Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

Management of Transitions of Control in Cooperative Autonomous Vehicles in Mixed Traffic

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April 2021

A dissertation submitted to the University of Dublin in partial fulfilment of the requirements for the degree of MAI

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Abstract

Recent industry developments in automated vehicles have focused on ensuring that vehicles can drive autonomously in a variety of traffic conditions. It is expected however, that in certain scenarios vehicles will need to handover control to the (human) driver for a long period. In response, there has been increasing focus on managing transition areas, where multiple vehicles reach their functional limits and must perform a Transition of Control (handover vehicle control to the driver). In the absence of a traffic management system these transition areas can become hazardous with numerous vehicles performing transitions of control and in some cases minimum risk manoeuvres (where the vehicle comes to a stop).

This research explores two traffic management systems implemented to reduce the negative effects of transitions of control in cooperative autonomous vehicles entering transition areas. The transition areas being examined are the planned and unplanned blockages of an exit lane in a four arm intersection. To achieve this, an extensive literary review was conducted in which these two future transition areas were identified as having limited research done on them. Two road networks were created to replicate the traffic conditions at both planned and unplanned lane closures, and two management systems were developed to ensure that vehicles can traverse the networks smoothly. Finally the intersection was simulated at multiple vehicle penetrations and congestion levels.

This report evaluates the simulations conducted. For an unplanned closure, this report fails to identify a satisfactory traffic management system to increase safety and efficiency. The proposed system increased the time to collision (TTC) incident rate by 14% and decreased the mean trip duration by 10%. For a planned closure in the exit lane of an intersection, the proposed traffic management system does improve the performance of the intersection in terms of safety and efficiency, TTC incidents decreased by 11% and the mean trip duration decreased by 17%.

Acknowledgements

I wish to acknowledge Dr. Mélanie Bouroche for her continued support and advice throughout my research. Dr. Bouroche never hesitated to answer any of my queries and I am very grateful for her help and insight.
I would like thank Mohit Garg for his continued technical support throughout my research. He never failed to help with an issues I faced.
Finally, I would like to thank my friends and family for their help and support over the last year.

Acronyms

ACC Adaptive Cruise Control. 24

AD automated driving. 9, 11

ADAS Advanced Driver Assistance System. 24

AVs Automated vehicles. 5, 9, 11, 14, 16

BASt Bundesanstalt für Straßenwesen. 5

CACC Cooperative Adaptive Cruise Control. 24

CAMs Cooperative Awareness Messages. 13

CAV Cooperative Autonomous Vehicles. 2, 8

CPM Collective Perception Message. 14

CVs Cooperative Vehicles. 10, 12–14, 16–18

DENM Decentralized Environmental Notification Message. 14

HDVs human driven vehicles. 5, 16

KPIs Key Performance Indicators. 44

LOS Level of Service. 29

MRM Minimum Risk Manoeuvre. 7, 9, 11, 15

NACV Non Autonomous Cooperative Vehicle. 8

NCAV Non Cooperative Automated Vehicle. 8

NHTSA National Highway Traffic Safety Administration. 5

ODD Operational Design Domain. 2, 5, 11

OEMs original equipment manufacturers. 11, 28, 53

PET Post Encroachment Time. 44, 45, 47, 56

RSI roadside infrastructure. 12, 16

SAE Society of Automotive Engineers. 2

SSM Surrogate Safety Measure. 45

TAs Transition Areas. 2, 9, 11

TMS Traffic Management System. 2, 9, 15–17

ToC Transitions of Control. 2, 5, 6, 8, 9, 11, 14, 15

TOR Take Over Request. 9

TraCI Traffic Control Interface. 24

TransAID Transition Area for Infrastructure-Assisted Driving. 5, 9, 14–16

TTC Time to Collision. 44, 47, 54

V2I Vehicle to Infrastructure. 7

V2V Vehicle to Vehicle. 7

V2X Vehicle to Anything. 7

VDA Verband der Automobilindustrie. 5

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1 Introduction

In the near future automated vehicles will become commonplace on public roads, as the concept of highly automated vehicles becomes a reality. This can be seen with the release of Cadillac's Super Cruise in 2018 [9] and Tesla's autopilot release in 2015 [10], along with states such as California, Florida, Nevada, Pennsylvania and Texas giving the green light to the testing of automated vehicles on public roads [11]. A common misconception about these vehicles is that they are fully autonomous, when in fact they are only partially autonomous. Partially autonomous vehicles have an *Operational Design Domain (ODD)* in which they can perform automated driving but outside of which the driver must retake control of the vehicle. This passing of control from vehicle to driver (or vice versa) is called a *Transitions of Control (ToC)*.

1.1 Background

Partially autonomous vehicles will have varying levels of driving capability. These levels are defined by the *Society of Automotive Engineers (SAE)*, and range from Level 0 which is human driven to Level 5 which is fully autonomous [1]. In between lies partially autonomous vehicles. Multiple studies show that as the SAE Level of a vehicle rises the human's alertness in the vehicle falls [12]. If a vehicle performs a ToC, there is little certainty about the (human)driver's level of reaction. As a result, vehicles may experience speed fluctuations and delayed reaction times preceding a transition while the driver familiarises themselves with their surroundings. A transition in one vehicle is a minor safety concern. However, when it occurs in multiple vehicles in a small area the effects can be compounded, these areas are called *Transition Areas (TAs)*.

1.2 Project Objective

The overarching objective of this thesis is to investigate the development of a *Traffic Management System (TMS)* that allows *Cooperative Autonomous Vehicles (CAV)* to maintain their autonomous capabilities when approaching and exiting a four-way, 3-lane approach intersection, when one of the exit lanes is blocked.

1.3 Motivation

The motivation behind this research is that autonomous vehicles are being introduced to public roads to increase both safety and efficiency. However, when vehicles arrive at a TA in the seconds preceding a transition the vehicles will decrease the roads safety and efficiency as the driver's awareness increases. It is therefore of paramount importance that a system is put in place in order to manage autonomous vehicles approaching a TA, to:

- guide them through without performing a transition

or in the case a transition is required the TMS must

- mitigate the negative affects of the transition.

1.4 Challenges

The challenge faced by researchers trying to mitigate and manage the effect of these transitions is that there is little standardisation among autonomous vehicles that come from different manufacturers. Different manufacturers are competing to release the new best vehicle and some are reluctant to share information on the capabilities of the vehicles [11]. This lack of information from some manufacturers means it is difficult for researchers to:

- Identify scenarios where vehicles in the future will perform a transition. This is made more challenging as it is unclear what actions autonomous vehicles will be forbidden from undertaking but which human drivers instinctively do.
- Understand how vehicles will react in a ToC, as actions of every individual vehicle will vary on the alertness of its driver but also on how the driver is informed of the transition and how slowly control is granted [13].
- Evaluate how vehicles will react to the advice of a TMS when entering a ToC.

1.5 Approach

This work builds on the experimental approach in the leading research in this area, the TransAID Horizon 2020 Project[1]. The TransAID project was a collaboratively funded research project by the EU and leading manufactures such as Hyundai, it focused on the management and mitigation of the negative effects surrounding multiple vehicles performing a transition of control. This projects goal is to add two additional scenario's to those covered in the TransAID project.

1.6 Roadmap

The remainder of this report is structured as follows.

- **Chapter 2 - State of the Art:** documents previous research in this area and assess its implications on the area of the management of transitions of control.
- **Chapter 3 - Scenario Description:** outlines the two Use Cases that will be investigated by this project.
- **Chapter 4 - Methodology:** illustrates the approach taken in simulating the previously defined Use Cases.

[1] `https://www.transaid.eu/`

- **Chapter 5 - Results and Discussion:** analyses the results of the simulations and assesses what their implications are.
- **Chapter 6 - Conclusion:** evaluates the strengths and weaknesses of the approach taken. It re-iterates the key findings and results of the report and discusses future work in this area.

2 State of the Art

This chapter discusses the current state of knowledge in the area of Transitions of Control in autonomous vehicles. It addresses why a ToC might occur and how vehicle(s) handle them. Various levels of autonomous driving are described as well as the types of vehicles that will drive on future roads. The TransAID Horizon 2020 project is covered and the chapter concludes by looking at how to prevent vehicles exceeding their ODD and the communication and infrastructure that can be expected on public roads in the future.

2.1 Background

Automated vehicles (AVs) are being introduced onto public roads to reduce road accidents and increase traffic efficiency. This is based on their improved driving and detection capabilities over human drivers. These vehicles have been designed to handle a large variety of traffic conditions from motorways [14], to busy urban areas with vulnerable road users (cyclists and pedestrians) [3]. Vehicle automation enables a reduction in human error - estimated to cause roughly 90% of all accidents on the road [15]. However, despite the driving capabilities of these vehicles, there will be a transition period, during which *human driven vehicles (HDVs)* and AVs will share the road. Over time the expectation is that the penetration rates of AVs will rise (Section 2.1.1) along with their driving capability leading to safer greener roads [1].

