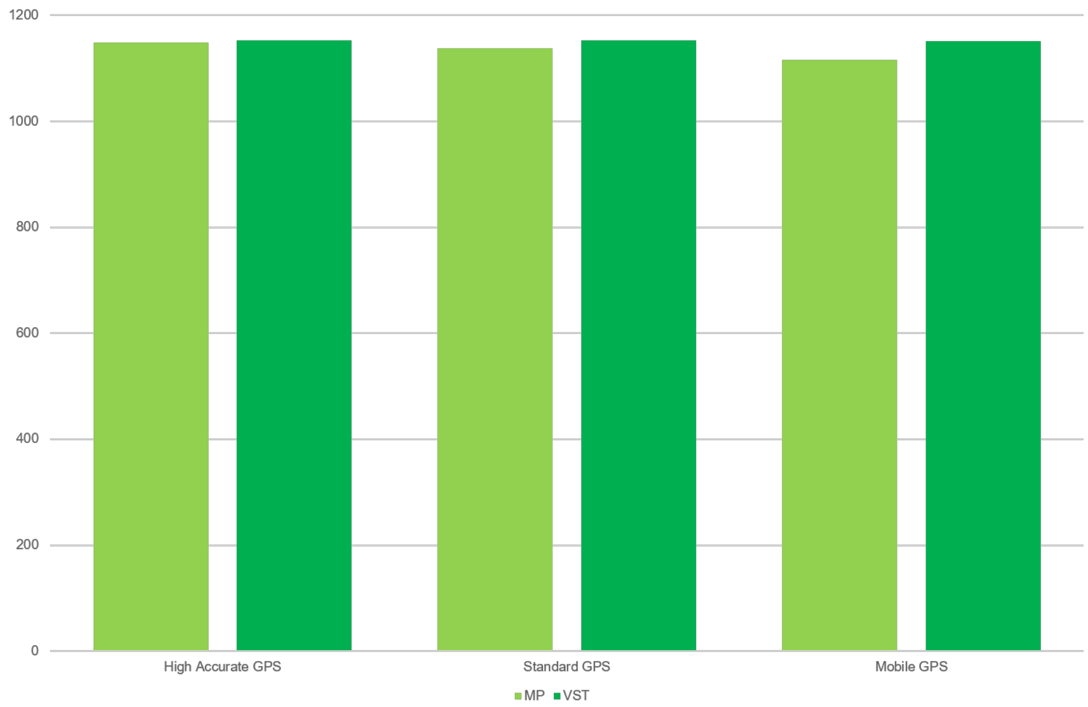

Figure 19: Vehicle throughput in Scenario 2

– Vehicle throughput decreases from a 0.34% to a 3.17% for MPC and from a 0.01% to a 0.05% for VST.

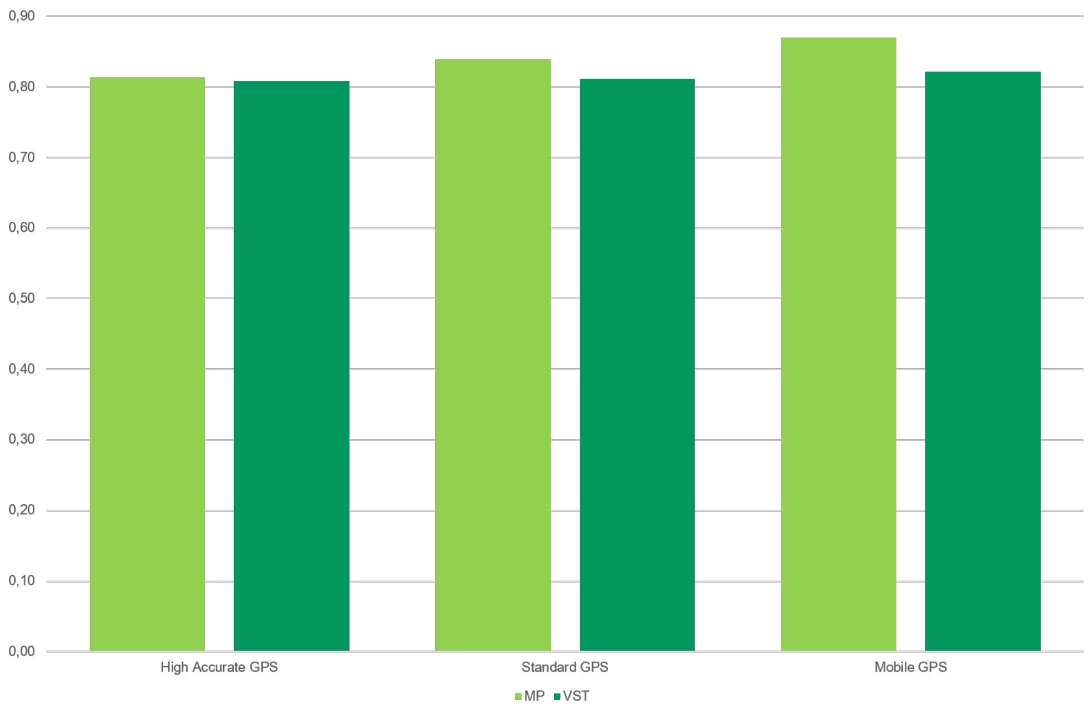

Figure 20: Vehicle stops in Scenario 2

– Average vehicle stops increase from a 0.71% to a 7.62% for MPC and from a 0.36% to a 1.69% for VST.

In this Scenario 2, with saturated traffic condition, VST performs better with Standard GPS error than MPC without errors applied and VST has imperceptible performance changes when errors are added, especially in vehicle throughput and vehicle stops. It can be appreciated how MPC starts suffering when errors are added, but still, it is not that important and the LOS remains *"D"* for all of the situations.

5.3 Scenario 3

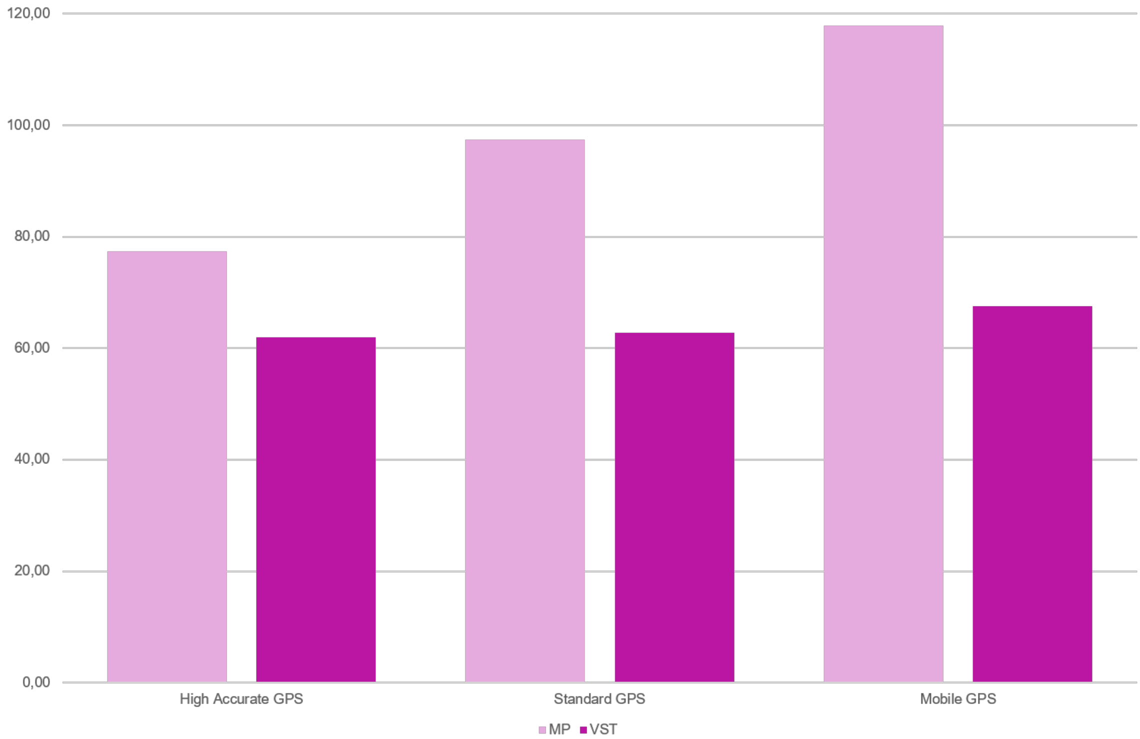

Figure 21: Vehicle delay in Scenario 3 (s)

– Average vehicle delays increase from a 24.93% to a 90.45% for MPC and from a 1.46% to a 9.11% for VST.

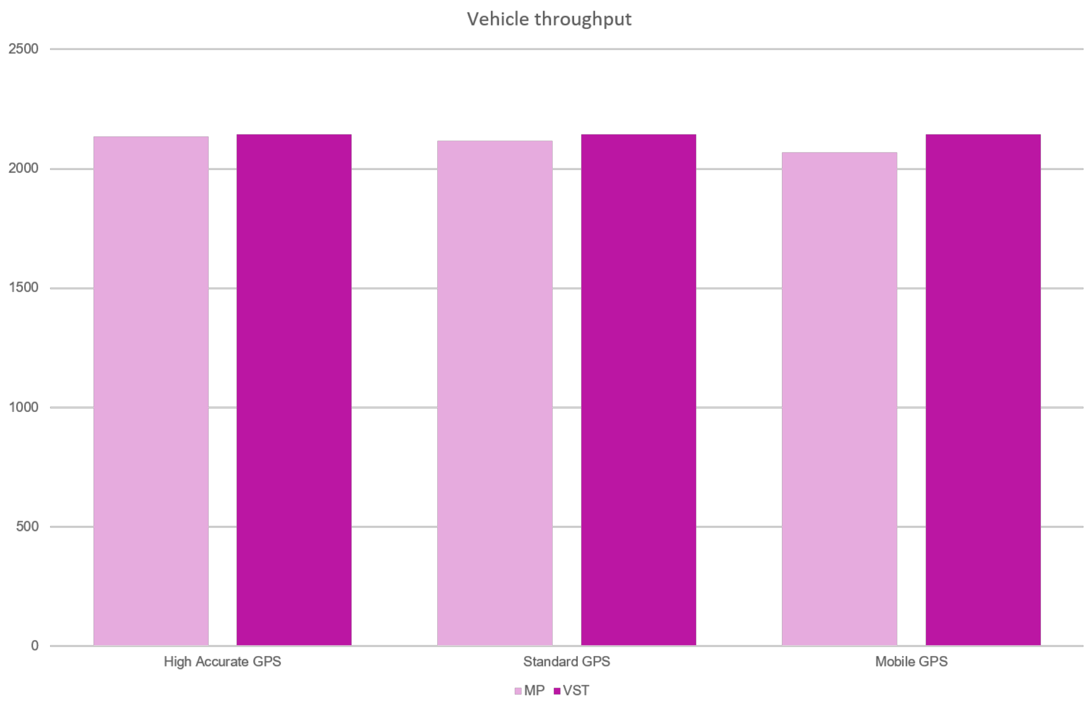

Figure 22: Vehicle throughput in Scenario 3

- Vehicle throughput decreases from a 0.51% to a 3.58% for MPC and from a 0.04% to a 0.09% for VST.

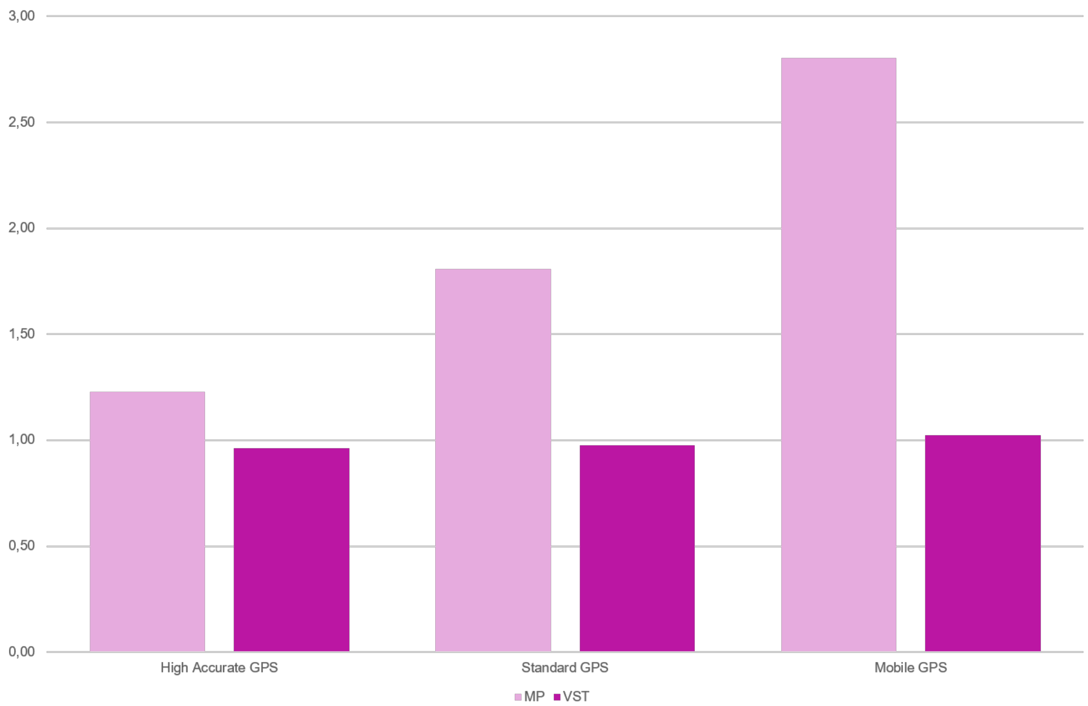

Figure 23: Vehicle stops in Scenario 3

– Vehicle stops increase from a 27.99% to a 191.62% for MPC and from a 1.46% to a 6.60% for VST.

Scenario 3, with its over-saturated condition, is where fluctuations start being very perceptible. It can be stated that MPC performance is dreadful and even VST with mobile GPS error performs better than MPC without error. The overall LOS *"E"* even gets worse for MPC to *"F"* when errors are added to the data. However, VST appears to be very stable, especially in vehicle throughput where VST performs a bit better with Standard GPS errors added, but still has some issue performance when referring to vehicle delays and vehicle stops, especially with mobile GPS error.

5.4 Results summary

Table 6: Average vehicle delay

	Average vehicle delay (s)					
	High Accurate GPS		**Standard GPS**		**Mobile GPS**	
Scenario	*MP*	*VST*	*MP*	*VST*	*MP*	*VST*
1	32.39	32.22	32.79	32.75	33.53	33.53
2	43.75	43.31	46.13	43.40	47.94	44.71
3	77.31	61.89	97.34	62.79	117.86	67.52

Table 7: Average vehicle throughput

	Average vehicle throughput					
	High Accurate GPS		**Standard GPS**		**Mobile GPS**	
Scenario	*MP*	*VST*	*MP*	*VST*	*MP*	*VST*
1	877	885	858	884	825	882
2	1148	1152	1138	1152	1116	1152
3	2134	2143	2117	2145	2068	2144

Table 8: Average vehicle stops

	Average vehicle stops					
	High Accurate GPS		**Standard GPS**		**Mobile GPS**	
Scenario	*MP*	*VST*	*MP*	*VST*	*MP*	*VST*
1	0.78	0.77	0.78	0.78	0.79	0.79
2	0.81	0.81	0.84	0.81	0.87	0.82
3	1.23	0.96	1.81	0.97	2.80	1.02

6 Discussion

The first thing that can be stated is that the maximum capacities established in STM and HCM are below the ones that can be achieved under a CV environment. This is due to the obtaining of LOS better than the worst, which is *"F"*, in most of the cases. Therefore, CVs can improve the LOS and the capacity in isolated signalized intersections.

Table 9: Intersection LOS based on average delay

	High Accurate GPS		**Standard GPS**		**Mobile GPS**	
Scenario	*MP*	*VST*	*MP*	*VST*	*MP*	*VST*
1	C	C	C	C	C	C
2	D	D	D	D	D	D
3	E	E	F	E	F	E

This will translate into cost and money savings, aside from environmental benefits. Nonetheless, it is not known how worth it will be, as nowadays connected vehicles are not an affordable product for the most of the population, and how difficult and expensive it would be implementing these controllers and maintain them since they process a huge amount of information that need powerful computers to give instant results.

Overall, the VST methodology performs better than the MPC, having a higher total vehicle throughput, smaller average delays and less average number of stops per total number of vehicles. This can be especially noticed in over-saturated conditions, where MPC even decreases the LOS with lower GPS quality.

When more simulations were executed for VST with higher errors, it turned out that the results were very similar, although always following the same pattern of getting higher delays, lower vehicle throughput and more vehicle stops when errors were higher.

It can be then affirmed that VST is pretty much non-sensitive to errors, whilst MPC is more sensitive. This can be explained because of the different nature of the output got when the errors are added and the different ways of execution that each algorithm follows. VST detects all the cars in a very big range (1 kilometer as mentioned before) and then calculates the time arrival based on speed and distance to the stop bar for all the vehicles, without skipping none. When errors are implemented they may affect in a similar way to every car so that the time passage prediction is not that much affected by it. Meanwhile, on the other hand, MPC creates misprediction at all times directly by generating wrong queue lengths by either not considering stopped cars that are actually in the queue or considering more not moving cars in the queue than the ones that are really in the queue.

It is important to note that the framework of this project has been almost simplified to the fullest. For instance, it has been created an unrealistic and idealized network which is a cross perfect intersection where errors are implemented according to its particular perpendicular geometric design, but not all the intersections meet the same plant in real life. Therefore, the methodology used is only applicable to this case.

Other features that remove complexity can be the no consideration of right turns with yields, the prohibition of overtaking and lane changing, the use of the same type of private car, the simplified vehicle behavior model and the full CVs environment. Furthermore, the considered scenarios are not realistic but can be assumed as a down-to-earth representation of different types of traffic conditions.

The straightforwardly approximated queue length with the space occupied by the car length plus the safety distance considered can lead to a big limitation of the model. The assumption of infinite storage capacity on each approach is a problem because if a lane can only accommodate a certain queue length, some movements may be blocked.

In addition, it has not been considered how estimations can be sensitive to interrupted traffic from the same lane or from adjacent parking lots, driveways or vehicles in parallel roads which do not interfere in the intersection but may introduce significant noises to the vehicle speeds estimations. Thus, the proposed strategies are only suitable for estimation at isolated signalized intersections.

All in all, with the study limitations, it can be concluded that, depending on which one, some control strategies can be feasible and suitable to implement in a real-life environment because they can properly work with data provided by CVs, even when some errors appear in the sent position.