However, before vehicles reach full automation, it is recognised that there will be situations that AVs are unable to handle and will need to perform a ToC [14]. There are two types of ToC:

- Upward ToC - Control is passed from driver to vehicle.
- Downward ToC - Control is passed from vehicle to driver.

There are six different cases for a ToC as shown in Table 2.1 [12].

2.1.1 Levels of Autonomous Driving

The SAE have described 6 levels of autonomy ranging from HDVs to fully automated vehicles that will travel on public roads in the near future, see Figure 2.1. While there are other level systems defined by different authorities such as *Bundesanstalt für Straßenwesen (BASt)*,*Verband der Automobilindustrie (VDA)* and *National Highway Traffic Safety Administration (NHTSA)*, the remainder of this report will be referring to the SAE system. This system is based around the role of the driver of the vehicle rather than the vehicles driving capabilities [1]. It also clearly outlines which entity is in control of each of the three main driving tasks of:

Types of Transitions of Control			
Type	**Initiator**	**Direction**	**Description**
Optional	Driver	Downward	An optional ToC may happen if the driver would feel safer controlling the vehicle themselves
Mandatory	Driver	Downward	A mandatory transition may occur when road regulations restrict one form of driving, i.e, if automation is forbidden in a rural area with poor road markings then ToC would be mandatory.
Optional	Driver	Upward	An optional upward transition may occur when driving on a motorway for a long period.
Mandatory	Driver	Upward	Occurs if the driver cannot handle the current situation.
Mandatory	**Vehicle**	**Downward**	Currently optional driver initiated downward ToC are the most prevalent [11]. But they typically happen in one vehicle, while vehicle initiated downward transitions can cause Transitions Areas(which will be discussed in Section 2.2). **In future when this report refers to a ToC it is referring to a mandatory vehicle initiated downward Transitions of Control**
Mandatory	Vehicle	Upward	Occurs if the driver is non-responsive to a hazard and the vehicle initiates collision avoidance.

Table 2.1: Outlines ToC types

- Longitudinal control – acceleration & deceleration
- Lateral control – steering, turning corners & lane changing
- Monitoring of the environment

A lot of studies in this area focus mainly on the human factors that contribute to the safety and efficiency of ToC [14]. They cite that one of the main contributors to the safety and efficiency of ToCs is driver awareness, the more automated a vehicle is, (notable above Level 2), the less alert the driver will be.

This in turn will lengthen the time taken for a ToC as the driver must regain full situational awareness before taking control of the vehicle [12]. Thus although vehicles of Level 1 and 2 may occasionally need to perform a ToC, they will be relatively quick, because the driver must be paying full attention to at least two primary driving tasks [16]. Zhenji et al. [17] found that 12 to 20 seconds is needed for a driver who was focusing on non-driving tasks in automated mode to regain situational awareness. Gold et al. [13] found that longer take-over request times (i.e. time to perform the hand-over of control) leads to more efficient transitions.

2.1.2 Classes of Vehicles

Vehicles will vary in both automation level and communication capabilities and are listed below [16].

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.1: SAE Automation Levels [1]

Human Driven Vehicle (HDV) – SAE Level 0, 1, or 2

HDVs are controlled primarily by the driver. These vehicles do not have the capacity to communicate with either surrounding infrastructure or other vehicles using *Vehicle to Anything (V2X)*[1] communication. HDVs can be SAE Level 1 or Level 2 and therefore may need to perform a ToC. As discussed in the previous section these ToC are anticipated to be handled quickly as the driver should have full situational awareness. It is not possible for a HDV to perform a Minimum Risk Manoeuvre (MRM) [2].

[1] V2X is made up for two forms of communication:

- Vehicle to Infrastructure (V2I)
- Vehicle to Vehicle (V2V)

[2] Discussed further in Section 2.2

Non Autonomous Cooperative Vehicle (NACV) – SAE Level 1 or 2

NACVs[3] can communicate with surrounding vehicles and infrastructure using V2X communication. This allows them to both receive and emit warning messages to other vehicles and engage in cooperative lane changing. Like HDV, they may need to perform ToCs at times, but these ToCs are expected to be short and inconsequential. Like HDVs they are not capable of MRMs.

Non Cooperative Automated Vehicle (NCAV) - SAE Level 3 or 4

In NCAVs, the driver plays a secondary role in controlling the vehicle. NCAVs do not have the capability to communicate with their surroundings. NCAVs will need to perform ToCs when they reach their functional limit (ODD). The duration of this ToC will be longer if the vehicle was at SAE Level 4 as the driver will be out of the loop. If the driver does not respond to the ToC within a certain threshold a MRM will be performed.

Cooperative Autonomous Vehicles (CAV) - SAE Level 3 or 4

CAVs are like NCAVs in that the vehicle controls the primary driving tasks. CAVs have the ability to communicate with surrounding infrastructure and vehicles using V2X, respectively. They can receive and emit warning messages to other vehicles and engage in cooperative lane changing. Like NCAVs, CAVs will need to perform ToCs when they reach their functional limit (ODD). If the driver does not respond to the ToC on time an MRM will be performed.

Table 2.1 summarises the different vehicle types and their capabilities.

Capability	**HDV**	**NACV**	**NCAV**	**CAV**
SAE	Level 0, 1, 2	Level 1, 2	Level 3, 4	Level 3, 4
Communication	-	V2X	-	V2X
ToC Time	short	short	long	long
MRM	No	No	Yes	Yes
Cooperative Vehicle (CV)	No	Yes	No	Yes
Automated Vehicle (AV)	No	No	Yes	Yes

Table 2.2: Vehicle classes and their capabilities

2.2 ToC and MRM

As mentioned in Section 2.1, automated vehicles have been observed in simulations to improve road safety and throughput compared to HDVs due to their increased driving capabilities. Thus as a ToC will result in a change of responsibility of the driving task, the driving capability of the vehicle will

[3]There is a distinct difference between Connected (automated) vehicles and Cooperative (automated) vehicles. While they both have the capability to receive information from infrastructure and other cooperative vehicles. Only cooperative vehicles are necessarily going to follow the instructions while connected vehicles may use the provided information to benefit their own safety & efficiency rather than the road as a whole [18].

decrease as well as decreasing the safety and efficiency [14].

A ToC is sometimes necessary, because AVs may be about to enter an area with improper road markings or unable to detect a path around an obstacle, at which point the decrease in driving performance is necessary for continued driving. The decrease after a ToC is due to HDVs, fluctuating speed, headway and braking rates. These imperfections are increased after a ToC as the driver works to regain situational awareness. ToCs also result in a change in the environment for surrounding vehicles, as vehicles will need to give transitioning vehicles increased headway [19]. After a ToC, the risk of a collision for a vehicle is higher as the driver may not have regained full situational awareness. A study conducted by the California Department of Motor Vehicles, found that 1 out of every 178 ToCs from 2014 to July 2017 was followed[4] by an accident [11].

These driving imperfections occurring in one vehicle are a minor concern, but of bigger concern are areas where multiple AVs or all the AVs present need to perform a ToC. These areas are called Transition Areas (TAs) and can cause an accumulation of traffic safety and efficiency issues. An example of where a TA might occur is merging from a motorway en route to a rural town. The rural road may have insufficient infrastructure to support automated driving (AD). Therefore, all AVs will need to perform a downward ToC to continue. TAs were the main point of interest for the Transition Area for Infrastructure-Assisted Driving (TransAID) 2020 Horizon Project [14].

A ToC[5] is issued when the AV's functionality cannot handle the situation it is about to enter (i.e. it will be leaving its Operational Design Domain). The driver must be on hand to take control. The vehicle issues a *Take Over Request (TOR)*, the vehicle begins a timer. If the driver does not take control in the required time, the vehicle will perform a *Minimum Risk Manoeuvre (MRM)*. This involves the vehicle slowly decelerating before coming to a stop.

This will result in the vehicle stopping in the center of its lane and remaining there until the driver takes control of the vehicle. Once an MRM is started it can be stopped if the driver takes back control of the vehicle[20]. An MRM is an inefficient manoeuvre as the vehicle is left stationary in its ego-lane[6]. However an MRM does maximise safety.

Figure 2.2 provides a timeline of the events when a vehicle reaches the end of its ODD and must perform a ToC.

2.3 TransAID

The TransAID 2020 Horizon Project (September 2017 to August 2020) is the first and largest project to develop and demonstrate a *Traffic Management System (TMS)* that enables the smooth coexistence of mixed traffic at TAs[7]. TransAID identified possible or future TAs, then developed TMSs to reduce (or in some cases mitigate) them. TransAID developed 5 services each with a number of use cases. These services as outlined by Wijbenga et al. [21] centre around 3 main aims:

[4] It is worth noting that it is not clear that the ToCs caused the accidents, but rather the accidents occurred during or shortly after the ToC

[5] Vehicle initiated, downward ToC

[6] The Ego-Lane of a vehicle is the lane the vehicle is currently in

[7] While there is other research on TMSs that aid traffic at transition areas this research tends to heavily reference the TransAID project [19].

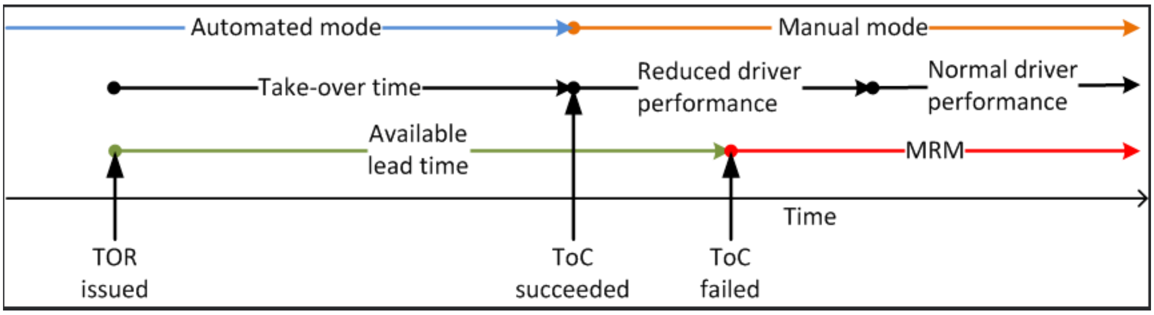


Figure 2.2: Timeline of a ToC [2]

- **Prevent a ToC/MRM** – Applying a TMS to prevent CAVs reaching their functional/system limit and therefore needing to perform a ToC/MRM.
- **Manage an MRM** – In some situations it may not be possible to predict and therefore prevent a ToC. In this instance the system needs to be able to handle any resulting MRMs (i.e. by providing a safe spot for the vehicle to occupy) as these are far more disruptive than ToCs and last until the driver is able to retake control.
- **Distribute ToCs/MRMs** – In some situations, a ToC/MRM may not be preventable, but they may be predictable. Therefore, it is beneficial to spread the ToCs out over a large period to prevent a TA occurring while also performing all the necessary ToCs.

To achieve these three goals TransAID developed five Services which are outlined by Wijbenga et al. [5].

Service 1 – Prevent ToC/MRM by providing vehicle path information

When CAVs encounter a situation where their target lane is blocked by an obstacle (i.e. collision or roadworks) and the vehicle cannot detect a path around it. The vehicle will be provided with detailed information about the path that it should take to overcome the obstacle and reach target lane to avoid performing a ToC/MRM. This path instruction could encourage the vehicle to violate traffic laws such as entering a bus lane.

Service 2 – Prevent ToC/MRM by providing speed, headway and/or lane advice

When a large number of *Cooperative Vehicles (CVs)* need to change lane i.e.

- diverging/merging onto a motorway
- approaching an intersection with an approach lane blocked

To make merging of vehicles more efficient, a TMS is present that provides the merging vehicles with speed and headway instructions to ensure that they can find an appropriate gap to merge into. This may involve speeding up or slowing down but can also involve instructing CVs in the target lane to alter their speeds to allow for lane changing, this is called Cooperative Lane Changing.

Service 3 – Prevent ToC/MRM by traffic separation

When two motorways are merging i.e. two, 2-lane motorways merging to create one 4-lane motorway, it can be beneficial to split the traffic into dedicated lanes based on automation level i.e. CVs and HDVs move to separate lanes. This reduces the number of interactions CAVs will have with non-AVs and therefore reduce the impact of stochastic human driving. Furthermore, the reduction of vehicle interactions means that CAV platoons can form/remain in place.

Service 4 – Manage MRM by guidance to a safe spot

This service is normally seen as an additional service to the other four services. When CAVs perform a ToC there is always the likelihood that the driver will be non-responsive resulting in an MRM. When this occurs the vehicle slowly decelerates until it stops in the ego-lane. This service was developed to assign a safe spot for vehicles to pull into if an MRM occurs, that way it will reduce the effect on traffic flow and safety. This safe spot can take the form of a parking place [20] or an area in front of roadworks or a collision.

Service 5 – Distribute ToC's by scheduling ToCs

When ToCs can be predicted but are not avoidable, such as if a road is known to have improper road markings and is therefore unable to support *automated driving (AD).*TransAID proposes informing the oncoming vehicles about the no-AD zone and distributing their ToCs both spatially and temporally to prevent the occurrence of a TA. Instead of all CAVs performing a ToC when they detect the region.

2.4 Operational Design Domain(ODD)

When an AV reaches the end of its functional limit and needs to perform a ToC/MRM it is said to have reached the end of its ODD. There is a strong correlation between the end of an ODD and the start of a TA, as an ODD marks the need for AVs to perform a ToC while TAs mark multiple AVs performing a ToC [18]. With this knowledge it might appear routine to identify where TAs will occur, if the ODDs of vehicles can be identified, then a TMS can be put in place to manage it. But this raises two issues:

1. It requires *original equipment manufacturers (OEMs)* to agree to build their systems in similar ways so an ODD in one make of vehicle will also be an ODD in another make of vehicle.
2. The other issue is that there are several parameters that can cause an ODD such as:
    - Weather
    - Road markings
    - Digital map information
    - Vehicle speed

Each of these parameters have many more sub-parameters that can cause an ODD, and their effects are accumulative. If road markings are in a reasonable condition but the weather is treacherous, that could cause an ODD, but the same road markings in different weather would not cause an ODD. This means that TransAID cannot attempt to prevent ToCs from occurring, but rather try to avoid/manage ToCs that might regularly occur.

TransAID tries to counteract the relationship between ODDs and TAs by providing AVs with information to ensure that they remain within their ODD. Another method of preventing a ToC would be for an AV to alter their speed when leaving their ODD [18]. Driving is safer when done at a slower speed so if the vehicles slightly altered their performance when they exceed one of the key parameters for their ODD they may be able to stay in AD mode.

2.5 Supporting Communication and Infrastructure

All of the previously discussed advances in vehicles driving capabilities and TMSs to prevent ToCs, will not happen independently of other factors. Alongside investment and research in the technology in the vehicles, similar investment will be needed in deployment of new infrastructure and the communication capability in vehicles.

2.5.1 Infrastructure

TransAID's TMSs rely on the presence of roadside infrastructure (RSI) that can detect:

- lane blockages
- vehicles
- vehicle speed and position
- safe spots

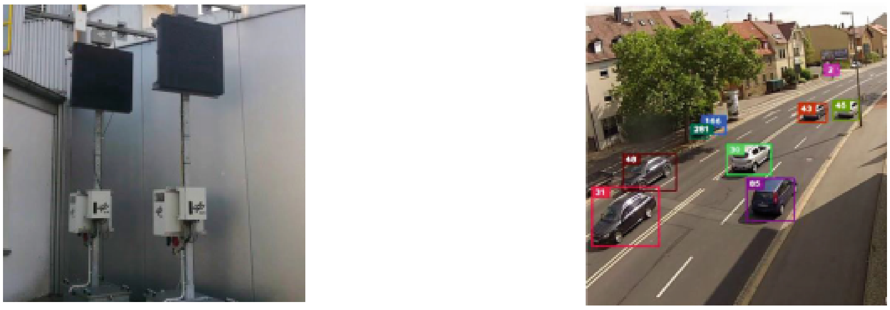
The paper by Lytrivis et al. [22] proposes that the infrastructure required for the transition period when SAE level 0 to 4 exist on public roads is still in need of investment. It points out that tech and automotive companies are investing heavily into the vehicles of the future but are leaving infrastructure behind. As a result, the INFRAMIX EU[8] project has been set up which will investigate:

1. the needed advancement in digital infrastructure to enable infrastructure to mitigate TMSs to numerous CVs at high speeds
2. the required upgrades in the physical infrastructure to cope with the new safety challenges of mixed traffic

This source does somewhat disagree with another a paper by Lu a et al. [1] that demonstrates how TransAID is developing the infrastructure along with its TMSs. Although these two sources paint the current state of research into infrastructure in a different light, it is clear that the infrastructure required for the transition period still requires research and investment. The infrastructure will also need to be present on public roads for TransAID's proposals to operate.