This is the case of VST, which performs quite well in all the situations, unlike MPC which has troubles in congested situations. So in the first case, standard GPS and mobile GPS can also be a reliable source of information. It must be remembered that the mobile GPS is based on errors in open field data and that in cities these errors will increase.

7 Conclusion

An isolated four-approach intersection with only through and left-turning movements has been tested with two different traffic signal controllers under a fully CV environment to figure out whether they can work with error implemented on the estimation inputs.

The MPC and the VST were the algorithm strategies used, resulting in that VST is more stable when errors are added because it considers all the vehicles, unlike MPC which erroneously counts less or adds more vehicles to the account, creating misprediction and worst performance.

These algorithms and the scenarios where they have been tested have been very simplified due to the time and the resources available. This allows a wide range of possibilities for future extension of the project.

For future development, the intersection can be more complex in different ways. For example, the algorithms can be implemented on networks considering public transport, bicycles, pedestrians, different types of private vehicles, heavy traffic or different penetration rates. Some traffic modes might require priority (e.g., public transportation vehicles, emergency vehicles) and to deal with it the objective function can be changed for the total passenger delay, for transit vehicles, or the total value of the time, for emergency vehicles. Other performance measures, such as users delay for all the vehicles or emissions, or even a mix of both can be considered down the road.

Another way to add complexity could be by incorporating extra movements to the intersection, planning turning trajectories and lane changings with the coexistence of conventional, connected and/or automated vehicles. This can be translated in disruptions in communications or environments with lower CV penetration rates or lack of communication between intersections. Ongoing efforts can be made not only in the cooperation between the vehicles and the intersections but also among intersections, becoming an arterial or network control. In case the work wants to be implemented in CAVs environments, minimum green times can be reduced to less than 5 seconds according to [37].

Another aspect to investigate is the cybersecurity issues that can appear. For instance, privacy protection of individual users might be infringed when vehicles or people are identified when traveling in the network and vehicle's safety can be an issue in case of falsified or manipulated data.

Moreover, one thing that these simulations do not consider at the moment, is that the controllers do not receive any information nor feedback on the driver behavior and driver routing choice in particular. It can be expected that drivers change their routing choice when arriving at the intersection if the traffic light gives the right of way in favor of some exit nodes due to traffic flow conditions. The driver's behavior can also be implemented in the acceleration framework. It would be interesting if some future works will take into account those behaviors since they can stabilize or unstabilize the queuing in the network.

The module of queue length estimation can be replaced if necessary by more complex algorithms that are based in the distance and front vehicle status, allowing more accurate detection in real networks when the in-queue vehicle speed is greater than zero but still considerably low. Another thing that could be studied is the range of detection in both controllers, how big it should be for appropriate performance for example.

As previously mentioned in section 6, some further studies should consider that some adjacent parking lots, driveways or vehicles in parallel roads may result in higher sensitivity for estimations of traffic volume and thus noises in the vehicle trajectories.

Regarding user-based controllers, it is known that some conventional solutions like High Occupancy Vehicles (HOV) lanes have been fooled out with some trickeries such as inflatable dolls. Thus, it is proposed that future studies focus more on public transportation priority instead of giving some advantages to private cars with high occupancy or shared cars. Information sent to the controller can be manipulated very easily by users.

Above all, the main goal of taking advantage of the opportunity of CVs is not encouraging the use of the private car because, otherwise, traffic volumes will reach some values that could not be handled in the limited space that urban arteries provide. Instead, the aim should be improving traffic flow and making it smoother through the city thanks to the public and sustainable transport systems that can complement mobility.

If possible, field tests with actual CVs and GPS should be carried out in a near future to analyze results and be able to gain valuable insights into CVs urban traffic control with errors and select the one that fits better for cities.

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A Appendix 1: Results Max Pressure Control

A.1 Vehicle delays

Table A1: Vehicle delay for MPC with High Accurate GPS in Scenario 1

Scenario 1	**High Accurate GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	33.41	29.66	36.71	35.48	24.07	31.88	39.13	36.33	32.55	32.08	32.31
Simulation 2	24.66	29.92	34.14	43.30	33.18	30.77	33.77	36.61	32.21	32.89	32.55
Simulation 3	30.69	28.98	34.16	40.09	28.64	29.60	38.28	38.77	32.25	32.34	32.29
Simulation 4	28.46	30.26	33.90	34.74	22.73	29.43	40.23	37.95	31.24	31.01	31.12
Simulation 5	26.34	27.60	32.00	43.16	29.54	30.56	34.69	41.51	31.17	33.29	32.22
Simulation 6	30.82	31.23	41.33	35.85	26.18	29.09	32.91	39.87	33.25	31.26	32.25
Simulation 7	34.39	31.33	40.17	39.76	25.68	28.27	39.69	44.85	34.82	32.47	33.65
Simulation 8	28.85	31.02	42.86	39.20	31.44	29.67	38.39	37.59	33.47	32.86	33.17
Simulation 9	26.48	33.83	35.30	42.14	29.15	30.90	34.15	37.62	34.11	32.29	33.20
Simulation 10	23.32	26.42	36.18	35.78	29.33	31.27	41.26	36.51	28.72	33.09	30.90
Simulation 11	28.40	33.18	40.22	40.13	28.08	32.52	39.43	39.60	34.49	33.70	34.10
Simulation 12	30.73	30.79	38.71	37.03	28.39	30.24	36.32	39.36	33.03	32.51	32.77
Simulation 13	29.12	28.90	39.48	40.81	29.49	31.04	37.51	41.60	32.64	33.74	33.20
Simulation 14	31.29	31.80	30.87	38.56	29.70	29.65	37.97	38.33	33.10	32.53	32.81
Simulation 15	28.01	29.79	33.33	28.03	28.45	28.82	38.38	39.55	29.41	32.07	30.75
Simulation 16	29.07	32.48	33.53	37.68	28.62	28.77	36.94	42.94	33.03	32.70	32.86
Simulation 17	27.20	30.10	35.26	37.42	25.85	30.45	38.20	40.62	31.52	32.55	32.03
Simulation 18	26.27	30.47	33.05	35.45	26.83	27.82	38.25	38.16	30.86	30.93	30.89
Simulation 19	27.73	30.13	39.50	36.11	24.45	29.60	37.98	42.30	31.88	32.14	32.01
Simulation 20	27.38	30.55	30.68	38.84	31.36	28.83	38.81	42.85	31.61	33.57	32.60
Mean	28.63	30.42	36.07	37.98	28.06	29.96	37.61	39.65	32.27	32.50	32.39

Table A2: Vehicle delay for MPC with Standard GPS in Scenario 1

Scenario 1	**Standard GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	29.62	29.11	37.25	37.32	23.92	31.30	36.87	38.57	31.90	32.03	31.96
Simulation 2	28.09	33.27	36.97	40.36	28.47	33.32	33.13	35.70	34.15	32.71	33.43
Simulation 3	30.94	29.65	34.65	39.47	27.85	28.83	36.19	37.63	32.53	31.34	31.92
Simulation 4	28.68	28.66	32.47	33.19	22.55	29.35	39.92	41.00	30.07	31.54	30.81
Simulation 5	28.51	26.94	33.70	42.70	28.87	34.36	32.72	39.04	31.46	34.05	32.75
Simulation 6	33.46	29.04	43.32	35.43	27.33	27.78	33.05	39.70	33.01	30.91	31.96
Simulation 7	36.22	29.11	39.72	37.51	26.38	29.92	36.03	42.91	33.69	32.53	33.12
Simulation 8	29.86	32.01	42.00	38.16	29.10	28.67	41.10	36.90	33.79	32.10	32.96
Simulation 9	25.99	34.60	37.95	42.62	29.17	31.55	35.44	37.73	34.73	32.74	33.75
Simulation 10	24.18	30.16	37.54	39.34	28.71	31.77	39.44	38.01	31.48	33.27	32.38
Simulation 11	25.86	34.08	42.04	38.61	31.37	34.67	42.31	37.49	34.17	35.33	34.74
Simulation 12	29.07	32.24	36.38	42.03	29.59	33.56	35.74	37.77	34.03	33.79	33.91
Simulation 13	31.15	32.47	34.21	43.44	26.55	31.74	36.25	39.23	34.69	32.59	33.61
Simulation 14	29.49	32.90	37.96	42.03	34.43	29.76	35.02	36.44	34.79	32.85	33.83
Simulation 15	27.73	30.96	32.66	30.42	27.38	30.15	43.12	38.72	30.31	32.73	31.52
Simulation 16	29.59	33.64	32.24	37.17	32.97	27.30	35.29	39.11	33.42	31.91	32.66
Simulation 17	29.14	29.90	41.05	41.12	25.97	28.69	37.07	43.65	33.29	32.28	32.79
Simulation 18	31.04	32.96	32.59	35.58	28.38	27.84	37.27	41.64	33.03	31.93	32.48
Simulation 19	25.40	31.59	38.27	35.82	24.23	30.91	37.15	40.94	31.87	32.27	32.06
Simulation 20	24.46	33.61	33.58	38.55	28.82	31.38	39.58	40.68	32.55	33.70	33.13
Mean	28.92	31.35	36.83	38.54	28.10	30.64	37.13	39.14	32.95	32.63	32.79

Table A3: Vehicle delay for MPC with Mobile GPS in Scenario 1

Scenario 1	**Mobile GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	32.19	28.03	36.40	38.92	26.44	33.98	34.06	35.72	32.27	32.81	32.54
Simulation 2	25.41	30.04	38.59	42.73	31.17	30.94	31.49	34.34	32.86	31.79	32.33
Simulation 3	30.49	34.38	37.11	37.65	30.82	30.20	33.27	37.43	34.54	32.27	33.38
Simulation 4	28.02	29.66	30.80	33.59	23.96	28.66	38.98	39.65	30.26	31.10	30.68
Simulation 5	30.54	28.22	35.25	41.94	29.53	30.39	36.64	37.10	32.49	32.39	32.44
Simulation 6	27.45	31.63	39.83	36.68	28.26	32.22	29.60	41.52	32.69	33.04	32.86
Simulation 7	37.77	33.06	35.52	40.67	25.92	33.13	36.69	40.37	35.99	33.32	34.68
Simulation 8	29.82	34.37	41.53	40.31	30.57	32.01	41.49	37.81	35.27	34.15	34.72
Simulation 9	29.85	39.76	38.27	40.86	26.42	42.43	38.69	36.14	37.58	37.15	37.36
Simulation 10	24.15	27.86	36.23	38.96	26.92	34.44	39.86	34.19	30.22	33.27	31.76
Simulation 11	27.27	37.11	37.53	38.16	30.01	36.82	39.74	36.72	35.27	35.51	35.39
Simulation 12	28.33	30.48	40.93	40.86	31.00	32.71	31.77	39.79	33.38	33.62	33.50
Simulation 13	27.20	31.21	34.17	43.61	27.92	33.24	38.68	39.39	33.43	33.87	33.66
Simulation 14	31.76	35.07	35.52	41.68	32.11	33.66	39.47	35.13	35.91	34.32	35.12
Simulation 15	28.88	31.08	35.28	30.37	27.88	35.01	41.95	38.22	30.89	34.91	32.87
Simulation 16	34.13	31.59	33.60	36.00	25.54	30.18	36.96	37.06	33.33	31.37	32.34
Simulation 17	28.60	38.13	37.51	39.73	21.82	35.06	33.02	40.91	36.20	33.18	34.69
Simulation 18	28.84	34.96	32.24	34.79	32.03	30.12	39.07	40.23	33.21	33.78	33.49
Simulation 19	28.59	33.51	34.06	36.70	26.93	31.61	39.82	38.36	33.15	32.81	32.99
Simulation 20	29.30	30.92	37.69	39.86	31.58	31.56	33.70	42.34	33.25	34.14	33.70
Mean	29.43	32.55	36.40	38.70	28.34	32.92	36.75	38.12	33.61	33.44	33.53

Table A4: Vehicle delay for MPC with High Accurate GPS in Scenario 2

Scenario 2	**High Accurate GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	28.86	36.81	51.70	60.92	29.88	33.06	47.31	73.84	41.94	43.53	42.75
Simulation 2	30.89	36.52	54.05	67.69	33.20	41.23	53.53	57.67	44.20	44.28	44.24
Simulation 3	38.08	34.41	53.58	52.56	35.91	40.97	46.72	67.19	41.09	46.08	43.62
Simulation 4	33.05	32.71	47.80	64.56	33.93	35.52	52.48	58.84	41.35	42.04	41.69
Simulation 5	32.16	37.59	52.14	73.32	36.58	39.71	51.86	52.16	45.42	43.14	44.29
Simulation 6	35.35	37.62	45.74	61.02	35.87	37.92	49.60	68.28	43.16	45.40	44.28
Simulation 7	39.04	37.33	56.71	69.19	33.47	34.41	54.93	51.95	46.76	40.21	43.52
Simulation 8	31.75	36.79	46.59	70.96	35.75	32.83	46.65	70.28	43.73	43.59	43.66
Simulation 9	30.99	40.47	55.80	60.59	33.15	34.40	47.49	65.38	44.44	42.25	43.35
Simulation 10	31.49	38.88	56.00	57.88	34.74	38.23	47.10	68.17	43.03	44.77	43.90
Simulation 11	32.92	38.71	56.18	64.94	35.72	35.09	47.13	55.27	45.24	40.97	43.14
Simulation 12	35.06	39.46	46.81	71.65	34.12	35.79	53.65	69.10	46.32	44.66	45.48
Simulation 13	34.32	38.45	48.97	56.60	33.58	40.05	56.22	63.24	42.73	45.61	44.18
Simulation 14	32.88	38.60	55.47	67.05	37.93	39.82	43.87	58.73	45.58	44.01	44.80
Simulation 15	34.36	35.66	48.88	60.28	33.88	38.78	54.75	64.11	42.36	44.78	43.59
Simulation 16	33.76	35.30	48.89	60.11	35.42	36.25	56.02	72.67	41.96	45.96	43.97
Simulation 17	36.01	36.93	51.12	56.18	32.50	36.02	51.60	67.82	42.42	44.11	43.25
Simulation 18	30.79	40.47	45.88	68.73	32.98	35.63	46.26	56.89	44.80	40.72	42.79
Simulation 19	33.55	38.69	50.95	70.82	33.52	35.06	44.46	64.70	45.75	42.10	43.98
Simulation 20	31.19	37.06	53.99	62.23	30.56	42.30	42.25	69.62	43.10	45.78	44.45
Mean	33.32	37.42	51.36	63.86	34.13	37.15	49.69	63.80	43.77	43.70	43.75

Table A5: Vehicle delay for MPC with Standard GPS in Scenario 2

Scenario 2	**Standard GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	30.56	37.54	55.63	69.15	39.42	38.43	55.28	76.42	44.98	49.46	47.27
Simulation 2	30.59	35.71	53.47	75.45	34.87	43.66	51.66	61.17	45.45	46.38	45.91
Simulation 3	34.54	47.03	48.45	55.15	33.55	45.36	46.08	64.99	46.11	46.97	46.55
Simulation 4	28.57	38.34	48.26	72.19	31.33	39.15	49.69	54.34	44.59	41.83	43.22
Simulation 5	31.29	41.74	53.67	68.61	34.81	40.38	52.33	73.66	46.30	47.93	47.11
Simulation 6	30.78	39.08	48.84	62.87	37.72	41.69	51.52	57.59	43.51	45.31	44.41
Simulation 7	38.47	44.19	56.38	72.94	31.97	42.03	55.58	54.36	50.49	43.90	47.22
Simulation 8	35.83	37.07	43.22	68.86	34.57	37.77	51.54	66.70	43.98	45.37	44.67
Simulation 9	29.89	49.30	50.81	68.18	33.56	49.78	51.61	61.69	49.23	48.93	49.08
Simulation 10	31.30	42.89	62.76	58.03	31.78	40.74	51.45	68.40	45.55	45.78	45.67
Simulation 11	36.28	47.32	57.60	59.56	37.08	44.80	46.54	52.97	48.76	44.91	46.88
Simulation 12	34.89	38.18	44.30	63.40	37.39	37.26	51.78	64.24	43.44	44.50	43.98
Simulation 13	33.59	51.92	45.51	60.04	33.01	57.74	59.83	66.63	48.99	54.45	51.74
Simulation 14	37.87	36.22	56.19	89.54	33.69	43.57	46.90	57.53	50.70	44.81	47.78
Simulation 15	38.25	37.38	48.16	57.31	36.35	36.27	57.18	67.68	43.26	45.48	44.39
Simulation 16	33.04	40.94	48.48	64.92	39.61	41.94	50.90	62.38	45.36	46.74	46.05
Simulation 17	41.47	45.61	47.28	55.62	34.10	40.89	51.07	56.47	46.99	43.93	45.49
Simulation 18	30.69	46.38	50.80	69.85	29.87	39.73	50.49	55.13	48.23	41.90	45.12
Simulation 19	33.19	39.50	48.57	62.31	34.71	39.40	51.37	60.97	43.97	44.28	44.12
Simulation 20	30.31	41.54	53.57	67.99	33.27	43.88	44.59	62.90	46.09	45.87	45.98
Mean	33.57	41.89	51.10	66.10	34.63	42.22	51.37	62.31	46.30	45.94	46.13