According to Khan et al. [3], the RSIs (or Roadside Units (RSUs)) that are expected to exist on public roads can be seen in Figure 2.3.
The RSI consists of a pole with a mounted camera capable of state-of-the-art object detection, that perceives both vehicle speed and path. This information can then be fed into the infrastructure computer system as inputs and used to determine how best to execute the TMS.

[8] https://www.inframix.eu/



(a) Physical make up of a RSI (b) View from the object detection camera in the RSI

Figure 2.3: Examples of RSI and its detection software [3]

2.5.2 Communication

Another key aspect to TransAID's proposals is communication, having a state-of-the-art RSI that can detect vehicles and their velocities is of limited use unless it can communicate with the CVs. There are two main categories of communication, Infrastructure-to-Vehicle (I2V) and Vehicle-to-anything(V2X) [23].

The perception of an *automated vehicle (AV)* is what an autonomous vehicle can detect using its sensors (i.e., radar or lidar-sensors) and cameras. To increase the safety and efficiency of road networks it is therefore necessary to improve vehicles perception capability. However, increasing the perception capability of individual vehicles is not the only answer as this range is limited. As vehicles will be unable to detect road users that are behind an object or in poor weather the vehicle's sensors ability may be diminished. Rather, if CVs are present the method proposed by Khan et al. for improving perception is Collective Perception. This is when CVs forward information about surrounding objects (road users) onto nearby CVs to increase their perception boundary [3]. This means that CVs knowledge of the road is no longer dictated by its sensor and camera range but rather by their communication range.

The TMSs being designed by TransAID [23] assume that all CVs have common communication capabilities and intend to use the shared information through selected communication messages such as CAM, DENM and CMP.

Cooperative Awareness Messages (CAMs)

This method is deployed by all vehicles and infrastructure capable of V2X communication.

- CVs will send out their position and velocity to surrounding vehicles and infrastructure. To allow surrounding vehicles to consider their own relative path and calculate the collision risk
- Infrastructure will emit their position as well as their communication zone.

These messages will be sent out periodically.

Decentralized Environmental Notification Message (DENM)

These messages are sent out when a CVs encounters a road hazard. There are two types of DENM.

1. Caused by the vehicle itself (e.g. an emergency brake): the vehicle will emit a DENM with the time, start point and end point. Once the action is complete it will terminate the DENM.
2. A road hazard (e.g. ice on the road): the vehicle will send a DENM to surrounding vehicles stating what the condition is and where it begins and ends. However, the vehicle will not terminate the DENM, it will remain in the area supported by surrounding RSI until the condition ceases.

Collective Perception Message (CPM)

As explained above collective perception is when CVs share information about surrounding road users that they have detected with nearby CVs. These messages are sent out by CVs every 1 second. Like CAM, this information can be used by receiving CVs to calculate what their next step should be. This communication method is seen as a key step in the introduction of cooperative vehicles.

2.6 Summary

A lot of research has been done on the mitigation of the effects of a ToC, by examining the human factors behind regaining control of the vehicle. TransAID's work is currently the most progressive research into the area of mitigation and handling of ToCs. The infrastructure to enable automated driving is currently being researched and developed. There is still a need to examine scenarios that will challenge AVs when they arrive on public roads. While ToCs may need to occur in certain instances, in others they can avoided if a capable TMS is available.

3 Scenario Description

This chapter examines two of the Use Cases investigated by the TransAID project and proposes two further TAs which will be examined in detail.

3.1 Overview of TransAID Use Cases

In the TransAID report there are two Use Cases in Service 2:

1. Use Case 2.3 - Intersection handling due to an incident (Unplanned Blockage)
2. Use Case 2.4 - Intersection Handling due to road works (Planned Blockage)

Describing the behaviour of vehicles when an approach lane to an intersection is blocked [5]. The intersection described in the TransAID project is a four way intersection with a 3-lane approach which is a common feature around Dublin, one example is where the Dodder Park road meets the Rathfarnham Park Road which is shown in Figure 3.1 . Use Cases 2.3 and 2.4 can be seen in Figure 3.2a & 3.2b.

Figure 3.1: Rathfarnham park road can be seen running North to South, while the Dodder Park runs East to West [4]

The aim of these Use Cases is to prevent a ToC/MRM. The Use Cases outlined above can be found in more detail at Wijbenga et. al, [16] and [5], however the TMS that TransAID developed is described briefly below:

- The right most lane of a 3-lane signalised intersection is blocked by an incident/roadworks.

(a) Use Case 2.3

(b) Use Case 2.4

Figure 3.2: TransAID Use Cases [5]

- An RSI is present and capable of detecting roadworks and incidents.
- The RSI will detect the obstruction and inform CVs that the lane is blocked and that they need to merge into the middle lane to perform the right turn.
- Under normal circumstances (without the TMS), CAVs would approach the obstruction and perform a ToC upon detecting that their target lane is blocked.
- The TMS allows CVs looking to turn right more time to enter the middle lane (an action which previously would have been forbidden when turning right). They will do this using cooperative lane changing, by merging into an empty spot in the middle lane or by receiving information from the TMS about an available opening.
- HDVs will still need to change lane closer to the obstruction.
- NCAVs will still need to perform a ToC and possibly an MRM when they detect the obstruction.

The aim of the TransAID approach is to reduce the number of vehicle interactions by spreading out the lane changing required both in space and time, while also removing the need of CAVs to perform a ToC and MRM.

3.1.1 Research Gap

Use Cases 2.3 and 2.4 involve the development of a TMS to handle a situation when an approach lane to an intersection is blocked. With Use Case 2.3 examining a planned blockage like a roadworks and Use Case 2.4 examining an unplanned blockage like a collision. However, TransAID did not examine the scenario when the exit lane is blocked. Despite this situation being as likely to occur as an incident or roadworks in an approach lane, there has been little research published on a TMS for handling this scenario.

Looking at this research gap presents interesting opportunities.

1. The scenario when an exit to an intersection has a planned closure presents an opportunity to work on a scenario AVs may struggle to solve it without the help of a TMS. This gives a clear goal of developing a TMS that enables AVs pass through the intersection as efficiently as HDVs.

2. The second scenario of an unplanned blockage in the exit lane, presents an opportunity to work on a situation that cannot be solved without the use of a TMS. Therefore, this research may be able to transform a road situation that is currently a common issue and unsolvable problem into partially solved.

3.2 Proposed Use Cases

This section outlines the Use Cases proposed for this project which aim to fill the research gap outlined in section 3.1.1.

3.2.1 Use Case A : Intersection handling when an exit lane faces an planned blockage (e.g. Roadworks)

Summary

The TMS provides lane advice to CVs exiting the intersection to avoid the obstructed lane and instead use the temporarily available lane. While also providing lane advice to vehicles approaching the intersection along the obstructed arm to avoid the temporarily closed lane and use the other lanes for turning right and going straight.

Background

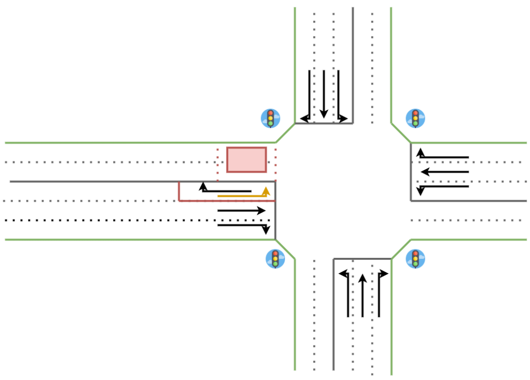


Figure 3.3: Use Case A

The exit of one arm of a four way intersection has a planned blockage(roadworks), see Figure 3.3. To aid traffic intending to use the closed lane, one of the approach lanes on the affected arm has been closed, to allow vehicles use it.
AVs encountering this situation that do not detect the temporary road signs will not know how to handle the situation and will need to perform a ToC to overcome this obstacle.
An RSI is present that can detect temporary rule alterations and is capable of sending the lane advice to oncoming CVs thus decreasing the number of ToCs likely to occur.

Objective

Prevent ToCs and MRMs in CVs by providing them with increased perception along with safe and efficient lane advice.

Actors and relations

- **RSI:** Detects roadworks blocking the exit lane and resulting blockage of the right turning (adjacent) approach lane. It sends the TMS to CVs whose target lane is blocked, provides information such as speed, headway and lane advice.
- **CV:** Receive information from the RSI(s) about target lane being blocked, follow lane and speed advice from the RSI. Can perform lane changing through cooperative lane changing using V2V communication.
- **NCAV:** As these vehicles cannot receive messages from the RSI, they may still need to perform a ToC/MRM when detecting their obstructed target lane.
- **HDV:** Normal driving and merging options.

The effects of late perception by HDV and NCAV can be mitigated by cooperative lane changing in the queue of traffic, as seen in TransAID Use Case 1.3 [5].

Scenario(s)

One exit of a 4 way, three lane approach intersection is blocked due to roadworks, with the adjacent lane on the approach, closed to allow traffic looking to exit the intersection use it (see Figure 3.3). The temporary road signs will allow vehicles looking to use the closed lane use the middle lane to perform a left turn. CVs approaching the intersection with the intention to turn right using the closed adjacent lane will be informed by the RSI that their lane is blocked and will be instructed to change into the middle lane and perform the turning manoeuvre from there. CVs looking to exit the junction through the obstructed lane will be instructed to use the now closed right lane.

Expected benefits

There will be two main benefits from this TMS:

1. Reduction in ToC/MRMs
2. CVs approaching the intersection will perform lane changing over the communication range of the RSI rather than within the vehicles perception range. This will spread out the lane changing and therefore minimise vehicle interactions and increase flow.

Functional constraints / dependencies

- RSI capable of detecting lane blockages.
- RSI capable of sending information about the TMS.

- CVs capable of receiving and executing the TMS from the RSI.
- NACVs will follow lane advice and speed given by the TMS.
- CVs can communicate through V2V communication

3.2.2 Use Case B : Intersection handling when an exit lane is blocked by an Unplanned Incident

Summary

The TMS provides lane advice to CVs looking to exit the intersection through the blocked exit that they may overtake the collision. While also informing CVs approaching on the arm with the blockage to vacate the adjacent lane and instead use the middle lane to facilitate overtaking vehicles.

Background

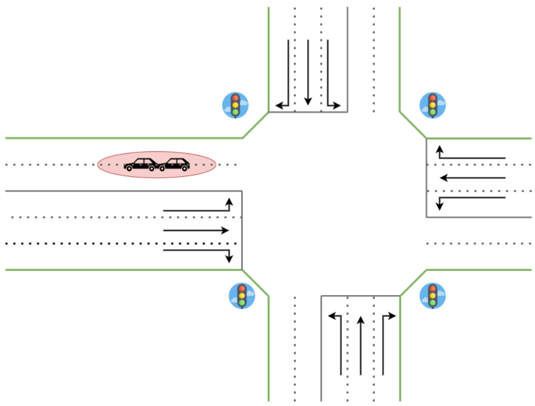


Figure 3.4: Use Case B

One of the exit lanes in an intersection has an unplanned blockage, see Figure 3.4. The only way to bypass the blockage is to perform an overtake manoeuvre that under normal circumstances would be illegal.

Automated vehicles looking to exit the intersection through the effected lane would need to perform a ToC on approach to this obstacle. As they would not be capable of performing an illegal overtake and therefore would be unable to overcome the blockage.

Objective

Prevent ToCs & MRMs while also increasing the efficiency of the intersection. It aims to achieve this by providing CVs with lane advice.

Actors and relations

- **RSI:** Detects the incident blocking the exit lane and sends the TMS to CVs that require it.
- **CVs:** Receives information from RSI and follows the instructions. Can perform lane changing through cooperative lane changing using V2V communication.
- **NCAVs:** As they cannot receive messages from the RSI, they may still need to perform a ToC/MRM if they find their target lane is blocked (by the incident). They will also occupy the adjacent lane to the blockage as they will not receive the messages telling them to do the contrary.
- **HDV:** Normal driving and merging options, they too will occupy the adjacent lane to the blockage for the same reason as AVs.

Scenario(s)

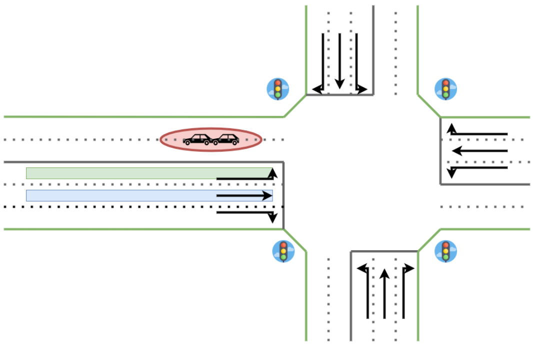


Figure 3.5: Use Case B

CVs are approaching 4-way three approach intersection, see Figure 3.5. One of the exit lanes becomes blocked due to a collision. The RSI detects the collision and informs all CVs approaching and aiming to use the adjacent(green) lane to turn left, to stay clear of that lane and instead perform the turning manoeuvre from the middle (blue) lane. CVs looking to exit the intersection through the blocked exit are informed they may use the adjacent(green) lane to overtake the collision if it is safe to do so.

Expected benefits

There will be two main results from this TMS:

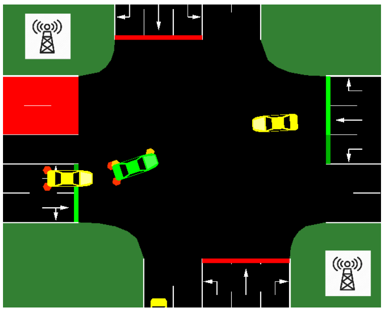
1. CVs approaching the adjacent lane will perform lane changing over the communication range of the RSI rather than within vehicles perception range. This in turn will minimise vehicle interactions, and keep the adjacent lane clear.
2. ToC and MRMs will be reduced because CVs looking to exit the intersection through the obstructed lane, will be informed they may overtake using the adjacent lane if it is unoccupied.

Functional constraints / dependencies

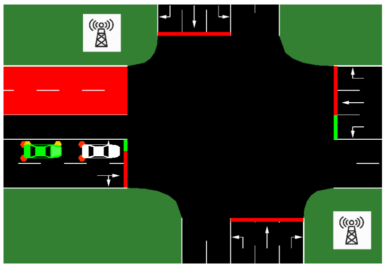
- RSI capable of detecting lane incidents.
- RSI capable of sending the TMS.
- CVs capable of receiving and executing the TMS from the RSI.
- CVs will follow lane advice and speed given by the TMS.
- CVs can communicate through V2V communication

3.2.3 Issue with Design

Early on in the development of Use Case A and B, it was observed that in both scenarios the middle lane of the left arm of the intersection, was becoming congested. The issue was occurring because vehicles wishing to turn left and vehicles wishing to continue straight were sharing the one lane. This meant that if a vehicle that intended to use the top exit was waiting for a gap in the traffic all vehicles intending to go straight needed to wait behind it, this is illustrated in Figure 3.6a. Likewise, if a vehicle wishing to go straight was at the lights but only the filter arrow was green, all left turning vehicles are prevented from passing, see Figure 3.6b. This meant an additional layer needed to be added to the TMS. That CVs in the "middle" lane wishing to go straight could use the rightmost lane if it was clear, likewise HDVs that experienced a delay could do the same.



(a) Access to right arm of the intersection impeded by left turning vehicle



(b) Access to top arm of the intersection impeded by vehicle wishing to continue straight

Figure 3.6: Implementation issues

3.2.4 Vehicle Behaviour

This section outlines vehicles behaviour when approaching Use Case A and B. As outlined in TransAID project, when no TMS is in place it is assumed that 25% of AVs will be able to detect and handle the situation themselves. With the implementation of the TMS, it is expected that 75% of all CVs will be able to handle the situation themselves. This adds to the realism of the simulations as the RSI may not have the capacity to communicate with all the necessary vehicles and vehicles that do receive the TMS may not be capable of following its advice.

The flow charts for Use Case A and B can be seen in Appendix A and B respectively.

3.3 Summary

As mentioned in section 2.4, it is not possible for researchers to identify all future TAs, while the TransAID project has identified numerous TAs there is still a research gap. The two Use Cases proposed in this chapter aim to narrow that gap. With the proposed TMSs aiming to ensure that CVs in the future are able to smoothly traverse a four arm intersection with a blocked exit lane.

4 Methodology

This section covers the methodology behind the simulations that were used to examine the proposed Use Cases. The simulator used is discussed as will the vehicle models used to represent traffic. The traffic composition is explained and the vehicle parameters are outlined. This section concludes by documenting the intersection's physical properties.

4.1 Simulator

There are 4 different groups of simulators that are available to use for traffic simulation[24], they are:

1. **Macroscopic** – Considers the road networks overall metrics, considering traffic density and distribution.
2. **Microscopic** – Focuses on the individual vehicle, it allows different models for different vehicles and allows these vehicles to be individually assessed.
3. **Mesoscopic**: Is a mixture between microscopic and macroscopic it groups vehicles together and allows these groups be considered.
4. **Sub microscopic**: Every aspect of every vehicle can be simulated from accelerating to gear changing.