Table A6: Vehicle delay for MPC with Mobile GPS in Scenario 2

Scenario 2	**Mobile GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	32.87	36.12	57.85	58.50	36.10	36.48	52.90	74.60	42.74	47.15	44.99
Simulation 2	36.01	38.20	54.19	69.58	35.55	47.30	51.20	57.29	46.68	47.27	46.98
Simulation 3	39.96	64.66	51.33	53.93	30.99	62.94	47.86	66.76	55.53	54.70	55.11
Simulation 4	37.37	42.99	45.60	64.86	41.37	40.91	48.86	53.07	46.80	44.48	45.64
Simulation 5	32.26	40.85	50.85	65.45	32.65	35.98	56.52	73.32	45.11	45.70	45.40
Simulation 6	35.86	42.56	49.15	57.13	33.41	43.27	49.91	71.65	45.06	48.14	46.60
Simulation 7	39.81	39.25	56.77	62.56	34.90	47.82	57.87	54.50	46.33	47.29	46.80
Simulation 8	38.97	34.14	44.93	64.81	43.19	38.25	45.47	64.65	42.42	46.03	44.21
Simulation 9	34.84	40.83	47.48	61.38	33.74	46.37	48.37	58.99	44.79	46.55	45.67
Simulation 10	36.95	40.52	50.43	49.23	36.50	40.84	56.72	73.02	42.61	48.53	45.55
Simulation 11	38.49	40.11	54.80	68.82	39.75	35.86	55.23	54.80	47.85	42.96	45.46
Simulation 12	35.89	40.53	46.16	63.99	39.58	42.94	53.46	62.10	44.94	47.24	46.10
Simulation 13	42.44	44.89	51.39	64.89	41.67	48.97	55.54	66.36	49.34	52.01	50.69
Simulation 14	37.82	55.03	56.82	86.86	38.80	50.90	46.09	57.55	58.66	49.13	53.97
Simulation 15	36.63	50.74	43.93	64.17	35.69	53.49	51.24	72.65	49.77	53.10	51.44
Simulation 16	34.29	46.88	47.25	57.27	39.82	53.80	56.68	72.33	46.66	55.00	50.85
Simulation 17	32.02	57.28	59.12	59.12	29.46	51.84	60.19	57.54	52.12	49.14	50.64
Simulation 18	38.99	41.28	52.09	64.09	35.27	37.42	43.84	56.68	46.76	41.75	44.30
Simulation 19	34.25	57.31	55.72	57.32	36.08	45.62	50.44	71.41	52.00	49.74	50.90
Simulation 20	32.53	46.03	51.88	59.74	42.00	48.86	43.44	56.27	46.58	48.41	47.50
Mean	36.41	45.01	51.39	62.69	36.83	45.49	51.59	63.78	47.64	48.22	47.94

Table A7: Vehicle delay for MPC with High Accurate GPS in Scenario 3

Scenario 3	**High Accurate GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	45.48	77.36	74.49	119.30	45.58	60.83	85.67	133.82	78.48	76.26	77.37
Simulation 2	43.87	72.25	69.34	127.78	44.10	71.57	75.12	93.34	77.08	70.12	73.62
Simulation 3	47.88	65.17	71.20	109.45	42.66	63.12	65.11	164.03	71.60	80.89	76.29
Simulation 4	50.01	87.51	58.63	125.79	42.04	85.50	69.89	90.18	84.42	75.43	79.95
Simulation 5	45.12	62.60	70.45	126.95	38.44	66.45	82.30	121.91	72.75	73.71	73.23
Simulation 6	42.42	85.89	67.59	92.00	40.28	96.32	93.09	91.46	75.51	82.52	79.02
Simulation 7	43.03	61.94	65.12	108.46	47.71	90.01	73.20	100.49	67.98	80.86	74.36
Simulation 8	46.90	65.93	65.72	94.61	46.08	60.64	76.55	133.70	67.56	75.14	71.31
Simulation 9	48.61	87.25	69.57	100.12	43.26	71.84	67.56	93.69	79.68	69.72	74.72
Simulation 10	47.12	74.29	63.30	152.14	46.12	73.53	83.54	141.77	83.46	83.07	83.27
Simulation 11	46.92	85.78	67.45	131.14	47.90	64.27	83.09	124.35	85.11	74.72	79.99
Simulation 12	52.93	77.02	66.60	98.82	44.32	80.31	68.14	90.38	75.17	73.25	74.21
Simulation 13	45.13	67.28	65.51	113.35	45.42	91.99	71.88	102.38	72.04	81.87	76.97
Simulation 14	45.22	77.90	59.79	117.11	47.19	71.50	78.26	104.78	76.26	73.61	74.92
Simulation 15	47.49	64.36	64.92	131.02	41.61	55.37	84.16	156.21	74.98	76.78	75.89
Simulation 16	48.04	87.70	66.85	117.09	45.70	91.45	71.14	117.01	83.15	84.59	83.87
Simulation 17	47.97	86.26	67.52	133.71	47.00	70.16	80.60	97.92	85.11	72.08	78.63
Simulation 18	49.84	71.67	64.44	155.06	43.98	71.75	73.90	155.37	83.58	83.88	83.73
Simulation 19	42.99	65.40	66.53	135.63	44.95	74.46	65.37	157.68	75.78	85.20	80.43
Simulation 20	44.95	60.53	64.84	131.51	43.91	63.95	84.19	128.52	72.90	76.13	74.52
Mean	46.60	74.20	66.49	121.05	44.41	73.75	76.64	119.95	77.13	77.49	77.31

Table A8: Vehicle delay for MPC with Standard GPS in Scenario 3

Scenario 3	**Standard GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	49.46	87.89	78.14	142.90	46.09	85.66	111.07	129.68	89.38	89.73	89.55
Simulation 2	71.65	92.19	60.21	264.09	53.28	86.66	73.42	191.45	121.42	99.85	110.71
Simulation 3	55.70	72.06	89.70	128.77	50.55	91.11	75.19	163.93	82.12	95.87	89.09
Simulation 4	53.17	122.36	60.80	138.99	49.28	97.38	65.50	129.63	103.64	90.35	97.01
Simulation 5	66.80	63.65	66.67	226.62	59.03	64.29	84.01	160.08	98.13	86.17	92.20
Simulation 6	45.49	95.07	68.08	169.46	50.71	126.80	77.23	181.27	96.94	116.57	106.76
Simulation 7	45.95	134.44	72.45	87.80	49.55	198.58	75.77	85.20	96.39	126.54	111.46
Simulation 8	45.08	105.84	65.03	180.65	48.22	82.22	91.82	245.23	102.36	111.25	106.77
Simulation 9	49.82	105.92	78.59	131.17	42.15	99.53	76.32	109.36	95.69	86.01	90.84
Simulation 10	45.91	104.53	71.41	109.33	45.59	101.69	72.20	115.44	88.45	88.70	88.58
Simulation 11	50.36	82.40	72.36	181.04	42.38	83.44	83.89	125.98	96.15	83.25	89.83
Simulation 12	56.70	108.55	79.03	153.84	50.98	99.10	79.66	149.55	102.46	95.29	98.90
Simulation 13	51.39	66.54	75.49	132.22	58.58	73.99	81.59	111.38	77.93	79.39	78.66
Simulation 14	39.95	168.30	81.00	144.21	46.91	136.63	82.25	164.68	124.84	116.78	120.78
Simulation 15	52.67	88.70	70.89	166.52	51.62	84.10	90.75	260.57	95.28	114.58	104.96
Simulation 16	43.47	164.34	69.42	105.48	42.98	186.60	67.34	104.40	113.93	123.11	118.51
Simulation 17	54.47	119.88	70.01	109.75	52.13	102.73	72.08	98.02	97.27	86.83	92.09
Simulation 18	60.09	134.96	61.61	124.02	53.97	100.66	76.73	105.84	107.88	88.46	98.27
Simulation 19	51.25	61.07	67.20	126.65	52.85	72.61	79.68	143.24	73.11	83.62	78.29
Simulation 20	48.91	85.43	76.34	136.94	48.47	81.74	90.35	100.27	87.52	79.58	83.54
Mean	51.91	103.21	71.72	148.02	49.77	102.78	80.34	143.76	97.54	97.10	97.34

Table A9: Vehicle delay for MPC with Mobile GPS in Scenario 3

Scenario 3	**Mobile GPS Vehicle delay (s)**										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	44.49	144.45	80.47	124.27	47.50	102.28	86.13	139.56	110.65	96.87	103.77
Simulation 2	40.58	121.90	70.01	132.63	41.17	127.62	82.07	120.57	100.12	101.18	100.64
Simulation 3	57.45	90.77	85.54	131.25	59.60	109.12	71.19	154.54	90.60	102.80	96.78
Simulation 4	67.50	98.31	66.03	161.12	80.84	89.81	60.19	124.77	102.39	92.56	97.49
Simulation 5	44.67	182.12	76.76	128.68	38.92	167.86	86.09	196.24	128.28	135.38	131.78
Simulation 6	49.52	92.54	84.28	133.40	62.68	99.12	87.56	135.86	90.82	97.84	94.34
Simulation 7	57.55	167.93	69.85	121.01	56.71	258.02	77.63	159.92	122.71	173.15	147.85
Simulation 8	49.58	92.68	91.57	154.29	65.60	81.87	108.66	192.17	95.98	106.21	101.06
Simulation 9	49.33	87.77	70.18	258.61	48.96	70.64	111.76	280.59	111.31	114.02	112.66
Simulation 10	80.88	215.75	106.72	99.74	70.67	195.62	107.64	116.74	144.14	137.75	140.92
Simulation 11	57.32	97.74	71.72	188.27	51.30	87.98	104.10	94.92	106.29	83.23	94.93
Simulation 12	63.91	173.01	74.10	101.35	50.40	185.55	58.63	114.26	121.92	126.09	123.99
Simulation 13	74.82	93.75	139.37	205.96	80.86	137.77	105.82	229.65	117.03	139.00	128.05
Simulation 14	81.23	206.23	70.48	141.50	69.23	174.59	90.39	131.86	148.01	131.17	139.49
Simulation 15	56.58	80.02	72.89	130.49	71.98	99.19	79.06	133.82	85.32	98.73	92.03
Simulation 16	56.78	246.93	67.55	174.32	60.43	167.82	75.48	151.66	167.46	130.19	148.68
Simulation 17	55.30	136.68	70.98	147.80	53.80	119.07	99.03	141.79	112.84	106.42	109.64
Simulation 18	46.55	230.94	85.37	100.93	46.70	244.48	76.15	100.19	140.29	143.97	142.13
Simulation 19	41.70	142.21	66.79	150.52	42.56	108.57	71.64	162.01	113.76	102.22	108.07
Simulation 20	46.43	187.61	69.18	120.16	46.06	258.21	93.96	107.20	127.38	158.71	142.95
Mean	56.11	144.47	79.49	145.31	57.30	144.26	86.66	149.42	116.87	118.88	117.86

A.2 Vehicle throughput

Table A10: Vehicle throughput for MPC with High Accurate GPS in Scenario 1

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	97	188	45	94	94	197	52	100	424	443	867
Simulation 2	96	193	53	96	98	196	48	93	438	435	873
Simulation 3	94	200	45	91	103	198	48	99	430	448	878
Simulation 4	96	192	44	96	93	198	48	92	428	431	859
Simulation 5	102	198	46	97	95	194	50	99	443	438	881
Simulation 6	99	199	49	95	96	200	47	98	442	441	883
Simulation 7	101	202	50	97	100	199	45	96	450	440	890
Simulation 8	99	202	46	91	90	191	49	98	438	428	866
Simulation 9	100	202	52	94	99	202	50	94	448	445	893
Simulation 10	103	196	48	92	101	194	51	92	439	438	877
Simulation 11	97	199	46	104	103	192	49	89	446	433	879
Simulation 12	96	195	48	96	96	199	50	96	435	441	876
Simulation 13	91	195	46	90	100	198	46	100	422	444	866
Simulation 14	96	203	49	100	98	196	52	96	448	442	890
Simulation 15	98	194	49	93	100	198	48	94	434	440	874
Simulation 16	94	199	50	98	98	198	49	95	441	440	881
Simulation 17	103	200	48	93	96	198	52	95	444	441	885
Simulation 18	100	201	50	93	102	193	49	91	444	435	879
Simulation 19	103	205	49	98	95	192	45	94	455	426	881
Simulation 20	96	188	49	90	100	192	49	94	423	435	858
Mean	98	198	48	95	98	196	49	95	439	438	877

Table A11: Vehicle throughput for MPC with Standard GPS in Scenario 1

Phase	1	2	3	4	5	6	7	8	Ring 1	Ring 2	Total
Simulation 1	97	188	45	93	94	197	52	100	423	443	866
Simulation 2	95	192	53	96	98	196	48	93	436	435	871
Simulation 3	94	200	45	91	103	198	48	99	430	448	878
Simulation 4	96	192	44	96	93	198	48	92	428	431	859
Simulation 5	102	197	46	97	94	194	50	99	442	437	879
Simulation 6	99	197	49	96	96	200	47	99	441	442	883
Simulation 7	97	198	49	96	100	194	45	93	440	432	872
Simulation 8	98	200	44	87	87	183	48	95	429	413	842
Simulation 9	100	202	52	93	97	202	50	91	447	440	887
Simulation 10	101	189	46	90	98	192	50	90	426	430	856
Simulation 11	97	198	46	104	103	191	49	89	445	432	877
Simulation 12	96	193	47	89	95	198	49	87	425	429	854
Simulation 13	90	182	44	85	98	191	43	90	401	422	823
Simulation 14	91	201	48	98	95	193	51	93	438	432	870
Simulation 15	98	194	49	93	100	197	46	94	434	437	871
Simulation 16	79	173	45	85	86	178	45	80	382	389	771
Simulation 17	102	199	48	93	96	198	52	94	442	440	882
Simulation 18	97	194	47	89	102	189	49	90	427	430	857
Simulation 19	99	202	49	97	91	188	44	89	447	412	859
Simulation 20	91	183	45	83	92	185	45	88	402	410	812
Mean	96	194	47	93	96	193	48	92	429	429	858

Table A12: Vehicle throughput for MPC with Mobile GPS in Scenario 1

Phase	1	2	3	4	5	6	7	8	Ring 1	Ring 2	Total
Simulation 1	92	172	41	85	86	186	51	91	390	414	804
Simulation 2	94	187	51	95	92	190	47	91	427	420	847
Simulation 3	89	193	45	89	103	190	47	96	416	436	852
Simulation 4	86	183	39	85	90	180	46	84	393	400	793
Simulation 5	101	192	44	95	93	188	48	93	432	422	854
Simulation 6	96	191	48	91	94	194	45	90	426	423	849
Simulation 7	93	191	47	89	94	183	41	84	420	402	822
Simulation 8	98	200	44	87	87	183	48	95	429	413	842
Simulation 9	96	190	48	90	92	190	46	87	424	415	839
Simulation 10	87	170	41	78	90	164	46	83	376	383	759
Simulation 11	96	199	46	104	102	190	49	87	445	428	873
Simulation 12	93	187	47	88	93	195	45	82	415	415	830
Simulation 13	83	157	41	82	90	182	40	83	363	395	758
Simulation 14	91	201	48	98	95	193	51	93	438	432	870
Simulation 15	88	177	42	83	83	175	44	78	390	380	770
Simulation 16	79	173	45	84	85	178	45	80	381	388	769
Simulation 17	102	199	48	93	96	197	52	94	442	439	881
Simulation 18	93	178	43	86	96	174	47	86	400	403	803
Simulation 19	97	197	46	93	91	181	42	83	433	397	830
Simulation 20	96	187	49	90	99	192	49	94	422	434	856
Mean	93	186	45	89	93	185	46	88	413	412	825

Table A13: Vehicle throughput for MPC with High Accurate GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	127	249	60	124	126	254	68	136	560	584	1144
Simulation 2	126	254	68	126	128	257	64	120	574	569	1143
Simulation 3	125	262	61	119	132	262	64	125	567	583	1150
Simulation 4	128	260	63	125	125	260	63	122	576	570	1146
Simulation 5	134	261	62	122	125	254	64	126	579	569	1148
Simulation 6	127	260	64	127	125	261	63	126	578	575	1153
Simulation 7	130	264	67	126	130	259	62	125	587	576	1163
Simulation 8	128	263	61	117	118	252	64	129	569	563	1132
Simulation 9	128	263	67	124	128	259	67	123	582	577	1159
Simulation 10	135	257	63	122	133	253	68	121	577	575	1152
Simulation 11	128	261	62	132	129	248	66	121	583	564	1147
Simulation 12	128	252	63	124	128	262	66	126	567	582	1149
Simulation 13	122	257	63	125	128	254	62	130	567	574	1141
Simulation 14	125	266	64	131	128	255	67	126	586	576	1162
Simulation 15	124	247	65	124	132	258	63	122	560	575	1135
Simulation 16	123	260	63	127	131	260	64	122	573	577	1150
Simulation 17	132	261	64	125	125	253	68	126	582	572	1154
Simulation 18	132	264	66	122	132	252	63	121	584	568	1152
Simulation 19	134	270	64	128	126	255	59	121	596	561	1157
Simulation 20	128	246	64	121	127	251	63	127	559	568	1127
Mean	128	259	64	125	128	256	64	125	575	573	1148

Table A14: Vehicle throughput for MPC with Standard GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	126	244	60	124	124	253	68	135	554	580	1134
Simulation 2	125	253	68	126	123	256	64	120	572	563	1135
Simulation 3	125	262	61	118	132	262	64	125	566	583	1149
Simulation 4	128	260	62	125	125	260	63	121	575	569	1144
Simulation 5	133	260	62	122	125	253	64	127	577	569	1146
Simulation 6	122	249	62	120	122	251	62	118	553	553	1106
Simulation 7	130	263	67	126	130	259	62	125	586	576	1162
Simulation 8	126	252	58	113	115	239	63	125	549	542	1091
Simulation 9	128	263	67	124	128	259	67	123	582	577	1159
Simulation 10	135	256	63	122	132	253	68	121	576	574	1150
Simulation 11	128	261	62	132	129	248	66	115	583	558	1141
Simulation 12	129	252	63	119	128	262	66	118	563	574	1137
Simulation 13	122	257	63	122	128	253	61	130	564	572	1136
Simulation 14	124	266	64	131	128	255	67	126	585	576	1161
Simulation 15	124	245	65	124	130	257	63	127	558	577	1135
Simulation 16	121	260	63	125	130	260	64	122	569	576	1145
Simulation 17	123	259	62	118	120	240	64	116	562	540	1102
Simulation 18	132	264	66	122	132	251	62	121	584	566	1150
Simulation 19	133	270	64	128	125	254	59	121	595	559	1154
Simulation 20	128	244	64	121	127	251	63	128	557	569	1126
Mean	127	257	63	123	127	254	64	123	571	568	1138

Table A15: Vehicle throughput for MPC with Mobile GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	126	244	60	124	124	253	68	134	554	579	1133
Simulation 2	123	240	65	125	122	244	61	118	553	545	1098
Simulation 3	116	245	61	110	126	243	61	116	532	546	1078
Simulation 4	127	258	62	125	125	260	63	121	572	569	1141
Simulation 5	132	250	59	119	120	241	60	118	560	539	1099
Simulation 6	127	260	64	129	127	261	63	129	580	580	1160
Simulation 7	117	240	63	111	119	230	55	107	531	511	1042
Simulation 8	121	250	54	105	112	235	60	117	530	524	1054
Simulation 9	122	249	66	122	120	252	63	118	559	553	1112
Simulation 10	135	257	63	122	130	253	67	121	577	571	1148
Simulation 11	126	261	62	132	128	248	66	115	581	557	1138
Simulation 12	127	249	62	114	126	257	63	113	552	559	1111
Simulation 13	120	247	60	116	127	245	58	129	543	559	1102
Simulation 14	119	263	63	126	122	247	64	121	571	554	1125
Simulation 15	120	244	61	118	124	252	60	111	543	547	1090
Simulation 16	116	249	60	127	127	245	63	122	552	557	1109
Simulation 17	131	261	64	120	125	253	68	122	576	568	1144
Simulation 18	131	264	66	122	132	250	62	121	583	565	1148
Simulation 19	133	269	64	130	125	253	57	125	596	560	1156
Simulation 20	128	244	64	121	126	251	63	128	557	568	1125
Mean	125	252	62	121	124	249	62	120	560	556	1116