Previous studies investigating ToC in mixed traffic use microscopic simulation, as per most studies using Eclipse's SUMO simulator [7], [20], [19]. Microscopic is very useful for analysing ToCs in mixed traffic as it allows for vehicles of various SAE levels of automation to be modelled differently. This is an important aspect of managing ToCs as there needs to be a difference in the vehicle's behaviour before, during and after a ToC. Numerous studies have found that driving performance is reduced after a ToC due to reduced situational awareness [12], [25], this in turn causes the vehicle to have:

- Decreased reaction time
- Increased headway fluctuations
- Increased braking intensity
- Decreased lane keeping

A key motive for the use of SUMO[1] in scientific papers is that SUMO is open source, which means that it can be repeated and critiqued by other researchers [19]. Using SUMO for the simulations

[1] `https://www.eclipse.org/sumo/`

also allows the use of the applications like Traffic Control Interface (TraCI) this allows for retrieving and altering vehicle parameters mid-simulation [26].

4.2 Modelling Vehicles

Vehicles of varying levels of automation and communication capabilities will have different driving performances when on the roads in the future. Therefore, when running simulations to examine the effect of a TMS on these vehicles it is necessary to model them differently. This also ensures that there is a clear differentiation in driving performance before and after a ToC. Assessing the proposed scenarios, it is clear different aspects of driving will need to be modelled the main three are [7]:

- Car following models
- Lane changing model
- ToC model

These models and their key attributes will be discussed in the preceding subsections

4.2.1 Car Following Models

As the proposed scenario is examining traffic flow with three classes of vehicle:

1. cooperative autonomous vehicles
2. non-cooperative autonomous vehicles
3. human driven vehicles

there is a need for three car following models. Building on the research done by Mintsis et. al [7], one car model will be defined for each of the classes mentioned above.

Advanced Driver Assistance System (ADAS)

AVs are being designed with the intention of making the roads safer and more efficient. To do this an *Advanced Driver Assistance System (ADAS)* has been developed which uses tools such as *Adaptive Cruise Control (ACC)*. ACC allows vehicles maintain their desired headway with the vehicle in front of them while also providing them with the capability to maintain their desired speed in the absence of a leading vehicle. This is done with the use of radar and lidar detectors and works to remove the inconsistencies of human driving error [7].

An extension to the ACC functionality is Cooperative Adaptive Cruise Control (CACC) system, which allows connected vehicles to benefit from V2X communication. Although there is limited research done on this technique so far, it has been shown to hold benefits for traffic safety and efficiency as it allows the vehicles to reduce headway because of increased reaction time as a result of V2V communication [27]. These improvements are reiterated again by Xiao et. al [28] with vehicles using CACC experiencing less critical situations and smoother acceleration and deceleration when travelling in a platoon of vehicles using ACC.

The car following model used to represent this class of vehicles has been adapted from both Mintsis et. al [7] and Lucken et. al [19]. It uses 4 controllers to ensure that the vehicles can perform to their full potential while also performing collision avoidance. The 4 controllers are:

- **Speed Control Mode** - This is identical for vehicles using CACC and ACC and ensures they maintain their desired speed when there is no lead vehicle.
- **Gap Control Mode** - Ensures desired time headway is maintained when in the presence of a lead vehicle.
- **Gap-closing Control Mode** - Used to transfer vehicle speed control between the previous two controls, i.e. when a lead vehicle is present but is still beyond the given threshold of the Gap Control mode.
- **Collision Avoidance Mode** - This is introduced when the lead vehicle is too close to the follower vehicle and harder deceleration is required.

Manual Driving Model

Models are required for HDV as they differ from automated vehicles in that their:

- speed and headway can fluctuate
- reaction times can vary and are generally longer
- breaking intensity is harsher

The model being deployed for the experiments will be taken from Lücken et al. [19]. It uses the built-in car following model in SUMO, which is based on the Krauss model. The Krauss model uses a series of equations to represent the stochastic nature of human driving. With several equations used to represent how HDVs desired headway and speed will fluctuate in accordance to drivers attention. The lower the drivers attention, the more severe the deviations in headway and speed.

4.2.2 Lane Changing

Reviewing the scenarios in Section 3.2, it is clear that an essential aspect is for vehicles to be able to change lanes. SUMO has its own built in lane changing model, LC2013 model [29]. The model was developed to imitate the lane changing actions of HDVs. While the model is advanced in that it considers right of way, surrounding vehicle's speeds and positions it is meant to model HDV and not AVs which will deviate due to their enhanced driving capabilities and safety factors [7].

However, the LC2013 model in SUMO has several parameters and therefore through parameterisation it is possible to create a model that will imitate AVs. While this parameterisation has been carried out by TransAID [7], it is important to look at the different types of lane changes that can take place, what parameters are used and how altering them allows the model to represent AVs.

Firstly, it is important to consider why vehicles change lane, the LC2013 model observe three key reasons, Strategic, Cooperative and Tactical. Figure 4.1 below has been taken from TransAID [7] to indicate the 3 types of lane changing that can be used and the motivation behind them.

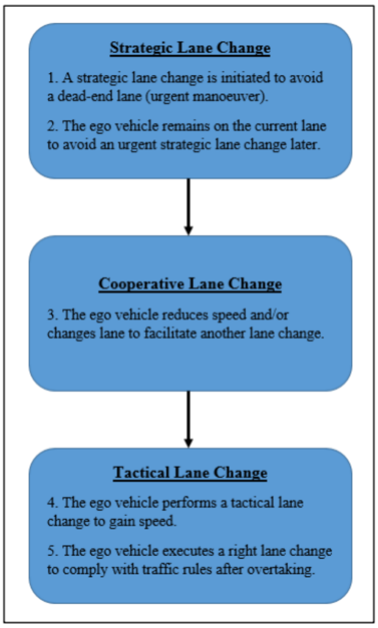


Figure 4.1: Types of lane changing

Strategic Lane Changing

Strategic Lane Changing is done when a vehicle is approaching an end to its lane. This end can be because of a collision, roadworks or it can simply be because it is not the vehicles target lane. For example, in Figure 4.2 below, we see that the vehicle wishes to carry on straight through the intersection (green path), but is currently in the lane for going exiting through the top exit. Therefore the vehicle must move to the left into the middle lane.

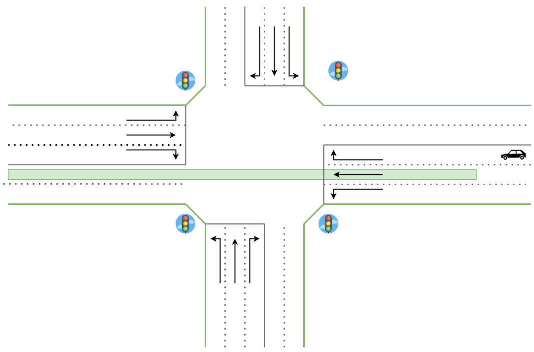
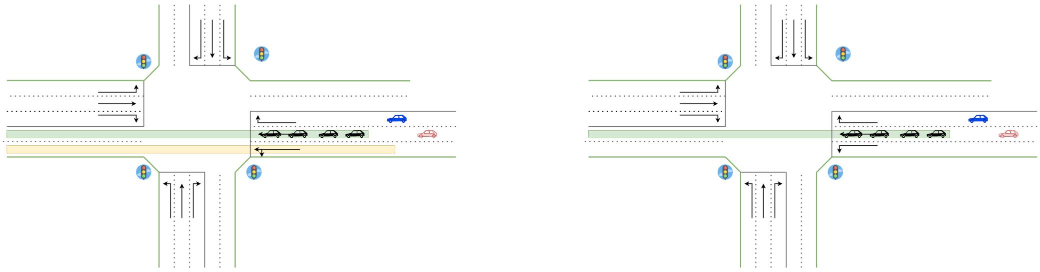


Figure 4.2: Strategic lane changing

Cooperative Lane Changing

Cooperative lane changing is done by vehicles that occupy the target lane of a vehicle that is attempting to perform a Strategic Lane Change. Thus if a vehicle is approaching the end of a lane and cannot find space to merge into the target lane, vehicles in the target lane can change lane if it does not hinder their own strategic progress. An example of this can be seen in Figure 4.3a below, where the foe[2] vehicle (red vehicle) is able to perform a lane changing manoeuvre to facilitate the ego vehicle(blue vehicle) entrance to the ”middle”(green) lane because the intersection allows vehicles in both the ”left”(yellow) and ”middle” lanes to exit straight through the intersection.



(a) Cooperative lane changing when the foe vehicle(red vehicle) can change lane

(b) Cooperative lane changing when the foe vehicle(red vehicle) cannot change lane

Figure 4.3: Cooperative Lane Changing

If the vehicle in the target lane cannot change lane, due their own strategic constraints, they can slow down. In doing so they create a space for the other vehicle to perform a strategic lane change. An example of this can be seen in Figure 4.3b, where the foe vehicles only route through the intersection is in the ”middle” (green) lane, therefore the foe vehicle slows down and allows the ego vehicle(blue vehicle) enter the middle lane, rather than occupy the space itself.

Tactical Lane Changing

Tactical lane changing is done by vehicles to overtake a slow leader. Consider the example shown in Figure 4.4. The green vehicle is behind a (red) heavy goods vehicle and wishes to overtake it so that it can continue going at its desired speed. This is a tactical lane change as the vehicle is in its target lane but wishes to be going faster.

Figure 4.4: Tactical lane changing

Parameterisation

To ensure that different vehicle types lane changing characteristics were represented correctly TransAID carried out a sensitive analysis on four of the parameters in the LC2013 model. These param-

[2]The foe vehicle in this instance is the vehicle preventing another vehicle from changing lane

eters can be seen in Table 4.1. [7]

Parameter	Definition
lcStrategic	Willingness to perform a strategic lane change.
lcKeepRight	Willingness for a vehicle to follow the "keep right" rule of the road, in which all vehicles should remain in the right-most lane where possible.
lcSpeedGain	Willingness to perform a tactical lane change.
lcAssertive	Readiness to lane change into a position with lower frontal and rear headway.

Table 4.1: For lcStrategic, lcKeepRight and lcSpeedGain high value equals earlier changes

However, this analysis failed to find a strong change in lane changing behaviour as a result of changing lcStrategic, lcKeepRight or lcSpeedGain. So, it was decided that while these three parameters are important, they did not require parameterisation and therefore they were given their default values for all automation types.

On other hand lcAssertive was found to have large impact on the lane changing behaviour of the vehicles. However, this parameter presented some complexities, as it did not acknowledge the vehicle's relative speed. Meaning that if a following vehicle was going faster (positive relative speed) than the vehicle itself, then the gap would be too small, while if the following vehicle was slower the gap would be large. This made the parameterisation quite difficult and instead for the first iteration of the TransAID project lcAssertive values that replicated the behaviour put forward by the *original equipment manufacturers (OEMs)* was used. After running the first iteration of the TransAID project and analysing the behaviour of the vehicles it was decided to proceed with the values shown in Table 4.2

Automation level	lcAssertive
L0 (HDV)	1.1-1.3
L2 (Partially Autonomous	1.1-1.25
L4 (Fully Autonomous)	0.8-0.9

Table 4.2: lcAssertive values for each automation level. Values were obtained from Mintsis et al. [7]

4.2.3 ToC model

The last aspect of vehicles that require modelling is the ToC process. The duration of a ToC is primarily based on the driver's awareness. A ToC in a vehicle with an SAE level less than 3 is seen as a minor traffic concern as the driver is meant to be giving the road their full attention. However, for vehicles with an SAE level greater than 2, where the driver's attention is not fully on the road the ToC time is extended. There is considerable evidence to suggest that after a ToC the driver's awareness can still be diminished [12]. The model used by TransAID to show driver performance after a ToC is the same as the model noted in Section 4.2.1.

Autonomous vehicles in SUMO that have the ability to perform a ToC can either be prompted by TraCI or can trigger one themselves if given the *dynamicToCThreshold* parameter. This parameter is time bound. If a vehicle needs to perform a strategic lane change (Section 4.2.2) but their path is blocked and they cannot continue driving for the time specified by the *dynamicToCThreshold* parameter a ToC is triggered [2]. An example of this can be seen in Figure 4.5, the blue vehicle's route requires it enter the middle lane, however as the middle lane is occupied and it cannot continue in its ego lane it will perform a ToC.

The value used to represent this parameter is taken from the TransAID project [7] as per Table 4.3. The value is given in the form of a normal distribution, where mean and standard deviation are given first in the brackets, while the min and max value is given in the square brackets. The distribution ensures all individual vehicles have unique values.

Parameter	Value
dynamicToCThreshold	normal(9.0, 0.5); [8.0, 10.0]

Table 4.3: Dynamic ToC Threshold value [7]

When a dynamic ToC occurs there is a probability that the ToC will need an MRM, the probability used is 5% (SUMO's default value [2]) which means every 5 out of every 100 ToCs will result in an MRM. The MRM will cease after the vehicles reaction time has surpassed.

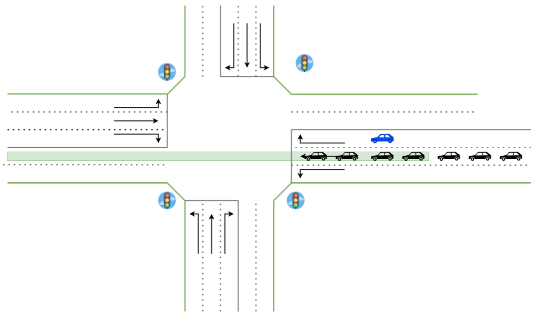


Figure 4.5: Example of where dynamicToCThreshold would cause a ToC

4.2.4 Traffic Flow

The next step is to establish the *Level of Service (LOS)* that will be applied along with the penetration rates of the various vehicle types.

Traffic Levels

The LOS of a road network indicates what percentage of the road's max capacity is present. LOS is normally denoted as A, B, C... and can be seen in Figure 4.6 [30]. To obtain the max capacity of the intersection, 6000 HDV were simulated passing through the unimpeded (i.e. no roadworks and no collision) intersection and the number of vehicles to pass in an hour was obtained, this was repeated three times and an average taken. The result was 3,582 vehicles. Using this 4 LOS were calculated and can be seen in Table 4.4. The use of only LOS A, B, C and D follows the TransAID project where it was found that using higher numbers of vehicles causes large changes in traffic behaviour and KPI performance that could not be attributed to any one reason [16]. Other papers such as Alms et al. [20] and Maerivoet et. al [31] use only LOS B, C and D as it was found LOS A is free flowing regardless of the use of a TMS. However, A, B, C and D will be used for the proposed scenarios.

Level of Service	Description	Volume-to-Capacity Ratio
A	Highest driver comfort; free flowing	<.60
B	High degree of driver comfort; little delay	0.60 – 0.70
C	Acceptable level of driver comfort; some delay	0.70 – 0.80
D	Some driver frustration; moderate delay	0.80 – 0.90
E	High level of driver frustration; high levels of delay	0.90-1.00
F	Highest level of driver frustration; excessive delays	>1.00

Figure 4.6: LOS that will be used to simulate the Use Cases

Capacity	LOS A	LOS B	LOS C	LOS D
3,582 (veh/h/l)	1,432	2,149	2507	2,865
Capacity ratio	40%	60%	70%	80%

Table 4.4

Penetration rates

Vehicles reactions to the TMS will vary depending on their distinct communication capability. The vehicles will also adjust their driving depending on their automation level. Therefore it is necessary to establish the penetration rates of the various vehicles. The penetration rates in Table 4.5 have been adopted from the TransAID Project [7] as it is the most developed project in this area.

4.2.5 Vehicle Parameters

The final parameters for the vehicles are shown in Appendix C. The parameters have been adopted from Mintsis et. al[7] and are mimicked closely in similar studies [19]. The values comprise of both

Vehicle Mix	HDV	SAE Level 1/2	SAE Level 1/2 (Coop.)	SAE Level 3/4	SAE Level 3/4 (Coop.)
All HDV	100%	-	-	-	-
All L4-CAV	-	-	-	-	100%
Penetration 1	60%	15%	15%	5%	5%
Penetration 2	40%	20%	20%	10%	10%
Penetration 3	10%	30%	30%	15%	15%

Table 4.5: Vehicle Penetration Rates

discrete values and normal distributions. In the case of values with a normal distribution the mean is presented along with the standard deviation in the brackets while the max and min possible values for that parameter are in the square brackets.