Table A16: Vehicle throughput for MPC with High Accurate GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	242	482	114	220	235	476	121	233	1058	1065	2123
Simulation 2	232	485	123	217	236	479	118	209	1057	1042	2099
Simulation 3	237	485	112	232	244	490	116	239	1066	1089	2155
Simulation 4	239	485	118	236	230	490	116	230	1078	1066	2144
Simulation 5	244	490	116	221	235	480	114	224	1071	1053	2124
Simulation 6	229	491	118	207	234	487	117	215	1045	1053	2098
Simulation 7	247	490	124	234	243	489	114	227	1095	1073	2168
Simulation 8	241	493	119	222	226	480	122	228	1075	1056	2131
Simulation 9	234	488	121	235	241	475	121	235	1078	1072	2150
Simulation 10	238	493	120	227	238	493	118	229	1078	1078	2156
Simulation 11	238	492	114	234	230	489	120	207	1078	1046	2124
Simulation 12	239	482	121	231	232	492	121	225	1073	1070	2143
Simulation 13	234	487	117	227	233	488	118	231	1065	1070	2135
Simulation 14	235	486	119	207	240	482	121	218	1047	1061	2108
Simulation 15	233	477	119	226	243	484	119	227	1055	1073	2128
Simulation 16	234	490	122	235	234	480	120	229	1081	1063	2144
Simulation 17	247	484	118	220	238	472	122	226	1069	1058	2127
Simulation 18	240	495	120	228	241	478	117	232	1083	1068	2151
Simulation 19	238	491	119	234	233	479	112	231	1082	1055	2137
Simulation 20	241	472	119	231	234	481	116	238	1063	1069	2132
Mean	238	487	119	226	236	483	118	227	1070	1064	2134

Table A17: Vehicle throughput for MPC with Standard GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	241	480	114	217	230	477	121	235	1052	1063	2115
Simulation 2	232	470	123	230	236	467	117	221	1055	1041	2096
Simulation 3	236	485	112	220	244	490	116	232	1053	1082	2135
Simulation 4	239	464	116	236	230	474	116	229	1055	1049	2104
Simulation 5	243	483	119	218	235	467	116	228	1063	1046	2109
Simulation 6	229	488	118	222	232	481	115	230	1057	1058	2115
Simulation 7	248	458	123	230	243	472	114	230	1059	1059	2118
Simulation 8	240	482	117	210	225	467	117	224	1049	1033	2082
Simulation 9	234	488	121	220	241	478	121	226	1063	1066	2129
Simulation 10	239	471	120	222	238	470	119	229	1052	1056	2108
Simulation 11	238	492	114	240	230	476	120	216	1084	1042	2126
Simulation 12	238	482	121	210	232	491	122	190	1051	1035	2086
Simulation 13	234	487	119	222	233	489	118	226	1062	1066	2128
Simulation 14	235	471	117	238	240	479	120	238	1061	1077	2138
Simulation 15	233	476	119	224	243	473	119	223	1052	1058	2110
Simulation 16	234	473	122	228	234	469	121	229	1057	1053	2110
Simulation 17	246	481	117	228	237	469	122	229	1072	1057	2129
Simulation 18	240	495	121	227	241	477	119	224	1083	1061	2144
Simulation 19	240	497	119	223	235	484	112	218	1079	1049	2128
Simulation 20	241	468	119	235	233	480	116	240	1063	1069	2132
Mean	238	480	119	225	236	477	118	226	1061	1056	2117

Table A18: Vehicle throughput for MPC with Mobile GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	242	482	114	232	231	478	121	237	1070	1067	2137
Simulation 2	232	461	123	230	236	458	117	221	1046	1032	2078
Simulation 3	238	469	112	206	245	474	115	217	1025	1051	2076
Simulation 4	228	450	115	238	226	449	115	236	1031	1026	2057
Simulation 5	242	488	119	221	235	474	118	215	1070	1042	2112
Simulation 6	232	475	118	224	239	470	110	235	1049	1054	2103
Simulation 7	230	485	124	230	236	488	115	223	1069	1062	2131
Simulation 8	229	465	111	217	216	449	114	226	1022	1005	2027
Simulation 9	234	493	121	211	241	477	120	220	1059	1058	2117
Simulation 10	238	417	118	234	238	425	119	240	1007	1022	2029
Simulation 11	237	492	114	241	229	489	118	216	1084	1052	2136
Simulation 12	239	470	121	212	232	470	119	199	1042	1020	2062
Simulation 13	224	451	113	196	222	470	110	189	984	991	1975
Simulation 14	225	431	112	213	231	434	115	225	981	1005	1986
Simulation 15	230	467	116	233	235	459	116	238	1046	1048	2094
Simulation 16	232	455	121	235	233	473	120	234	1043	1060	2103
Simulation 17	234	467	107	195	229	452	114	203	1003	998	2001
Simulation 18	235	400	115	201	236	395	112	209	951	952	1903
Simulation 19	237	486	117	238	227	478	110	232	1078	1047	2125
Simulation 20	241	467	119	234	233	462	116	237	1061	1048	2109
Mean	234	464	117	222	233	461	116	223	1036	1032	2068

A.3 Vehicle stops

Table A19: Vehicle stops for MPC with High Accurate GPS in Scenario 1

Scenario 1	High Accurate GPS										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.79	0.77	0.82	0.89	0.63	0.83	0.83	0.78	0.81	0.78	0.79
Simulation 2	0.66	0.75	0.83	0.93	0.82	0.77	0.73	0.86	0.78	0.79	0.79
Simulation 3	0.72	0.73	0.78	0.92	0.70	0.75	0.90	0.82	0.77	0.77	0.77
Simulation 4	0.70	0.74	0.82	0.82	0.62	0.78	0.85	0.80	0.76	0.76	0.76
Simulation 5	0.67	0.72	0.76	0.91	0.73	0.75	0.78	0.88	0.75	0.78	0.77
Simulation 6	0.77	0.79	0.84	0.86	0.66	0.75	0.87	0.89	0.81	0.77	0.79
Simulation 7	0.75	0.73	0.88	0.89	0.69	0.72	0.82	0.89	0.78	0.76	0.77
Simulation 8	0.67	0.77	0.87	0.84	0.78	0.76	0.80	0.85	0.77	0.79	0.78
Simulation 9	0.68	0.82	0.75	0.89	0.76	0.76	0.74	0.84	0.80	0.78	0.79
Simulation 10	0.66	0.72	0.75	0.79	0.74	0.77	0.88	0.80	0.73	0.79	0.76
Simulation 11	0.69	0.79	0.87	0.88	0.70	0.80	0.82	0.88	0.80	0.79	0.79
Simulation 12	0.74	0.73	0.81	0.84	0.71	0.74	0.86	0.89	0.77	0.78	0.77
Simulation 13	0.75	0.71	0.93	0.89	0.71	0.82	0.83	0.87	0.78	0.81	0.79
Simulation 14	0.76	0.76	0.69	0.87	0.73	0.73	0.88	0.90	0.78	0.79	0.78
Simulation 15	0.67	0.77	0.78	0.74	0.66	0.72	0.81	0.83	0.74	0.74	0.74
Simulation 16	0.74	0.81	0.78	0.89	0.72	0.80	0.82	0.92	0.81	0.81	0.81
Simulation 17	0.63	0.73	0.79	0.83	0.68	0.78	0.83	0.85	0.73	0.78	0.76
Simulation 18	0.65	0.78	0.84	0.84	0.61	0.68	0.82	0.85	0.77	0.71	0.74
Simulation 19	0.69	0.80	0.94	0.87	0.67	0.76	0.82	0.90	0.80	0.78	0.79
Simulation 20	0.73	0.78	0.73	0.83	0.76	0.76	0.84	0.89	0.78	0.80	0.79
Mean	0.71	0.76	0.81	0.86	0.70	0.76	0.83	0.86	0.78	0.78	0.78

Table A20: Vehicle stops for MPC with Standard GPS in Scenario 1

Scenario 1	Standard GPS										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.69	0.75	0.89	0.88	0.65	0.83	0.81	0.77	0.78	0.78	0.78
Simulation 2	0.64	0.82	0.85	0.90	0.72	0.82	0.75	0.82	0.80	0.79	0.80
Simulation 3	0.73	0.71	0.76	0.88	0.69	0.74	0.88	0.81	0.76	0.76	0.76
Simulation 4	0.71	0.73	0.80	0.81	0.61	0.77	0.83	0.88	0.75	0.77	0.76
Simulation 5	0.69	0.73	0.83	0.92	0.71	0.82	0.76	0.84	0.77	0.80	0.78
Simulation 6	0.84	0.78	0.90	0.85	0.70	0.72	0.85	0.82	0.82	0.75	0.79
Simulation 7	0.79	0.71	0.88	0.84	0.67	0.75	0.78	0.87	0.78	0.76	0.77
Simulation 8	0.70	0.81	0.84	0.83	0.71	0.74	0.77	0.81	0.79	0.76	0.77
Simulation 9	0.67	0.83	0.81	0.87	0.77	0.78	0.70	0.85	0.80	0.78	0.79
Simulation 10	0.65	0.76	0.80	0.83	0.72	0.78	0.88	0.86	0.75	0.80	0.77
Simulation 11	0.67	0.80	0.91	0.82	0.75	0.83	0.84	0.82	0.79	0.81	0.80
Simulation 12	0.71	0.73	0.81	0.90	0.72	0.78	0.80	0.87	0.77	0.79	0.78
Simulation 13	0.81	0.75	0.89	0.94	0.64	0.83	0.77	0.86	0.82	0.79	0.80
Simulation 14	0.68	0.79	0.83	0.91	0.79	0.75	0.82	0.84	0.80	0.78	0.79
Simulation 15	0.67	0.78	0.78	0.78	0.63	0.75	0.89	0.83	0.76	0.76	0.76
Simulation 16	0.73	0.85	0.76	0.86	0.77	0.76	0.80	0.88	0.82	0.79	0.80
Simulation 17	0.67	0.72	0.85	0.86	0.67	0.77	0.83	0.94	0.75	0.79	0.77
Simulation 18	0.73	0.80	0.87	0.82	0.64	0.70	0.78	0.89	0.80	0.73	0.77
Simulation 19	0.64	0.82	0.94	0.86	0.69	0.78	0.80	0.89	0.80	0.79	0.79
Simulation 20	0.68	0.85	0.76	0.83	0.74	0.79	0.84	0.86	0.80	0.80	0.80
Mean	0.71	0.78	0.84	0.86	0.70	0.78	0.81	0.85	0.78	0.78	0.78

Table A21: Vehicle stops for MPC with Mobile GPS in Scenario 1

Scenario 1	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.74	0.74	0.83	0.89	0.67	0.85	0.73	0.76	0.78	0.78	0.78
Simulation 2	0.63	0.77	0.86	0.92	0.77	0.75	0.72	0.86	0.78	0.77	0.78
Simulation 3	0.78	0.81	0.73	0.84	0.72	0.72	0.87	0.84	0.80	0.76	0.78
Simulation 4	0.65	0.70	0.85	0.78	0.66	0.78	0.83	0.82	0.72	0.77	0.74
Simulation 5	0.74	0.70	0.82	0.92	0.70	0.77	0.83	0.84	0.77	0.78	0.77
Simulation 6	0.71	0.81	0.79	0.81	0.70	0.78	0.78	0.88	0.78	0.78	0.78
Simulation 7	0.80	0.78	0.85	0.92	0.61	0.83	0.76	0.82	0.82	0.77	0.79
Simulation 8	0.71	0.82	0.89	0.87	0.75	0.84	0.79	0.83	0.81	0.81	0.81
Simulation 9	0.77	0.91	0.85	0.89	0.70	0.99	0.72	0.84	0.87	0.87	0.87
Simulation 10	0.61	0.74	0.78	0.83	0.70	0.80	0.89	0.82	0.73	0.79	0.76
Simulation 11	0.69	0.84	0.83	0.85	0.72	0.88	0.82	0.79	0.81	0.82	0.81
Simulation 12	0.69	0.71	0.89	0.90	0.73	0.78	0.76	0.90	0.77	0.79	0.78
Simulation 13	0.77	0.76	0.85	0.93	0.62	0.85	0.85	0.86	0.81	0.80	0.80
Simulation 14	0.69	0.84	0.81	0.91	0.76	0.82	0.88	0.85	0.82	0.82	0.82
Simulation 15	0.69	0.80	0.83	0.78	0.60	0.81	0.93	0.85	0.77	0.79	0.78
Simulation 16	0.76	0.83	0.78	0.88	0.64	0.77	0.84	0.88	0.82	0.77	0.80
Simulation 17	0.67	0.87	0.83	0.84	0.61	0.87	0.77	0.90	0.81	0.81	0.81
Simulation 18	0.68	0.82	0.81	0.79	0.72	0.71	0.79	0.86	0.78	0.75	0.77
Simulation 19	0.68	0.84	0.89	0.85	0.69	0.80	0.90	0.83	0.81	0.79	0.80
Simulation 20	0.75	0.76	0.84	0.87	0.78	0.78	0.78	0.89	0.79	0.80	0.80
Mean	0.71	0.79	0.83	0.86	0.69	0.81	0.81	0.85	0.79	0.79	0.79

Table A22: Vehicle stops for MPC with High Accurate GPS in Scenario 2

Scenario 2	**High Accurate GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.63	0.76	0.87	0.99	0.60	0.74	0.82	1.05	0.79	0.79	0.79
Simulation 2	0.67	0.77	0.88	1.06	0.70	0.79	0.86	0.99	0.82	0.82	0.82
Simulation 3	0.76	0.72	0.95	0.90	0.70	0.80	0.88	1.06	0.79	0.84	0.82
Simulation 4	0.72	0.70	0.87	1.02	0.69	0.74	0.90	0.95	0.79	0.79	0.79
Simulation 5	0.69	0.76	0.89	1.11	0.73	0.81	0.86	0.94	0.83	0.83	0.83
Simulation 6	0.76	0.78	0.83	0.90	0.69	0.80	0.90	1.06	0.81	0.85	0.83
Simulation 7	0.77	0.75	0.88	1.06	0.72	0.71	0.85	0.88	0.84	0.76	0.80
Simulation 8	0.69	0.75	0.87	1.06	0.72	0.71	0.88	1.02	0.81	0.80	0.81
Simulation 9	0.63	0.83	0.94	0.97	0.70	0.73	0.82	0.98	0.83	0.79	0.81
Simulation 10	0.63	0.78	0.94	0.97	0.72	0.75	0.88	1.02	0.80	0.82	0.81
Simulation 11	0.68	0.77	0.85	1.06	0.70	0.74	0.82	0.94	0.82	0.78	0.80
Simulation 12	0.73	0.82	0.89	1.11	0.67	0.74	0.88	1.05	0.87	0.81	0.84
Simulation 13	0.66	0.77	0.86	0.95	0.70	0.76	0.94	0.99	0.80	0.82	0.81
Simulation 14	0.66	0.81	0.92	1.08	0.79	0.80	0.84	0.97	0.85	0.84	0.85
Simulation 15	0.70	0.72	0.88	0.99	0.67	0.79	0.83	1.02	0.80	0.82	0.81
Simulation 16	0.68	0.73	0.79	0.97	0.66	0.73	0.89	1.02	0.78	0.79	0.78
Simulation 17	0.73	0.75	0.86	0.97	0.74	0.78	0.85	1.10	0.80	0.85	0.83
Simulation 18	0.67	0.78	0.85	1.05	0.73	0.71	0.84	0.99	0.82	0.79	0.80
Simulation 19	0.71	0.77	0.88	1.10	0.71	0.73	0.80	1.07	0.84	0.81	0.82
Simulation 20	0.67	0.72	0.92	1.02	0.70	0.81	0.84	1.12	0.80	0.86	0.83
Mean	0.69	0.76	0.88	1.02	0.70	0.76	0.86	1.01	0.81	0.81	0.81

Table A23: Vehicle stops for MPC with Standard GPS in Scenario 2

Scenario 2	**Standard GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.60	0.75	0.92	1.10	0.70	0.80	0.84	1.10	0.81	0.85	0.83
Simulation 2	0.65	0.72	0.93	1.15	0.69	0.84	0.81	1.03	0.83	0.84	0.83
Simulation 3	0.71	0.89	0.82	0.88	0.70	0.84	0.84	1.02	0.84	0.85	0.84
Simulation 4	0.64	0.75	0.81	1.06	0.66	0.76	0.90	0.93	0.80	0.79	0.80
Simulation 5	0.67	0.80	0.92	1.05	0.71	0.80	0.86	1.16	0.84	0.87	0.85
Simulation 6	0.72	0.80	0.82	0.91	0.71	0.85	0.87	0.96	0.81	0.85	0.83
Simulation 7	0.76	0.86	0.88	1.09	0.72	0.83	0.90	0.92	0.89	0.83	0.86
Simulation 8	0.73	0.76	0.83	1.04	0.70	0.75	0.86	0.96	0.82	0.80	0.81
Simulation 9	0.62	0.94	0.90	1.05	0.69	0.93	0.85	0.93	0.89	0.87	0.88
Simulation 10	0.61	0.81	0.98	0.95	0.70	0.77	0.91	1.02	0.81	0.82	0.82
Simulation 11	0.72	0.89	0.89	1.01	0.72	0.85	0.82	0.89	0.88	0.83	0.85
Simulation 12	0.71	0.81	0.86	1.00	0.73	0.76	0.88	0.95	0.83	0.80	0.82
Simulation 13	0.66	0.93	0.81	0.97	0.69	1.00	1.00	1.01	0.87	0.93	0.90
Simulation 14	0.74	0.77	0.91	1.46	0.73	0.88	0.85	0.94	0.93	0.86	0.90
Simulation 15	0.73	0.74	0.89	0.93	0.72	0.72	0.81	1.09	0.80	0.81	0.81
Simulation 16	0.62	0.81	0.83	1.04	0.70	0.77	0.86	0.96	0.82	0.80	0.81
Simulation 17	0.80	0.86	0.76	0.96	0.75	0.83	0.78	0.95	0.86	0.83	0.84
Simulation 18	0.66	0.90	0.89	1.03	0.69	0.80	0.89	0.95	0.87	0.81	0.84
Simulation 19	0.71	0.76	0.86	1.04	0.68	0.76	0.85	1.01	0.82	0.81	0.81
Simulation 20	0.65	0.76	0.89	1.09	0.73	0.80	0.87	1.05	0.82	0.85	0.83
Mean	0.69	0.82	0.87	1.04	0.71	0.82	0.86	0.99	0.84	0.84	0.84

Table A24: Vehicle stops for MPC with Mobile GPS in Scenario 2

Scenario 2	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.64	0.70	0.88	0.98	0.69	0.76	0.87	1.10	0.77	0.83	0.80
Simulation 2	0.71	0.77	0.88	1.08	0.70	0.90	0.85	1.01	0.84	0.87	0.86
Simulation 3	0.78	1.40	0.89	0.88	0.65	1.07	0.85	1.08	1.10	0.95	1.02
Simulation 4	0.75	0.80	0.82	1.04	0.76	0.80	0.92	0.90	0.84	0.82	0.83
Simulation 5	0.67	0.82	0.90	1.03	0.65	0.73	0.88	1.14	0.84	0.82	0.83
Simulation 6	0.76	0.82	0.88	0.87	0.64	0.81	0.94	1.06	0.82	0.84	0.83
Simulation 7	0.74	0.75	0.90	1.01	0.72	0.96	0.91	0.92	0.82	0.89	0.85
Simulation 8	0.78	0.72	0.85	0.99	0.79	0.76	0.87	0.97	0.80	0.83	0.81
Simulation 9	0.68	0.84	0.88	1.01	0.70	0.85	0.86	0.93	0.85	0.84	0.84
Simulation 10	0.67	0.82	0.90	0.87	0.74	0.78	0.90	1.12	0.80	0.85	0.83
Simulation 11	0.74	0.77	0.82	1.12	0.77	0.71	0.91	0.90	0.85	0.79	0.82
Simulation 12	0.76	0.84	0.85	0.98	0.75	0.78	0.90	0.96	0.85	0.83	0.84
Simulation 13	0.76	0.85	0.87	1.03	0.78	0.94	0.93	1.04	0.87	0.93	0.90
Simulation 14	0.71	1.23	0.92	1.37	0.77	0.98	0.78	0.94	1.12	0.90	1.01
Simulation 15	0.68	0.93	0.82	1.00	0.68	0.97	0.82	1.13	0.88	0.92	0.90
Simulation 16	0.63	0.83	0.75	0.96	0.72	0.97	0.92	1.04	0.81	0.92	0.87
Simulation 17	0.67	1.01	0.92	0.96	0.69	1.07	0.87	0.96	0.91	0.94	0.92
Simulation 18	0.73	0.77	0.89	0.98	0.74	0.76	0.79	0.99	0.82	0.81	0.81
Simulation 19	0.72	1.17	0.83	0.98	0.69	0.87	0.82	1.10	0.99	0.87	0.94
Simulation 20	0.68	0.83	0.89	1.00	0.83	0.90	0.83	1.01	0.84	0.90	0.87
Mean	0.71	0.88	0.87	1.01	0.72	0.87	0.87	1.01	0.87	0.87	0.87

Table A25: Vehicle stops for MPC with High Accurate GPS in Scenario 3

Scenario 3	**High Accurate GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.76	1.39	0.99	1.89	0.79	1.06	1.07	2.15	1.31	1.24	1.27
Simulation 2	0.76	1.16	0.94	1.65	0.74	1.23	0.99	1.17	1.15	1.08	1.11
Simulation 3	0.77	1.05	0.88	1.69	0.77	1.05	0.91	3.31	1.11	1.47	1.29
Simulation 4	0.77	1.52	0.82	1.86	0.77	1.71	0.97	1.32	1.35	1.34	1.35
Simulation 5	0.77	1.07	0.93	1.82	0.71	1.12	0.98	2.02	1.14	1.21	1.17
Simulation 6	0.77	1.40	0.86	1.21	0.71	1.58	1.15	1.20	1.16	1.26	1.21
Simulation 7	0.74	1.01	0.96	1.49	0.78	1.72	0.95	1.31	1.05	1.34	1.19
Simulation 8	0.79	1.16	0.89	1.31	0.75	1.02	0.99	1.77	1.08	1.12	1.10
Simulation 9	0.77	1.57	0.93	1.45	0.79	1.31	0.88	1.19	1.30	1.12	1.21
Simulation 10	0.79	1.13	0.90	2.61	0.77	1.17	1.01	2.07	1.34	1.25	1.30
Simulation 11	0.78	1.45	0.91	1.73	0.80	1.09	0.98	1.64	1.30	1.12	1.21
Simulation 12	0.84	1.20	0.87	1.35	0.75	1.35	0.94	1.18	1.12	1.14	1.13
Simulation 13	0.80	1.14	0.87	1.59	0.79	1.64	0.93	1.39	1.13	1.32	1.23
Simulation 14	0.77	1.26	0.83	1.61	0.75	1.20	0.98	1.35	1.17	1.10	1.14
Simulation 15	0.77	1.08	0.95	1.97	0.67	1.01	1.02	2.65	1.19	1.28	1.23
Simulation 16	0.79	1.51	0.87	1.76	0.77	1.53	0.92	1.79	1.34	1.35	1.34
Simulation 17	0.79	1.39	0.93	2.07	0.78	1.01	1.00	1.34	1.34	1.03	1.19
Simulation 18	0.78	1.27	0.88	2.53	0.74	1.29	0.99	2.73	1.38	1.45	1.42
Simulation 19	0.77	1.15	0.89	2.10	0.79	1.27	0.93	2.62	1.25	1.42	1.33
Simulation 20	0.73	1.04	0.88	1.91	0.74	1.10	1.05	1.89	1.14	1.19	1.17
Mean	0.78	1.25	0.90	1.78	0.76	1.27	0.98	1.80	1.22	1.24	1.23

Table A26: Vehicle stops for MPC with Standard GPS in Scenario 3

Scenario 3	**Standard GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.80	1.77	1.04	2.23	0.79	1.68	1.29	2.11	1.56	1.54	1.55
Simulation 2	1.12	1.84	0.85	6.68	0.79	1.61	0.96	3.20	2.62	1.69	2.16
Simulation 3	0.86	1.33	1.15	2.02	0.81	2.01	0.98	2.84	1.35	1.81	1.58
Simulation 4	0.79	2.75	0.84	2.15	0.83	1.81	0.91	1.87	1.96	1.51	1.74
Simulation 5	0.94	1.21	0.97	4.74	0.85	1.15	1.00	2.59	1.84	1.38	1.61
Simulation 6	0.78	1.73	0.90	3.02	0.78	2.79	1.01	3.53	1.70	2.32	2.01
Simulation 7	0.76	2.96	0.98	1.17	0.81	6.65	0.96	1.16	1.83	3.50	2.66
Simulation 8	0.73	2.16	0.88	3.13	0.76	1.78	1.09	4.43	1.88	2.06	1.97
Simulation 9	0.77	2.14	1.06	2.01	0.78	2.08	0.97	1.40	1.69	1.52	1.60
Simulation 10	0.77	2.20	0.93	1.69	0.77	1.92	0.93	1.66	1.62	1.49	1.56
Simulation 11	0.82	1.50	0.91	3.17	0.75	1.34	0.98	2.20	1.66	1.35	1.51
Simulation 12	0.89	2.60	1.01	2.38	0.83	2.08	1.04	2.55	1.98	1.77	1.88
Simulation 13	0.83	1.27	0.97	1.95	0.89	1.29	1.00	1.51	1.28	1.22	1.25
Simulation 14	0.69	4.44	1.00	2.32	0.75	2.93	1.06	2.79	2.75	2.20	2.48
Simulation 15	0.80	1.64	0.96	2.77	0.73	1.59	1.10	5.79	1.62	2.22	1.92
Simulation 16	0.74	3.66	0.93	1.46	0.75	4.99	0.89	1.35	2.22	2.79	2.50
Simulation 17	0.83	2.36	0.95	1.53	0.82	1.89	0.94	1.48	1.68	1.45	1.57
Simulation 18	0.85	3.53	0.88	1.75	0.84	2.00	1.00	1.38	2.27	1.49	1.89
Simulation 19	0.83	1.16	0.92	1.84	0.84	1.34	1.07	2.59	1.20	1.46	1.33
Simulation 20	0.77	1.62	1.01	2.00	0.79	1.52	1.14	1.43	1.44	1.30	1.37
Mean	0.82	2.19	0.96	2.50	0.80	2.22	1.02	2.39	1.81	1.80	1.81

Table A27: Vehicle stops for MPC with Mobile GPS in Scenario 3

Scenario 3	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.76	3.91	1.05	1.92	0.81	2.20	1.09	2.28	2.46	1.79	2.13
Simulation 2	0.70	3.23	0.92	2.09	0.69	2.98	1.03	1.65	2.15	1.95	2.05
Simulation 3	0.86	1.77	1.00	2.31	0.93	2.39	0.93	3.30	1.58	2.08	1.83
Simulation 4	0.99	1.76	0.92	2.94	1.50	1.65	0.88	2.13	1.77	1.64	1.70
Simulation 5	0.75	5.22	1.07	2.07	0.70	5.59	1.02	3.81	3.10	3.60	3.35
Simulation 6	0.81	2.09	1.00	2.26	0.88	1.79	1.11	2.40	1.72	1.65	1.69
Simulation 7	0.84	4.79	0.95	1.93	0.84	14.18	0.92	3.04	2.88	7.44	5.15
Simulation 8	0.78	2.22	1.12	3.12	0.91	2.36	1.28	4.42	1.97	2.39	2.18
Simulation 9	0.76	1.67	0.94	6.07	0.80	1.90	1.28	7.95	2.26	2.84	2.55
Simulation 10	1.42	6.52	1.21	1.38	1.11	6.58	1.21	1.89	3.50	3.58	3.54
Simulation 11	0.87	2.56	0.96	4.13	0.81	1.81	1.15	1.40	2.37	1.43	1.91
Simulation 12	0.92	5.05	0.99	1.55	0.80	5.22	0.87	1.50	2.92	2.98	2.95
Simulation 13	1.44	2.02	1.99	3.54	1.50	4.53	1.22	4.96	2.19	3.57	2.88
Simulation 14	1.12	9.53	0.94	2.75	0.90	6.16	1.12	2.06	5.15	3.46	4.29
Simulation 15	0.82	1.33	0.96	2.43	0.93	2.06	0.94	2.26	1.42	1.73	1.57
Simulation 16	0.86	10.07	0.91	3.41	0.84	5.56	0.97	2.29	5.46	3.28	4.36
Simulation 17	0.84	3.93	0.97	2.44	0.82	2.49	1.13	2.51	2.60	1.95	2.28
Simulation 18	0.74	6.34	1.16	1.54	0.77	6.66	0.95	1.46	3.31	3.38	3.35
Simulation 19	0.76	4.28	0.92	2.43	0.73	2.09	0.96	3.11	2.73	1.90	2.32
Simulation 20	0.75	5.17	0.94	1.81	0.75	9.59	1.10	1.93	2.95	4.95	3.94
Mean	0.89	4.17	1.05	2.61	0.90	4.39	1.06	2.82	2.72	2.88	2.80

B Appendix 2: Results Vehicle-based Signal Control

B.1 Vehicle delays

Table B1: Vehicle delay for VST with High Accurate GPS in Scenario 1

Scenario 1	**High accurate GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	29.86	33.56	35.58	35.73	25.99	36.17	30.85	33.26	33.42	32.71	33.06
Simulation 2	25.79	30.99	30.62	39.23	30.55	34.08	42.96	34.32	31.61	34.33	32.97
Simulation 3	24.05	33.09	36.07	37.24	27.81	32.63	35.86	36.85	32.30	32.81	32.56
Simulation 4	22.84	31.72	36.63	37.29	28.25	32.57	39.06	34.40	31.49	32.73	32.11
Simulation 5	23.07	29.60	31.30	34.30	23.76	32.24	39.17	40.71	29.28	33.10	31.17
Simulation 6	26.85	33.83	41.37	35.00	22.07	32.53	34.51	35.68	33.33	31.13	32.23
Simulation 7	25.41	31.60	37.94	39.05	23.92	32.06	32.48	37.88	32.50	31.51	32.01
Simulation 8	24.57	31.53	34.78	33.58	25.60	33.41	33.52	35.77	30.74	32.32	31.52
Simulation 9	27.43	31.39	35.54	42.85	26.69	32.32	34.45	40.08	33.37	32.95	33.16
Simulation 10	27.90	34.42	33.58	35.84	23.24	30.70	49.01	34.18	33.11	31.86	32.49
Simulation 11	24.54	35.75	43.48	33.51	23.51	30.54	41.71	36.11	33.60	31.31	32.47
Simulation 12	25.09	29.72	32.51	36.51	25.06	32.94	34.47	37.95	30.41	32.45	31.44
Simulation 13	27.30	31.33	36.04	38.31	25.71	32.83	34.79	37.87	32.47	32.54	32.51
Simulation 14	24.54	35.38	30.22	35.79	26.04	32.93	37.00	41.51	32.57	33.71	33.13
Simulation 15	28.08	31.36	40.58	31.51	25.48	31.95	40.81	38.46	31.71	32.80	32.26
Simulation 16	27.11	32.60	33.72	38.06	27.49	32.55	36.21	40.08	32.75	33.45	33.10
Simulation 17	24.93	30.40	39.47	32.40	26.62	30.07	40.73	34.69	30.55	31.56	31.06
Simulation 18	22.20	34.64	31.49	32.92	25.91	30.69	35.23	40.78	31.14	32.20	31.66
Simulation 19	24.55	31.20	37.16	40.74	25.71	30.06	36.32	37.32	32.41	31.41	31.93
Simulation 20	27.86	32.74	30.59	33.89	27.94	29.90	31.54	37.95	31.63	31.38	31.51
Mean	25.70	32.34	35.43	36.19	25.87	32.16	37.03	37.29	32.02	32.41	32.22

Table B2: Vehicle delay for VST with Standard GPS in Scenario 1

Scenario 1	**Standard GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	34.03	36.34	36.46	32.28	31.24	37.34	32.57	29.49	34.91	33.69	34.29
Simulation 2	27.68	31.78	29.18	38.80	33.73	30.72	34.42	34.08	32.11	32.53	32.32
Simulation 3	31.13	30.70	36.70	34.16	30.49	33.32	37.23	33.20	32.16	33.06	32.62
Simulation 4	26.74	29.62	33.35	35.44	33.88	32.03	38.01	33.43	30.66	33.39	32.02
Simulation 5	31.55	31.24	33.05	31.87	28.57	32.82	33.14	39.53	31.64	33.47	32.54
Simulation 6	31.79	33.18	37.34	31.64	26.98	37.28	32.01	35.18	32.99	33.98	33.49
Simulation 7	33.21	31.22	35.93	34.57	30.79	30.38	38.45	38.13	32.92	32.99	32.95
Simulation 8	28.32	32.29	34.57	32.30	33.95	32.24	31.01	33.63	31.65	32.77	32.20
Simulation 9	34.04	32.50	34.78	40.19	33.85	32.32	32.44	39.44	34.73	34.20	34.46
Simulation 10	28.65	30.07	34.40	34.88	34.05	30.54	46.74	32.68	31.22	33.68	32.45
Simulation 11	28.48	32.91	35.63	33.91	30.41	34.30	36.84	35.41	32.46	33.91	33.18
Simulation 12	28.29	31.06	35.00	35.63	27.23	34.16	30.23	34.84	31.85	32.35	32.10
Simulation 13	32.08	30.61	37.56	36.78	30.93	33.27	31.30	37.13	33.03	33.40	33.22
Simulation 14	32.49	32.22	29.49	34.70	32.42	33.20	35.26	38.09	32.53	34.34	33.43
Simulation 15	31.05	31.45	33.72	25.59	30.09	29.63	35.44	34.89	30.38	31.51	30.95
Simulation 16	34.39	33.61	27.93	37.50	32.96	31.13	34.40	37.06	34.00	33.19	33.60
Simulation 17	28.80	30.93	41.87	34.61	27.61	32.67	32.44	35.53	32.40	32.17	32.29
Simulation 18	26.12	32.83	30.15	30.03	28.32	31.62	29.47	33.36	30.43	30.97	30.70
Simulation 19	27.96	33.21	39.69	37.44	27.93	33.57	37.07	37.94	33.64	33.68	33.66
Simulation 20	29.48	33.36	26.46	34.19	36.04	29.44	36.25	35.69	31.86	33.08	32.48
Mean	30.31	32.06	34.16	34.33	31.07	32.60	34.74	35.44	32.38	33.12	32.75

Table B3: Vehicle delay for VST with Mobile GPS in Scenario 1

Scenario 1	**Mobile GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	37.64	35.56	37.03	31.70	28.01	38.21	36.75	28.97	35.33	33.80	34.55
Simulation 2	33.07	33.97	31.16	37.09	34.67	35.29	40.40	33.06	34.11	35.24	34.68
Simulation 3	32.13	34.40	40.44	34.50	32.38	34.25	33.27	35.26	34.55	33.93	34.24
Simulation 4	29.97	33.50	35.30	35.98	34.53	31.81	38.90	30.53	33.46	32.89	33.17
Simulation 5	28.50	32.66	36.13	30.08	31.58	34.79	35.51	37.86	31.50	34.89	33.18
Simulation 6	34.91	33.18	33.48	35.36	27.69	33.09	32.40	36.18	34.07	32.52	33.30
Simulation 7	37.79	35.48	37.40	34.61	28.16	32.86	33.84	37.84	36.03	32.98	34.52
Simulation 8	28.13	35.08	34.29	32.33	35.67	33.99	36.74	32.57	32.84	34.32	33.57
Simulation 9	32.96	34.36	31.43	37.58	32.17	32.50	29.55	36.49	34.38	32.94	33.66
Simulation 10	30.95	31.03	29.48	32.85	34.56	31.98	45.11	33.33	31.22	34.38	32.80
Simulation 11	29.48	33.43	34.75	33.71	32.11	36.27	35.21	34.24	32.77	34.75	33.74
Simulation 12	34.47	34.39	36.68	33.09	31.12	33.80	33.46	35.81	34.38	33.59	33.99
Simulation 13	36.83	32.34	34.34	36.74	33.51	32.41	33.43	38.13	34.48	34.05	34.26
Simulation 14	39.15	32.67	33.54	33.09	34.53	30.89	34.57	37.12	34.25	33.49	33.87
Simulation 15	32.05	32.68	35.24	27.03	29.79	31.82	33.20	33.56	31.63	31.89	31.76
Simulation 16	31.87	34.40	26.75	40.06	35.41	34.37	31.99	35.49	34.25	34.59	34.42
Simulation 17	33.94	29.56	39.53	31.60	30.31	33.75	30.80	30.10	32.08	31.87	31.98
Simulation 18	28.38	35.91	29.45	31.84	32.10	32.89	34.81	35.74	32.63	33.52	33.07
Simulation 19	31.11	30.46	38.32	34.41	31.42	31.94	34.49	36.61	32.31	33.13	32.71
Simulation 20	29.61	35.47	23.96	33.07	37.91	31.06	34.60	35.22	32.30	33.95	33.13
Mean	32.65	33.53	33.94	33.84	32.38	33.40	34.95	34.70	33.43	33.64	33.53

Table B4: Vehicle delay for VST with High Accurate GPS in Scenario 2

Scenario 2	**High Accurate GPS**										
	Average Delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	39.21	38.78	53.43	44.92	40.42	39.84	44.14	48.42	41.81	42.47	42.15
Simulation 2	37.34	43.40	47.88	49.83	37.79	45.85	48.02	47.70	44.04	44.68	44.36
Simulation 3	42.82	42.37	53.03	40.28	41.15	43.46	40.29	51.73	43.17	44.36	43.77
Simulation 4	49.31	39.46	41.58	45.79	41.87	40.10	47.37	41.64	43.28	41.62	42.45
Simulation 5	40.85	39.78	41.81	49.19	41.22	41.77	48.28	43.72	42.31	42.82	42.56
Simulation 6	42.13	39.42	32.96	53.05	40.01	40.17	44.67	53.25	42.29	43.52	42.90
Simulation 7	49.58	41.84	53.73	45.95	42.20	42.09	52.75	41.62	45.80	43.14	44.48
Simulation 8	37.65	40.87	43.04	47.84	39.70	38.92	40.59	45.86	41.81	40.87	41.34
Simulation 9	42.95	46.46	42.59	50.51	38.38	45.85	51.69	44.04	46.13	44.48	45.31
Simulation 10	31.95	42.91	51.17	52.26	42.58	44.20	42.91	52.42	43.27	45.44	44.35
Simulation 11	38.65	44.90	47.18	45.95	37.75	46.37	45.24	40.37	44.02	42.97	43.50
Simulation 12	40.93	41.40	47.21	48.66	40.29	42.28	50.36	44.45	43.51	43.24	43.37
Simulation 13	42.03	46.09	40.77	42.53	40.57	45.62	42.40	45.49	43.84	44.10	43.97
Simulation 14	39.70	42.92	44.75	52.34	39.27	41.80	42.09	44.55	44.54	41.88	43.21
Simulation 15	40.13	43.85	47.77	48.72	37.16	40.22	50.39	51.14	44.56	42.92	43.73
Simulation 16	41.27	40.97	45.42	47.55	41.83	42.99	40.58	52.17	43.00	44.46	43.74
Simulation 17	42.66	41.56	39.71	49.35	45.23	36.84	49.91	46.98	43.24	42.43	42.84
Simulation 18	40.05	42.71	44.14	46.46	41.34	43.41	48.90	44.11	43.08	43.69	43.38
Simulation 19	42.10	43.14	49.16	50.90	36.98	37.75	41.11	45.49	45.23	39.62	42.51
Simulation 20	41.68	40.91	46.48	42.04	43.34	45.53	36.16	39.54	41.97	42.67	42.32
Mean	41.15	42.19	45.69	47.71	40.45	42.25	45.39	46.23	43.54	43.07	43.31

Table B5: Vehicle delay for VST with Standard GPS in Scenario 2

Scenario 2	**Standard GPS**										
	Average Delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	30.73	42.00	52.09	49.94	31.05	40.76	47.13	53.24	42.28	42.25	42.27
Simulation 2	30.04	44.33	44.78	51.25	32.23	48.06	43.95	43.83	42.83	43.15	42.99
Simulation 3	35.40	43.83	46.74	43.17	37.26	45.31	39.35	53.08	42.14	44.53	43.35
Simulation 4	32.86	44.91	41.82	48.84	30.21	44.25	47.59	45.87	42.80	41.94	42.37
Simulation 5	33.00	44.68	49.99	51.95	38.42	43.92	45.03	43.07	44.12	42.65	43.39
Simulation 6	36.81	41.89	35.20	53.70	32.47	43.40	45.36	61.02	42.55	44.96	43.76
Simulation 7	35.19	45.23	51.69	55.57	33.13	43.76	54.64	45.48	45.94	42.91	44.44
Simulation 8	32.83	42.82	39.96	48.84	36.67	39.87	42.50	51.13	41.55	42.13	41.84
Simulation 9	35.74	47.79	44.55	46.86	38.07	44.74	40.33	46.38	44.57	43.11	43.84
Simulation 10	31.68	45.04	52.77	45.42	33.68	46.33	47.09	45.87	42.84	43.40	43.12
Simulation 11	31.40	45.55	53.85	53.37	34.28	46.06	47.78	44.51	45.11	43.22	44.19
Simulation 12	34.35	44.19	40.98	53.18	36.24	43.95	47.83	52.54	43.56	44.57	44.07
Simulation 13	32.20	46.21	42.23	44.63	35.25	47.66	48.92	48.64	42.35	45.19	43.78
Simulation 14	32.80	44.60	47.91	58.49	34.57	44.78	42.48	47.57	45.57	42.85	44.22
Simulation 15	36.16	43.58	44.65	44.96	40.15	42.28	45.86	51.39	42.37	44.17	43.29
Simulation 16	31.04	41.46	51.64	51.72	36.96	46.79	49.61	52.16	42.62	46.04	44.34
Simulation 17	35.35	44.29	37.21	47.20	36.16	43.17	46.94	41.11	42.08	41.63	41.86
Simulation 18	27.99	46.04	43.31	47.89	35.38	45.66	45.68	49.30	42.07	44.08	43.06
Simulation 19	32.77	46.50	48.53	53.02	32.15	41.96	46.21	54.68	45.03	43.02	44.05
Simulation 20	30.90	44.16	50.80	49.75	32.74	47.92	42.72	50.19	43.04	44.42	43.73
Mean	32.96	44.45	46.04	49.99	34.85	44.53	45.85	49.05	43.27	43.51	43.40

Table B6: Vehicle delay for VST with Mobile GPS in Scenario 2

Scenario 2	**Mobile GPS**										
	Average Delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	25.77	44.85	49.21	57.38	26.25	43.05	46.44	54.02	43.76	42.34	43.04
Simulation 2	24.69	46.23	57.65	49.61	25.13	49.44	49.36	47.52	43.64	43.58	43.61
Simulation 3	29.56	48.77	45.24	50.46	33.81	49.36	43.40	51.00	44.52	45.56	45.04
Simulation 4	28.70	51.61	43.48	53.30	26.12	51.32	47.34	48.34	46.02	44.70	45.36
Simulation 5	26.42	50.35	48.86	60.73	29.12	48.39	49.07	49.77	46.82	44.56	45.70
Simulation 6	27.41	47.71	42.82	57.71	24.20	49.58	48.73	55.62	44.79	45.11	44.95
Simulation 7	27.37	48.43	54.43	57.44	21.98	48.20	59.02	46.28	46.32	42.99	44.67
Simulation 8	28.17	47.24	47.64	47.28	30.12	42.03	41.34	48.45	42.95	40.91	41.93
Simulation 9	24.93	52.16	49.60	55.85	27.38	53.38	39.76	48.13	46.66	44.91	45.79
Simulation 10	26.05	45.51	52.39	51.01	25.69	48.17	49.02	48.55	42.90	43.16	43.03
Simulation 11	24.53	50.08	52.21	51.88	28.87	48.34	46.29	51.88	45.12	44.35	44.74
Simulation 12	27.69	50.17	44.14	53.71	30.08	48.05	50.31	56.23	45.14	46.02	45.59
Simulation 13	24.81	52.41	48.20	51.10	22.68	56.62	51.66	51.13	45.60	47.14	46.38
Simulation 14	27.07	48.72	51.10	54.13	29.48	50.28	46.30	48.91	45.55	44.84	45.20
Simulation 15	25.65	48.71	49.01	47.50	27.82	49.02	49.33	55.69	43.37	45.62	44.51
Simulation 16	22.50	46.62	50.74	53.52	26.45	54.31	45.32	54.58	43.44	47.07	45.27
Simulation 17	25.74	49.38	43.23	55.13	27.71	50.37	49.87	52.90	44.47	45.88	45.17
Simulation 18	23.62	50.70	44.17	50.78	29.87	48.68	43.76	56.05	43.87	45.34	44.59
Simulation 19	27.55	46.14	45.48	56.55	25.33	45.70	43.47	62.81	44.16	44.71	44.43
Simulation 20	25.86	48.25	54.99	51.32	24.54	50.61	45.84	58.65	44.50	46.03	45.27
Mean	26.20	48.70	48.73	53.32	27.13	49.24	47.28	52.32	44.68	44.74	44.71

Table B7: Vehicle delay for VST with High accurate GPS in Scenario 3

Scenario 3	**High accurate GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	53.71	61.46	68.85	86.94	54.32	53.14	52.49	96.53	66.04	62.84	64.44
Simulation 2	72.17	53.19	60.17	65.94	68.93	53.27	57.09	64.20	60.91	59.50	60.21
Simulation 3	73.23	54.68	70.09	66.18	60.00	55.66	59.09	78.73	62.91	62.06	62.48
Simulation 4	61.33	53.58	59.89	78.51	56.51	60.27	55.87	75.33	61.34	62.13	61.73
Simulation 5	57.46	57.30	64.93	75.47	55.21	50.57	60.52	77.82	61.99	58.83	60.41
Simulation 6	55.35	60.75	62.96	65.18	63.73	55.79	76.27	70.21	60.79	62.90	61.85
Simulation 7	55.35	56.93	62.06	67.94	56.10	60.11	69.65	65.39	59.50	61.36	60.42
Simulation 8	57.06	54.56	71.20	74.55	53.91	55.19	68.65	82.71	61.14	62.52	61.82
Simulation 9	58.12	59.36	65.59	66.90	51.94	55.46	67.08	78.65	61.42	61.03	61.23
Simulation 10	61.06	54.73	54.23	76.08	57.35	60.22	60.08	74.38	60.63	62.61	61.62
Simulation 11	66.67	53.63	64.56	75.36	56.69	53.48	70.53	61.62	62.54	57.83	60.21
Simulation 12	63.29	53.80	65.70	59.99	53.88	54.01	59.09	72.32	58.58	58.54	58.56
Simulation 13	69.52	60.03	62.16	80.50	55.21	52.30	62.87	64.85	66.79	56.87	61.81
Simulation 14	64.78	59.49	52.28	79.57	66.99	54.70	76.12	82.62	64.28	66.00	65.14
Simulation 15	55.23	58.70	60.23	79.73	61.71	55.78	58.91	88.10	62.69	64.45	63.58
Simulation 16	62.23	55.24	64.84	70.78	59.46	56.71	67.06	77.81	61.22	63.12	62.17
Simulation 17	55.39	56.33	61.83	91.29	57.77	56.87	60.73	74.36	64.25	61.33	62.80
Simulation 18	63.95	55.33	65.54	78.74	67.91	59.03	71.60	72.45	63.30	65.33	64.30
Simulation 19	64.87	54.94	63.34	76.21	65.23	55.38	65.53	71.23	62.65	62.08	62.37
Simulation 20	60.10	51.83	62.11	66.85	61.03	55.79	70.67	76.36	58.09	63.06	60.58
Mean	61.54	56.29	63.13	74.14	59.19	55.69	64.50	75.28	62.05	61.72	61.89

Table B8: Vehicle delay for VST with Standard GPS in Scenario 3

Scenario 3	**Standard GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	50.05	62.34	83.56	83.89	50.69	56.19	68.42	79.90	66.54	61.63	64.08
Simulation 2	52.44	61.92	70.68	80.75	49.72	56.34	56.44	70.54	65.02	57.92	61.50
Simulation 3	53.10	55.35	65.89	73.97	50.26	59.78	62.62	78.23	60.01	62.00	61.02
Simulation 4	57.50	60.59	66.38	90.12	51.38	62.65	57.37	84.00	66.97	64.22	65.60
Simulation 5	61.35	56.75	57.86	74.84	54.88	50.74	62.60	91.93	61.84	62.36	62.10
Simulation 6	47.92	58.54	64.95	75.23	53.12	58.95	69.22	87.94	60.57	65.27	62.93
Simulation 7	44.39	61.76	71.00	91.57	52.36	62.03	70.60	72.74	65.15	63.05	64.10
Simulation 8	59.26	59.43	59.92	78.97	54.76	59.24	59.99	90.61	63.49	65.32	64.40
Simulation 9	51.65	59.10	66.83	77.09	47.14	60.89	82.25	78.24	62.14	63.98	63.06
Simulation 10	50.90	58.77	54.25	77.67	50.94	59.30	66.71	85.08	60.59	63.87	62.23
Simulation 11	54.05	61.04	65.96	81.73	49.59	58.17	65.33	65.35	64.71	58.65	61.71
Simulation 12	58.86	53.41	66.01	71.81	49.49	54.50	57.98	78.51	60.03	58.97	59.50
Simulation 13	52.46	63.43	68.58	73.85	56.61	54.81	75.32	72.91	63.81	61.36	62.58
Simulation 14	50.17	63.63	66.15	84.95	55.13	57.60	75.56	92.89	65.68	66.89	66.29
Simulation 15	51.75	62.06	62.78	62.59	52.53	55.52	66.08	78.34	59.99	60.94	60.47
Simulation 16	51.18	57.51	69.32	75.13	47.31	56.74	71.58	94.17	61.35	64.54	62.93
Simulation 17	46.60	62.08	59.35	90.27	44.61	57.19	76.36	84.89	64.07	62.39	63.23
Simulation 18	50.39	61.23	65.79	72.75	57.39	63.41	56.24	84.31	61.86	65.80	63.80
Simulation 19	50.11	52.72	74.05	83.85	49.94	58.89	61.54	75.46	61.18	60.77	60.98
Simulation 20	49.34	55.21	66.08	84.90	48.18	63.75	64.54	83.64	61.63	64.91	63.27
Mean	52.17	59.34	66.27	79.30	51.30	58.33	66.34	81.48	62.83	62.74	62.79

Table B9: Vehicle delay for VST with Mobile GPS in Scenario 3

Scenario 3	**Mobile GPS**										
	Vehicle delay (s)										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	41.70	67.31	82.40	96.80	40.62	62.01	74.68	95.59	69.47	66.18	67.82
Simulation 2	38.24	66.51	68.34	93.70	37.91	68.70	69.05	89.68	66.49	66.21	66.35
Simulation 3	43.37	65.52	80.69	88.41	40.59	64.81	69.00	91.22	67.06	65.51	66.28
Simulation 4	41.64	66.11	71.36	104.38	39.24	69.47	75.05	96.52	69.44	69.18	69.31
Simulation 5	42.79	60.36	73.74	95.75	36.39	58.15	68.20	88.02	65.28	61.15	63.22
Simulation 6	39.14	69.60	73.25	96.79	38.57	64.01	74.76	106.99	69.30	69.00	69.15
Simulation 7	38.55	68.76	68.43	98.43	44.55	70.83	96.98	92.76	68.14	72.29	70.20
Simulation 8	44.17	65.75	79.07	96.84	44.35	61.32	72.54	102.07	68.79	67.92	68.36
Simulation 9	43.98	68.46	76.29	92.94	40.98	65.05	78.45	94.33	69.29	67.54	68.42
Simulation 10	43.47	68.29	62.90	92.43	40.28	69.96	74.08	97.52	67.39	69.83	68.61
Simulation 11	43.29	66.53	83.84	110.36	42.34	65.66	76.29	90.59	73.05	66.96	70.05
Simulation 12	46.02	64.51	68.47	81.69	38.71	67.10	65.20	90.27	64.52	65.55	65.04
Simulation 13	42.51	64.77	69.48	95.92	40.71	63.08	64.04	104.64	66.91	67.16	67.04
Simulation 14	44.97	65.90	67.41	90.32	43.96	67.76	87.50	84.39	66.74	68.18	67.46
Simulation 15	39.99	68.43	65.64	80.62	36.08	63.26	73.46	86.41	64.50	63.30	63.90
Simulation 16	42.42	65.21	69.64	97.93	43.05	65.39	67.15	95.05	67.86	67.09	67.48
Simulation 17	41.59	68.27	67.19	99.81	38.78	65.09	79.98	98.26	68.49	67.89	68.19
Simulation 18	44.06	67.40	72.73	87.30	43.88	72.23	78.59	100.78	67.17	72.73	69.92
Simulation 19	42.06	59.30	83.62	88.19	44.07	65.99	63.68	96.30	64.32	67.39	65.83
Simulation 20	38.66	64.35	77.19	94.22	36.90	65.48	79.53	105.76	66.35	69.39	67.87
Mean	42.13	66.07	73.08	94.14	40.60	65.77	74.41	95.36	67.53	67.52	67.52

B.2 Vehicle throughput

Table B10: Vehicle throughput for VST with High Accurate GPS in Scenario 1

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	97	193	45	96	96	198	52	103	431	449	880
Simulation 2	96	195	53	96	98	197	49	94	440	438	878
Simulation 3	96	200	45	94	103	199	49	99	435	450	885
Simulation 4	97	200	45	97	96	200	48	95	439	439	878
Simulation 5	104	203	47	97	95	194	50	99	451	438	889
Simulation 6	101	200	49	96	99	202	47	100	446	448	894
Simulation 7	103	203	51	97	101	199	46	96	454	442	896
Simulation 8	100	207	47	93	92	193	50	101	447	436	883
Simulation 9	100	203	52	93	99	203	51	94	448	447	895
Simulation 10	103	198	48	93	102	195	52	92	442	441	883
Simulation 11	98	202	47	104	103	193	50	90	451	436	887
Simulation 12	98	200	48	92	97	200	51	94	438	442	880
Simulation 13	94	196	48	92	102	200	47	100	430	449	879
Simulation 14	97	203	49	100	100	197	52	96	449	445	894
Simulation 15	98	196	50	92	103	198	48	95	436	444	880
Simulation 16	96	200	50	98	100	201	49	97	444	447	891
Simulation 17	103	202	49	94	97	199	52	96	448	444	892
Simulation 18	100	202	51	94	102	195	49	92	447	438	885
Simulation 19	103	207	50	99	95	193	45	98	459	431	890
Simulation 20	97	192	49	91	101	192	49	95	429	437	866
Mean	99	200	49	95	99	197	49	96	443	442	885

Table B11: Vehicle throughput for VST with Standard GPS in Scenario 1

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	97	188	45	96	95	198	52	102	426	447	873
Simulation 2	96	194	53	96	98	197	49	94	439	438	877
Simulation 3	96	200	45	94	103	197	48	99	435	447	882
Simulation 4	97	199	45	97	95	200	48	95	438	438	876
Simulation 5	103	202	47	98	95	194	50	100	450	439	889
Simulation 6	101	201	49	96	99	202	47	99	447	447	894
Simulation 7	103	203	51	97	100	199	45	96	454	440	894
Simulation 8	100	207	47	93	90	193	50	100	447	433	880
Simulation 9	100	203	52	95	99	202	51	96	450	448	898
Simulation 10	103	196	48	92	101	195	51	92	439	439	878
Simulation 11	98	200	47	104	103	193	50	92	449	438	887
Simulation 12	98	198	48	94	97	200	51	97	438	445	883
Simulation 13	94	196	48	93	102	199	47	101	431	449	880
Simulation 14	97	203	49	100	98	197	52	98	449	445	894
Simulation 15	98	195	50	92	101	198	48	96	435	443	878
Simulation 16	96	200	50	98	99	199	49	97	444	444	888
Simulation 17	103	200	48	96	97	198	52	98	447	445	892
Simulation 18	100	202	51	94	102	195	49	92	447	438	885
Simulation 19	103	207	50	98	95	193	45	97	458	430	888
Simulation 20	96	189	49	90	101	192	49	94	424	436	860
Mean	99	199	49	96	99	197	49	97	442	441	884

Table B12: Vehicle throughput for VST with Mobile GPS in Scenario 1

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	97	189	45	95	94	198	52	100	426	444	870
Simulation 2	96	193	53	96	98	196	49	94	438	437	875
Simulation 3	96	200	45	92	103	199	49	99	433	450	883
Simulation 4	96	197	44	98	95	200	48	97	435	440	875
Simulation 5	102	198	47	99	95	194	50	101	446	440	886
Simulation 6	99	200	49	96	97	202	47	98	444	444	888
Simulation 7	101	202	51	97	100	199	45	96	451	440	891
Simulation 8	100	202	47	96	90	192	49	101	445	432	877
Simulation 9	100	203	52	93	99	202	51	95	448	447	895
Simulation 10	103	196	48	93	102	195	51	92	440	440	880
Simulation 11	98	200	47	104	103	193	50	90	449	436	885
Simulation 12	97	195	48	92	97	200	51	93	432	441	873
Simulation 13	93	196	48	92	101	198	47	100	429	446	875
Simulation 14	96	203	49	100	98	197	52	98	448	445	893
Simulation 15	98	194	50	92	100	198	48	96	434	442	876
Simulation 16	96	200	50	99	99	199	49	100	445	447	892
Simulation 17	103	200	48	93	97	199	52	95	444	443	887
Simulation 18	100	202	51	95	102	195	49	92	448	438	886
Simulation 19	103	206	50	98	95	192	45	95	457	427	884
Simulation 20	96	188	49	91	101	192	49	95	424	437	861
Mean	99	198	49	96	98	197	49	96	441	441	882

Table B13: Vehicle throughput for VST with High Accurate GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	127	249	60	124	124	254	68	136	560	582	1142
Simulation 2	126	254	68	129	128	257	64	123	577	572	1149
Simulation 3	126	262	61	121	132	262	64	125	570	583	1153
Simulation 4	128	260	62	130	125	260	63	129	580	577	1157
Simulation 5	133	260	62	128	125	253	64	131	583	573	1156
Simulation 6	127	261	64	127	127	261	64	128	579	580	1159
Simulation 7	129	262	67	130	130	259	61	128	588	578	1166
Simulation 8	130	263	61	118	119	252	66	130	572	567	1139
Simulation 9	128	263	67	127	128	258	67	127	585	580	1165
Simulation 10	135	256	63	125	133	253	68	124	579	578	1157
Simulation 11	127	260	62	132	129	248	66	122	581	565	1146
Simulation 12	129	255	63	124	128	263	66	129	571	586	1157
Simulation 13	124	257	63	121	131	254	62	130	565	577	1142
Simulation 14	125	266	64	131	130	254	67	129	586	580	1166
Simulation 15	124	249	65	124	133	258	63	121	562	575	1137
Simulation 16	123	261	63	130	131	262	64	127	577	584	1161
Simulation 17	132	263	65	122	125	255	68	125	582	573	1155
Simulation 18	132	264	66	126	132	250	63	126	588	571	1159
Simulation 19	133	269	64	128	125	254	59	122	594	560	1154
Simulation 20	128	247	64	119	126	251	63	125	558	565	1123
Mean	128	259	64	126	128	256	65	127	577	575	1152

Table B14: Vehicle throughput for VST with Standard GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	127	249	60	124	127	254	68	134	560	583	1143
Simulation 2	126	255	68	130	128	257	64	124	579	573	1152
Simulation 3	126	262	61	121	132	262	64	127	570	585	1155
Simulation 4	128	260	62	130	125	260	63	129	580	577	1157
Simulation 5	133	261	62	124	125	253	65	126	580	569	1149
Simulation 6	129	261	64	124	130	262	64	125	578	581	1159
Simulation 7	132	264	67	127	130	259	62	126	590	577	1167
Simulation 8	128	262	61	121	118	251	64	132	572	565	1137
Simulation 9	128	263	67	124	128	259	67	125	582	579	1161
Simulation 10	135	258	63	122	133	254	68	121	578	576	1154
Simulation 11	128	261	63	132	129	248	66	117	584	560	1144
Simulation 12	129	256	64	124	128	263	66	127	573	584	1157
Simulation 13	124	257	64	120	131	254	62	129	565	576	1141
Simulation 14	125	266	64	132	130	255	67	129	587	581	1168
Simulation 15	124	248	65	124	134	257	63	127	561	581	1142
Simulation 16	124	261	63	129	132	261	64	126	577	583	1160
Simulation 17	132	262	65	122	125	254	68	125	581	572	1153
Simulation 18	132	264	66	125	132	251	63	125	587	571	1158
Simulation 19	134	270	64	128	126	254	60	124	596	564	1160
Simulation 20	129	248	64	118	127	251	63	123	559	564	1123
Mean	129	259	64	125	129	256	65	126	577	575	1152

Table B15: Vehicle throughput for VST with Mobile GPS in Scenario 2

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	127	249	60	124	127	254	68	136	560	585	1145
Simulation 2	126	256	68	130	128	257	64	124	580	573	1153
Simulation 3	126	262	61	122	132	262	64	127	571	585	1156
Simulation 4	128	261	63	126	126	260	63	124	578	573	1151
Simulation 5	136	262	62	124	125	256	65	126	584	572	1156
Simulation 6	129	261	64	124	130	261	64	126	578	581	1159
Simulation 7	132	264	67	126	131	259	62	125	589	577	1166
Simulation 8	131	263	62	119	120	253	66	130	575	569	1144
Simulation 9	128	263	67	124	128	258	67	125	582	578	1160
Simulation 10	135	256	63	124	133	253	68	122	578	576	1154
Simulation 11	128	261	63	132	129	248	66	117	584	560	1144
Simulation 12	129	256	64	120	128	263	66	120	569	577	1146
Simulation 13	124	257	64	120	131	254	62	129	565	576	1141
Simulation 14	126	266	64	132	130	255	67	126	588	578	1166
Simulation 15	124	247	65	124	132	258	63	123	560	576	1136
Simulation 16	124	260	63	130	132	259	64	128	577	583	1160
Simulation 17	133	263	66	120	125	255	68	122	582	570	1152
Simulation 18	132	264	66	123	132	250	63	122	585	567	1152
Simulation 19	134	269	64	130	126	254	59	125	597	564	1161
Simulation 20	130	247	64	121	127	251	63	126	562	567	1129
Mean	129	259	64	125	129	256	65	125	577	574	1152

Table B16: Vehicle throughput for VST with High Accurate GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	242	482	114	233	232	480	121	234	1071	1067	2138
Simulation 2	230	479	122	238	226	474	116	234	1069	1050	2119
Simulation 3	235	485	112	232	244	490	115	239	1064	1088	2152
Simulation 4	239	489	118	231	231	493	116	223	1077	1063	2140
Simulation 5	243	488	119	225	235	473	118	240	1075	1066	2141
Simulation 6	229	490	118	230	234	486	116	234	1067	1070	2137
Simulation 7	246	490	124	232	243	489	115	232	1092	1079	2171
Simulation 8	241	490	118	225	225	477	122	232	1074	1056	2130
Simulation 9	234	493	121	234	241	478	121	234	1082	1074	2156
Simulation 10	238	486	119	228	237	487	121	231	1071	1076	2147
Simulation 11	237	489	114	245	229	486	120	225	1085	1060	2145
Simulation 12	238	482	121	231	232	491	119	235	1072	1077	2149
Simulation 13	234	487	117	233	232	489	118	239	1071	1078	2149
Simulation 14	235	485	119	238	240	479	121	238	1077	1078	2155
Simulation 15	233	476	119	231	243	483	119	233	1059	1078	2137
Simulation 16	231	488	122	235	232	478	120	234	1076	1064	2140
Simulation 17	247	484	114	233	237	478	117	234	1078	1066	2144
Simulation 18	240	494	121	227	241	473	119	227	1082	1060	2142
Simulation 19	238	496	119	237	233	483	112	231	1090	1059	2149
Simulation 20	238	472	120	228	229	481	118	230	1058	1058	2116
Mean	237	486	119	232	235	482	118	233	1075	1068	2143

Table B17: Vehicle throughput for VST with Standard GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	242	483	114	235	235	479	121	238	1074	1073	2147
Simulation 2	232	483	123	237	236	479	117	227	1075	1059	2134
Simulation 3	237	485	112	232	244	490	115	239	1066	1088	2154
Simulation 4	238	485	118	234	230	493	116	229	1075	1068	2143
Simulation 5	242	483	119	235	234	473	116	244	1079	1067	2146
Simulation 6	229	489	118	230	234	484	117	240	1066	1075	2141
Simulation 7	248	488	124	230	243	492	115	230	1090	1080	2170
Simulation 8	241	495	118	223	226	479	122	235	1077	1062	2139
Simulation 9	233	493	121	226	238	475	121	229	1073	1063	2136
Simulation 10	238	486	119	231	235	487	121	232	1074	1075	2149
Simulation 11	236	485	113	244	229	485	120	224	1078	1058	2136
Simulation 12	237	477	120	230	230	490	120	230	1064	1070	2134
Simulation 13	235	488	119	227	235	494	119	233	1069	1081	2150
Simulation 14	235	484	119	238	240	478	121	239	1076	1078	2154
Simulation 15	233	475	119	233	243	483	119	233	1060	1078	2138
Simulation 16	234	491	122	239	234	480	120	234	1086	1068	2154
Simulation 17	248	486	116	223	238	479	120	224	1073	1061	2134
Simulation 18	239	495	120	237	241	474	119	232	1091	1066	2157
Simulation 19	240	494	119	234	235	479	112	229	1087	1055	2142
Simulation 20	241	473	119	235	233	481	115	240	1068	1069	2137
Mean	238	486	119	233	236	483	118	233	1075	1070	2145

Table B18: Vehicle throughput for VST with Mobile GPS in Scenario 3

Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Ring 1**	**Ring 2**	**Total**
Simulation 1	242	483	114	230	235	478	121	237	1069	1071	2140
Simulation 2	232	481	123	232	238	477	118	222	1068	1055	2123
Simulation 3	238	486	113	227	245	491	116	235	1064	1087	2151
Simulation 4	239	483	115	230	232	493	116	224	1067	1065	2132
Simulation 5	243	488	119	225	235	472	118	238	1075	1063	2138
Simulation 6	231	491	118	231	237	487	117	236	1071	1077	2148
Simulation 7	248	489	124	231	243	491	113	228	1092	1075	2167
Simulation 8	242	495	115	224	228	475	120	233	1076	1056	2132
Simulation 9	234	493	121	232	241	477	121	234	1080	1073	2153
Simulation 10	238	492	119	231	238	493	121	233	1080	1085	2165
Simulation 11	238	492	114	243	230	488	118	220	1087	1056	2143
Simulation 12	239	482	121	230	232	491	121	223	1072	1067	2139
Simulation 13	237	488	119	225	236	491	119	230	1069	1076	2145
Simulation 14	236	486	120	232	243	479	121	231	1074	1074	2148
Simulation 15	235	476	119	233	244	483	119	236	1063	1082	2145
Simulation 16	235	490	122	235	235	482	121	231	1082	1069	2151
Simulation 17	250	488	116	223	239	472	119	225	1077	1055	2132
Simulation 18	240	495	120	237	241	474	117	232	1092	1064	2156
Simulation 19	240	497	119	232	235	483	111	227	1088	1056	2144
Simulation 20	242	475	119	228	234	483	115	229	1064	1061	2125
Mean	239	488	119	231	237	483	118	230	1076	1068	2144

B.3 Vehicle stops

Table B19: Vehicle stops for VST with High Accurate GPS in Scenario 1

Scenario 1	**High Accurate GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.69	0.77	0.80	0.84	0.70	0.81	0.71	0.73	0.77	0.76	0.76
Simulation 2	0.75	0.75	0.75	0.84	0.73	0.80	0.84	0.79	0.77	0.79	0.78
Simulation 3	0.64	0.80	0.80	0.81	0.67	0.79	0.80	0.85	0.76	0.78	0.77
Simulation 4	0.59	0.77	0.82	0.85	0.75	0.81	0.85	0.79	0.75	0.79	0.77
Simulation 5	0.60	0.76	0.70	0.82	0.63	0.77	0.84	0.83	0.73	0.76	0.75
Simulation 6	0.67	0.81	0.84	0.82	0.58	0.78	0.83	0.82	0.78	0.75	0.77
Simulation 7	0.62	0.75	0.82	0.91	0.70	0.80	0.74	0.75	0.76	0.76	0.76
Simulation 8	0.61	0.77	0.74	0.77	0.61	0.83	0.74	0.82	0.73	0.77	0.75
Simulation 9	0.71	0.77	0.81	0.89	0.72	0.79	0.86	0.89	0.79	0.81	0.80
Simulation 10	0.78	0.83	0.83	0.82	0.64	0.73	0.87	0.78	0.82	0.73	0.78
Simulation 11	0.69	0.80	0.87	0.78	0.62	0.70	0.90	0.83	0.78	0.73	0.76
Simulation 12	0.67	0.75	0.73	0.82	0.64	0.81	0.82	0.86	0.74	0.79	0.76
Simulation 13	0.72	0.79	0.79	0.85	0.67	0.77	0.79	0.84	0.79	0.76	0.77
Simulation 14	0.61	0.81	0.71	0.84	0.65	0.81	0.79	0.86	0.76	0.78	0.77
Simulation 15	0.72	0.78	0.88	0.85	0.68	0.79	0.88	0.85	0.79	0.79	0.79
Simulation 16	0.71	0.77	0.84	0.86	0.69	0.81	0.80	0.85	0.78	0.79	0.79
Simulation 17	0.62	0.76	0.76	0.76	0.75	0.76	0.92	0.82	0.73	0.79	0.76
Simulation 18	0.61	0.81	0.80	0.88	0.66	0.76	0.76	0.86	0.78	0.76	0.77
Simulation 19	0.62	0.77	0.78	0.92	0.68	0.75	0.80	0.77	0.77	0.74	0.76
Simulation 20	0.72	0.79	0.76	0.79	0.69	0.76	0.71	0.84	0.77	0.76	0.76
Mean	0.67	0.78	0.79	0.84	0.67	0.78	0.81	0.82	0.77	0.77	0.77

Table B20: Vehicle stops for VST with Standard GPS in Scenario 1

Scenario 1	**Standard GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.77	0.85	0.80	0.78	0.79	0.87	0.73	0.65	0.81	0.79	0.80
Simulation 2	0.74	0.77	0.70	0.84	0.80	0.74	0.78	0.78	0.77	0.76	0.77
Simulation 3	0.74	0.81	0.78	0.79	0.70	0.82	0.88	0.82	0.78	0.80	0.79
Simulation 4	0.65	0.77	0.80	0.84	0.85	0.79	0.79	0.78	0.76	0.80	0.78
Simulation 5	0.74	0.75	0.72	0.80	0.71	0.79	0.78	0.83	0.76	0.78	0.77
Simulation 6	0.74	0.78	0.78	0.76	0.65	0.84	0.81	0.83	0.77	0.79	0.78
Simulation 7	0.74	0.73	0.78	0.81	0.81	0.75	0.78	0.77	0.76	0.77	0.77
Simulation 8	0.68	0.78	0.77	0.77	0.73	0.82	0.70	0.78	0.75	0.78	0.77
Simulation 9	0.78	0.82	0.77	0.85	0.83	0.83	0.80	0.88	0.81	0.83	0.82
Simulation 10	0.78	0.77	0.77	0.78	0.82	0.72	0.90	0.76	0.77	0.77	0.77
Simulation 11	0.76	0.75	0.77	0.78	0.72	0.81	0.82	0.78	0.76	0.78	0.77
Simulation 12	0.70	0.72	0.81	0.83	0.69	0.83	0.76	0.81	0.75	0.79	0.77
Simulation 13	0.80	0.79	0.85	0.83	0.75	0.78	0.74	0.83	0.81	0.78	0.79
Simulation 14	0.74	0.79	0.69	0.80	0.77	0.78	0.79	0.85	0.77	0.79	0.78
Simulation 15	0.79	0.78	0.76	0.74	0.74	0.72	0.79	0.79	0.77	0.75	0.76
Simulation 16	0.80	0.81	0.68	0.89	0.77	0.79	0.76	0.85	0.81	0.79	0.80
Simulation 17	0.67	0.78	0.85	0.81	0.74	0.81	0.83	0.82	0.77	0.80	0.78
Simulation 18	0.68	0.77	0.82	0.82	0.70	0.77	0.67	0.73	0.77	0.73	0.75
Simulation 19	0.70	0.83	0.88	0.87	0.74	0.79	0.82	0.78	0.81	0.78	0.80
Simulation 20	0.78	0.79	0.67	0.79	0.83	0.75	0.78	0.80	0.77	0.78	0.78
Mean	0.74	0.78	0.77	0.81	0.76	0.79	0.79	0.80	0.78	0.78	0.78

Table B21: Vehicle stops for VST with Mobile GPS in Scenario 1

Scenario 1	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.82	0.84	0.82	0.80	0.76	0.88	0.83	0.66	0.83	0.80	0.81
Simulation 2	0.81	0.80	0.74	0.80	0.81	0.81	0.84	0.78	0.79	0.81	0.80
Simulation 3	0.75	0.85	0.80	0.82	0.74	0.82	0.80	0.87	0.82	0.81	0.81
Simulation 4	0.73	0.79	0.84	0.86	0.85	0.78	0.79	0.71	0.80	0.78	0.79
Simulation 5	0.68	0.77	0.74	0.76	0.72	0.82	0.80	0.84	0.74	0.80	0.77
Simulation 6	0.83	0.80	0.76	0.83	0.68	0.78	0.87	0.83	0.81	0.78	0.79
Simulation 7	0.85	0.79	0.82	0.82	0.71	0.78	0.73	0.79	0.81	0.76	0.79
Simulation 8	0.71	0.79	0.74	0.77	0.78	0.84	0.78	0.77	0.76	0.81	0.78
Simulation 9	0.79	0.82	0.69	0.84	0.83	0.77	0.71	0.84	0.80	0.79	0.80
Simulation 10	0.82	0.82	0.69	0.78	0.82	0.75	0.86	0.78	0.80	0.79	0.79
Simulation 11	0.77	0.77	0.72	0.81	0.76	0.83	0.80	0.82	0.77	0.81	0.79
Simulation 12	0.80	0.79	0.83	0.78	0.74	0.80	0.82	0.82	0.80	0.79	0.79
Simulation 13	0.87	0.80	0.77	0.83	0.78	0.79	0.77	0.83	0.82	0.80	0.81
Simulation 14	0.85	0.78	0.73	0.79	0.80	0.77	0.71	0.86	0.79	0.79	0.79
Simulation 15	0.82	0.82	0.76	0.74	0.75	0.74	0.77	0.79	0.79	0.76	0.78
Simulation 16	0.76	0.82	0.74	0.88	0.78	0.86	0.76	0.80	0.81	0.82	0.81
Simulation 17	0.75	0.75	0.83	0.73	0.77	0.85	0.81	0.76	0.75	0.81	0.78
Simulation 18	0.70	0.82	0.78	0.85	0.75	0.79	0.78	0.77	0.80	0.78	0.79
Simulation 19	0.74	0.80	0.90	0.85	0.79	0.77	0.82	0.79	0.81	0.78	0.79
Simulation 20	0.77	0.85	0.61	0.75	0.86	0.82	0.76	0.82	0.78	0.82	0.80
Mean	0.78	0.80	0.77	0.80	0.77	0.80	0.79	0.80	0.79	0.79	0.79

Table B22: Vehicle stops for VST with High Accurate GPS in Scenario 2

Scenario 2	**High Accurate GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.73	0.77	0.87	0.84	0.73	0.78	0.82	0.82	0.79	0.78	0.78
Simulation 2	0.75	0.83	0.88	0.84	0.77	0.84	0.83	0.88	0.82	0.83	0.83
Simulation 3	0.77	0.79	0.93	0.79	0.80	0.81	0.75	0.90	0.80	0.82	0.81
Simulation 4	0.84	0.77	0.81	0.82	0.82	0.80	0.86	0.76	0.80	0.80	0.80
Simulation 5	0.79	0.76	0.87	0.88	0.77	0.80	0.86	0.84	0.80	0.81	0.81
Simulation 6	0.85	0.83	0.70	0.84	0.76	0.82	0.84	0.91	0.82	0.83	0.83
Simulation 7	0.88	0.81	0.91	0.83	0.82	0.78	0.87	0.80	0.84	0.80	0.82
Simulation 8	0.79	0.80	0.84	0.85	0.75	0.75	0.73	0.82	0.81	0.77	0.79
Simulation 9	0.76	0.84	0.82	0.87	0.75	0.85	0.84	0.78	0.83	0.81	0.82
Simulation 10	0.67	0.83	0.90	0.90	0.83	0.83	0.79	0.88	0.82	0.84	0.83
Simulation 11	0.76	0.82	0.76	0.83	0.72	0.84	0.79	0.76	0.80	0.79	0.80
Simulation 12	0.78	0.82	0.87	0.88	0.72	0.77	0.89	0.78	0.83	0.77	0.80
Simulation 13	0.73	0.85	0.78	0.79	0.76	0.83	0.81	0.82	0.80	0.81	0.81
Simulation 14	0.73	0.83	0.80	0.91	0.78	0.85	0.73	0.81	0.82	0.81	0.82
Simulation 15	0.74	0.78	0.88	0.85	0.71	0.80	0.81	0.91	0.80	0.80	0.80
Simulation 16	0.74	0.79	0.73	0.82	0.71	0.78	0.72	0.84	0.78	0.77	0.78
Simulation 17	0.81	0.81	0.66	0.89	0.86	0.77	0.76	0.90	0.81	0.82	0.81
Simulation 18	0.77	0.84	0.76	0.81	0.82	0.83	0.84	0.83	0.81	0.83	0.82
Simulation 19	0.82	0.81	0.77	0.90	0.75	0.76	0.73	0.84	0.83	0.77	0.80
Simulation 20	0.80	0.76	0.88	0.80	0.82	0.87	0.71	0.86	0.79	0.84	0.81
Mean	0.78	0.81	0.82	0.85	0.77	0.81	0.80	0.84	0.81	0.81	0.81

Table B23: Vehicle stops for VST with Standard GPS in Scenario 2

Scenario 2	**Standard GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.66	0.82	0.88	0.90	0.63	0.80	0.81	0.85	0.81	0.78	0.79
Simulation 2	0.67	0.83	0.81	0.93	0.66	0.88	0.80	0.85	0.81	0.81	0.81
Simulation 3	0.68	0.82	0.85	0.80	0.71	0.86	0.81	0.94	0.79	0.84	0.81
Simulation 4	0.68	0.83	0.82	0.84	0.65	0.85	0.87	0.82	0.80	0.80	0.80
Simulation 5	0.68	0.84	0.89	0.88	0.75	0.85	0.80	0.87	0.82	0.82	0.82
Simulation 6	0.76	0.84	0.77	0.83	0.66	0.90	0.80	0.94	0.81	0.85	0.83
Simulation 7	0.71	0.80	0.87	0.93	0.71	0.85	0.87	0.83	0.82	0.81	0.81
Simulation 8	0.73	0.82	0.80	0.83	0.71	0.80	0.81	0.86	0.80	0.79	0.80
Simulation 9	0.68	0.88	0.82	0.84	0.77	0.85	0.69	0.85	0.82	0.81	0.82
Simulation 10	0.67	0.79	0.89	0.82	0.74	0.85	0.82	0.83	0.78	0.82	0.80
Simulation 11	0.66	0.85	0.81	0.93	0.69	0.88	0.86	0.79	0.82	0.81	0.82
Simulation 12	0.69	0.85	0.80	0.91	0.66	0.85	0.86	0.88	0.82	0.82	0.82
Simulation 13	0.60	0.84	0.77	0.86	0.69	0.83	0.89	0.81	0.78	0.80	0.79
Simulation 14	0.65	0.86	0.84	0.98	0.72	0.89	0.81	0.84	0.84	0.83	0.84
Simulation 15	0.69	0.78	0.80	0.84	0.76	0.83	0.79	0.90	0.78	0.82	0.80
Simulation 16	0.63	0.80	0.79	0.89	0.65	0.84	0.81	0.84	0.78	0.79	0.79
Simulation 17	0.72	0.85	0.69	0.85	0.77	0.87	0.76	0.81	0.80	0.82	0.81
Simulation 18	0.64	0.85	0.77	0.81	0.75	0.80	0.83	0.87	0.79	0.81	0.80
Simulation 19	0.71	0.87	0.86	0.91	0.68	0.81	0.78	0.97	0.84	0.82	0.83
Simulation 20	0.71	0.82	0.86	0.87	0.71	0.85	0.90	0.94	0.81	0.84	0.83
Mean	0.68	0.83	0.82	0.87	0.70	0.85	0.82	0.86	0.81	0.82	0.81

Table B24: Vehicle stops for VST with Mobile GPS in Scenario 2

Scenario 2	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.60	0.82	0.83	0.98	0.58	0.82	0.82	0.88	0.81	0.78	0.79
Simulation 2	0.62	0.83	0.91	0.90	0.59	0.88	0.84	0.87	0.81	0.81	0.81
Simulation 3	0.63	0.92	0.87	0.86	0.67	0.89	0.78	0.91	0.84	0.83	0.83
Simulation 4	0.63	0.92	0.81	0.89	0.60	0.91	0.86	0.85	0.84	0.83	0.83
Simulation 5	0.60	0.95	0.85	0.96	0.62	0.89	0.83	0.91	0.86	0.83	0.84
Simulation 6	0.64	0.89	0.83	0.90	0.55	0.90	0.88	0.90	0.83	0.82	0.82
Simulation 7	0.61	0.87	0.87	0.94	0.59	0.88	0.85	0.88	0.83	0.81	0.82
Simulation 8	0.68	0.89	0.84	0.83	0.63	0.81	0.77	0.85	0.82	0.78	0.80
Simulation 9	0.59	0.91	0.93	0.94	0.62	0.93	0.75	0.78	0.85	0.81	0.83
Simulation 10	0.57	0.82	0.87	0.87	0.62	0.86	0.87	0.83	0.78	0.80	0.79
Simulation 11	0.59	0.85	0.81	0.89	0.62	0.87	0.83	0.88	0.80	0.81	0.81
Simulation 12	0.64	0.90	0.83	0.94	0.59	0.84	0.91	0.91	0.84	0.81	0.82
Simulation 13	0.52	0.91	0.89	0.91	0.55	0.94	0.92	0.87	0.82	0.83	0.83
Simulation 14	0.59	0.92	0.89	0.89	0.67	0.92	0.84	0.87	0.84	0.84	0.84
Simulation 15	0.60	0.84	0.88	0.85	0.63	0.90	0.79	0.95	0.79	0.84	0.82
Simulation 16	0.53	0.85	0.76	0.92	0.55	0.92	0.80	0.84	0.79	0.80	0.80
Simulation 17	0.59	0.91	0.80	0.93	0.66	0.93	0.84	0.93	0.83	0.86	0.84
Simulation 18	0.58	0.92	0.80	0.85	0.68	0.89	0.84	0.98	0.81	0.86	0.83
Simulation 19	0.65	0.88	0.80	0.95	0.61	0.89	0.81	0.99	0.83	0.84	0.84
Simulation 20	0.64	0.90	0.92	0.92	0.61	0.86	0.84	1.00	0.85	0.83	0.84
Mean	0.60	0.88	0.85	0.91	0.61	0.89	0.83	0.89	0.82	0.82	0.82

Table B25: Vehicle stops for VST with High Accurate GPS in Scenario 3

Scenario 3	**High Accurate GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.83	1.07	0.95	1.15	0.88	0.95	0.86	1.20	1.02	0.98	1.00
Simulation 2	0.99	0.89	0.84	0.96	0.93	0.90	0.85	0.92	0.92	0.91	0.91
Simulation 3	0.99	0.93	0.87	0.98	0.92	0.97	0.90	1.08	0.95	0.98	0.96
Simulation 4	0.85	0.95	0.86	1.07	0.89	0.99	0.84	1.08	0.94	0.97	0.96
Simulation 5	0.87	0.99	0.89	1.00	0.85	0.90	0.86	1.07	0.95	0.92	0.94
Simulation 6	0.87	1.02	0.86	0.96	0.91	0.93	1.00	1.00	0.96	0.95	0.95
Simulation 7	0.84	0.98	0.90	1.00	0.85	1.09	0.90	0.89	0.94	0.97	0.96
Simulation 8	0.88	0.98	0.93	1.07	0.81	0.92	0.93	1.10	0.97	0.94	0.95
Simulation 9	0.84	1.09	0.89	0.97	0.87	0.95	0.85	1.05	0.99	0.94	0.97
Simulation 10	0.91	0.92	0.82	1.03	0.87	1.03	0.82	1.00	0.93	0.96	0.95
Simulation 11	0.96	0.99	0.91	1.07	0.86	0.97	0.91	0.93	1.00	0.93	0.96
Simulation 12	0.94	0.93	0.92	0.90	0.85	0.95	0.86	0.97	0.93	0.92	0.93
Simulation 13	0.98	1.03	0.91	1.07	0.87	0.93	0.89	0.92	1.02	0.91	0.96
Simulation 14	0.91	1.08	0.78	1.20	0.93	1.01	1.01	1.07	1.04	1.00	1.02
Simulation 15	0.84	1.06	0.87	1.10	0.85	0.96	0.88	1.12	1.00	0.96	0.98
Simulation 16	0.91	1.03	0.89	1.03	0.88	0.98	0.90	1.00	0.99	0.95	0.97
Simulation 17	0.85	0.98	0.92	1.17	0.88	0.94	0.84	1.02	0.98	0.93	0.96
Simulation 18	0.90	0.98	0.93	1.03	0.95	1.02	0.95	1.03	0.97	1.00	0.98
Simulation 19	0.98	1.02	0.92	1.01	0.96	0.95	0.94	1.00	1.00	0.96	0.98
Simulation 20	0.86	0.89	0.86	0.95	0.89	0.94	0.95	1.08	0.89	0.96	0.93
Mean	0.90	0.99	0.89	1.04	0.89	0.96	0.90	1.03	0.97	0.95	0.96

Table B26: Vehicle stops for VST with Standard GPS in Scenario 3

Scenario 3	**Standard GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.80	1.04	1.01	1.21	0.83	0.96	0.94	1.07	1.02	0.96	0.99
Simulation 2	0.82	1.01	0.98	1.16	0.78	0.98	0.85	0.96	1.00	0.92	0.96
Simulation 3	0.83	0.94	0.88	1.02	0.83	1.01	0.88	1.04	0.92	0.96	0.94
Simulation 4	0.83	1.03	0.91	1.14	0.86	1.03	0.85	1.26	1.00	1.02	1.01
Simulation 5	0.91	0.97	0.91	1.02	0.86	0.89	0.88	1.20	0.96	0.95	0.96
Simulation 6	0.81	0.99	0.85	1.07	0.81	0.96	0.94	1.20	0.95	0.98	0.96
Simulation 7	0.75	1.06	0.98	1.23	0.81	1.11	0.95	0.98	1.01	1.00	1.01
Simulation 8	0.90	1.05	0.86	1.09	0.82	1.00	0.88	1.21	1.00	1.00	1.00
Simulation 9	0.77	1.04	0.95	1.04	0.81	1.07	0.98	1.01	0.97	0.99	0.98
Simulation 10	0.82	0.98	0.82	1.08	0.81	1.00	0.88	1.13	0.95	0.97	0.96
Simulation 11	0.86	1.06	0.93	1.14	0.82	1.03	0.88	0.97	1.02	0.96	0.99
Simulation 12	0.90	0.93	0.90	1.01	0.80	0.93	0.86	1.11	0.94	0.93	0.94
Simulation 13	0.86	1.09	0.92	1.03	0.88	0.96	0.93	1.00	1.01	0.95	0.98
Simulation 14	0.80	1.19	0.91	1.19	0.83	1.01	0.94	1.17	1.07	1.00	1.03
Simulation 15	0.82	1.09	0.87	0.96	0.76	0.94	0.90	1.02	0.98	0.91	0.95
Simulation 16	0.82	1.07	0.95	1.03	0.79	0.96	0.94	1.14	0.99	0.96	0.98
Simulation 17	0.77	1.03	0.87	1.15	0.77	0.94	0.97	1.08	0.98	0.93	0.96
Simulation 18	0.79	1.06	0.89	0.99	0.85	1.07	0.89	1.09	0.97	1.00	0.98
Simulation 19	0.83	0.99	0.96	1.14	0.82	0.98	0.91	1.03	0.98	0.95	0.97
Simulation 20	0.78	0.93	0.91	1.12	0.78	1.06	0.88	1.16	0.94	1.00	0.97
Mean	0.82	1.03	0.91	1.09	0.82	0.99	0.91	1.09	0.98	0.97	0.97

Table B27: Vehicle stops for VST with Mobile GPS in Scenario 3

Scenario 3	**Mobile GPS**										
	Vehicle stops										
Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean R1**	**Mean R2**	**Total mean**
Simulation 1	0.73	1.10	1.04	1.29	0.73	1.05	1.02	1.18	1.05	1.01	1.03
Simulation 2	0.70	1.05	0.96	1.16	0.68	1.06	0.93	1.15	0.99	0.98	0.98
Simulation 3	0.74	1.09	0.92	1.17	0.73	1.09	0.95	1.15	1.01	1.01	1.01
Simulation 4	0.69	1.10	0.95	1.30	0.73	1.09	0.98	1.27	1.03	1.04	1.04
Simulation 5	0.75	1.03	0.95	1.15	0.69	1.02	0.90	1.19	0.98	0.97	0.98
Simulation 6	0.73	1.15	0.92	1.23	0.69	1.02	0.96	1.50	1.05	1.04	1.05
Simulation 7	0.70	1.13	0.96	1.22	0.76	1.25	1.15	1.17	1.03	1.11	1.07
Simulation 8	0.76	1.14	0.97	1.25	0.73	1.01	0.97	1.22	1.06	0.99	1.03
Simulation 9	0.72	1.16	0.95	1.16	0.76	1.08	0.99	1.21	1.04	1.03	1.03
Simulation 10	0.76	1.09	0.93	1.19	0.71	1.17	0.95	1.23	1.02	1.06	1.04
Simulation 11	0.75	1.10	1.04	1.37	0.74	1.11	0.93	1.20	1.08	1.03	1.05
Simulation 12	0.78	1.02	0.91	1.08	0.70	1.11	0.94	1.20	0.97	1.02	1.00
Simulation 13	0.79	1.10	0.95	1.22	0.74	1.07	0.89	1.23	1.04	1.01	1.03
Simulation 14	0.75	1.10	0.89	1.15	0.73	1.12	1.06	1.08	1.01	1.02	1.01
Simulation 15	0.70	1.15	0.88	1.12	0.63	1.04	0.96	1.08	1.02	0.95	0.98
Simulation 16	0.75	1.12	0.93	1.25	0.74	1.10	0.92	1.18	1.05	1.02	1.03
Simulation 17	0.71	1.08	0.91	1.27	0.69	1.03	0.98	1.28	1.02	1.00	1.01
Simulation 18	0.72	1.16	0.96	1.13	0.73	1.22	1.02	1.30	1.03	1.10	1.07
Simulation 19	0.77	1.08	0.99	1.16	0.77	1.11	0.90	1.20	1.02	1.03	1.02
Simulation 20	0.68	1.06	1.03	1.22	0.68	1.10	0.97	1.40	1.00	1.05	1.03
Mean	0.73	1.10	0.95	1.20	0.72	1.09	0.97	1.22	1.02	1.02	1.02