Creating Vehicles in SUMO

To create the vehicle models for the simulation SUMO uses a Python script, named createVehTypeDistribution.py. This script reads in a text file (like the one shown in Figure 4.7) and a quantity. Which are used to produce the specified number of vehicles with the given parameters. This method allows all the vehicles in a particular class to take on the parameters specified. This adds to the realism of the simulations as all the vehicles of a particular type will have similar parameters but not the exact same.

```
carFollowModel  ;   CACC
color           ;   blue
vClass          ;   custom1

tau             ;   0.6
decel           ;   normal(3.0, 1.0);   [2.0, 4.0]
accel           ;   normal(1.5, 1.0);   [0.75, 2.0]
emergencyDecel  ;   9.0

actionStepLength    ;   0.1
lcAssertive         ;   normal(0.85, 0.02); [0.8, 0.9]


#TOC
param;  has.toc.device                      ;   true
param;  device.toc.automatedType            ;   L4-CV-
param;  device.toc.manualType               ;   L0-HDV-
param;  device.toc.reponseTime              ;   normal(4, 2.0);  [2, 15];
param;  device.toc.initialAwareness         ;   normal(0.6, 0.2); [0.3, 1.0];
param;  device.toc.recoveryRate             ;   normal(0.3, 0.1);  [0.1, 0.5];
param;  device.toc.tauCACCtoACC             ;   normal(1.5, 0.2);   [1.1, 2.0];
param;  device.toc.ogNewTimeHeadway         ;   1.6
param;  device.toc.ogChangeRate             ;   0.8
param;  device.toc.mrmDecel                 ;   3.0
param;  device.toc.useColorScheme           ;   true
param;  device.toc.dynamicToCThreshold      ;   normal(9.0, 0.5); [8.0, 10.0]



param; has.ssm.device                   ;   true
param; device.ssm.measures              ;   TTC DRAC PET
param; device.ssm.thresholds            ;   0.75 6.0 2.0
param; device.ssm.range                 ;   30.0
param; device.ssm.extratime             ;   5.0
param; device.ssm.file                  ;   Output-Files\SSM-L4-CV.xml
param; device.ssm.trajectories          ;   false
param; device.ssm.geo                   ;   false
```

Figure 4.7: Specifies the parameters for a given vehicle class (L4-CV)

Vehicle Journeys

To make the simulations more realistic it was important to ensure that the vehicles ran through the network randomly. There is a couple of different ways to do this in SUMO. One way is Duarouter, but it has limitations in that it needs to know the quantity of vehicles and their individual routes (a route being "bottom approach lane to top exit"). However, this diminishes the randomness of the vehicle's journeys.

Alternatively there is a SUMO python script called randomTrips.py which takes a vehicle type and a quantity and produces random trips through the intersection. However, these are pseudo random journeys, so that while they are random each time, it produced the same journeys for all the vehicle types. To correct this, the *seed* attribute was used, seed specifies a certain version of the pseudo random journey. So every time the simulation was run the seed was picked at random to produce stochastic journeys.

However, the random journeys could begin anywhere in the network, i.e., there was no guarantee that the majority of the journeys would pass through the intersection. To reduce the risk of this happening the *fringe-factor* option was enabled setting the likelihood that the journeys being produced ran from one edge of the network to another. The *fringe-factor* was set to 20, meaning it was 20 times more likely a journey produced would be from one network edge to another.

Now there was random journeys that ran through the intersection, the next challenge was modelling different vehicle types. There was a need to specify that any vehicle approaching from on the left and turning left (to the top exit) takes the vehicle class(vClass) "custom2" in order to allow the TMS function as expected. The outputted random journeys were parsed so all vehicles following that route had their vClass altered to "custom2".

4.3 Intersection

This section reviews the road networks on which the simulations will be run. The intersections for both Use Case A and B are similar but do differ and therefore will be examined separately. This section also outlines the traffic light system controlling the intersection and the road signs present. Finally it gives an overview of the network configuration.

4.3.1 Use Case A

To represent the roadworks in SUMO a re-router is used. Re-routers are used to close the two left exit lanes in the intersection.

To create a system that allows for the passage of cars on the opposite side of the road, a new lane was made that was restricted to vehicles of vClass *passenger*. This meant that any vehicles of *passenger* class knew how to handle the situation without the TMS and could pass through the networks. While the remainder of the AVs will have to perform a ToC and then detect the information about the path they can take.

A similar method is used for the approach lane. The "middle" lane is only accessible to vehicles that have the vClass *passenger* or *custom1*. All vehicles that are turning left will have a vClass *custom2*, these vehicles will be unable to use the middle lane to bypass the closed left lane. These vehicles that do not receive the TMS will reach the end of the closed left lane and then have to perform a ToC to enter the middle lane.

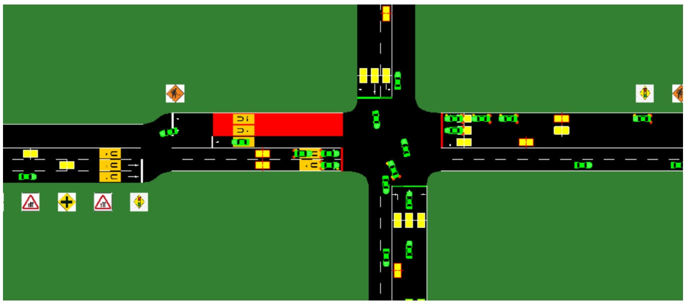


Figure 4.8: A screenshot of Use Case A in SUMO

The network in SUMO is shown in Figure 4.8, while the intended network is in Figure 4.9. The left-turning lane has been closed and is being used for traffic looking to exit the intersection on the left arm. The reason SUMO cannot display the network as intended is because the left-turning lane and the new exit lane would both meet, and SUMO does not allow two lanes going opposite directions to meet in that manner.

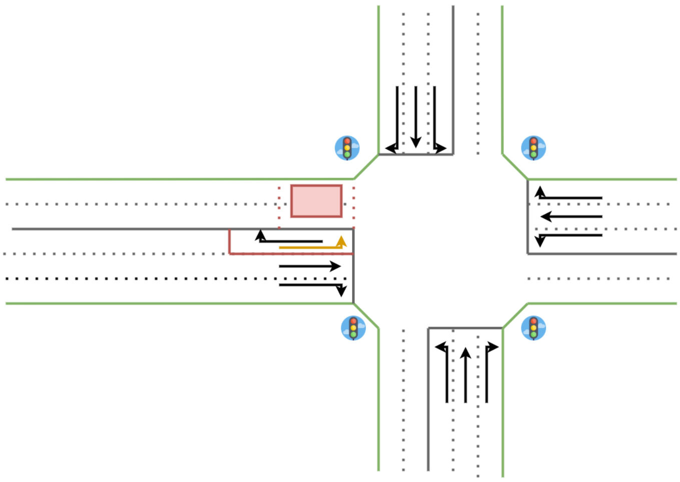


Figure 4.9: How the system Roadworks intersection would work in reality

Figure 4.10 below clarifies that the network (despite its appearance) is working as planned. It shows the connections between the lanes, these connections indicate the routes that the vehicles can take. This diagram shows that vehicles in the left most lane cannot proceed beyond the bend in the road without first changing into the middle lane.

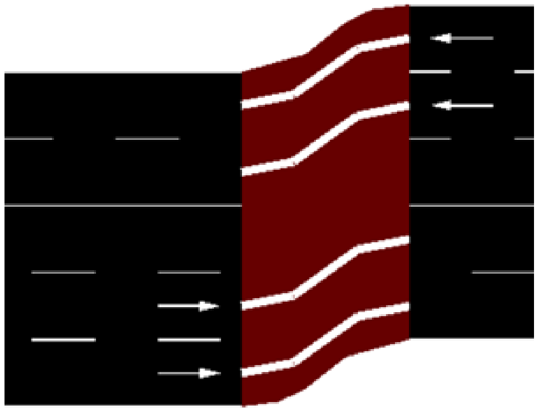


Figure 4.10: Lane connections in the roadworks

4.3.2 Use Case B

To represent the collision (unplanned closure) in SUMO, two 4m long vehicles are stopped in both the exit lanes of the left arm of the intersection, see Figure 4.11. Aside from that the network is conventional.

A limitation with SUMO however, is that vehicles will not perform opposite direction driving (overtaking) if they are on a two-lane edge, SUMO has implemented the assumption that if a vehicle is on a two-lane road, it would not need to overtake. This means that standard vehicles will not overtake the collision.

Only emergency class vehicles in SUMO can perform opposite direction driving when on a two-lane edge. When vehicles need to overtake they are converted to the vClass of *emergency* (all other attributes remain constant) and once the overtaking is complete, they revert back to their original class. Vehicles of the vClass *emergency* do drive more recklessly than other vehicle classes so the vehicle class is only changed for the overtaking manoeuvre.

4.3.3 Traffic Lights

The traffic lights for the intersection in the considered scenarios run on an 80 second loop, as intersection's signalised cycles traditionally last between 60-90 seconds [32]. These loops are separated by a 10 second all red time to allow pedestrians cross. The signal system allows all the approaches receive an equal amount of time to pass through the intersection. To replicate a real signalised intersection [32]. The amber light period is set to 4 seconds as it is default in the UK for amber lights to last between 4 and 6 seconds [33].

To ensure that the scenario's traffic lights represent a real intersection, the wait times can be altered if there is increased traffic at one of the approaches. This is common practise in Ireland [34]

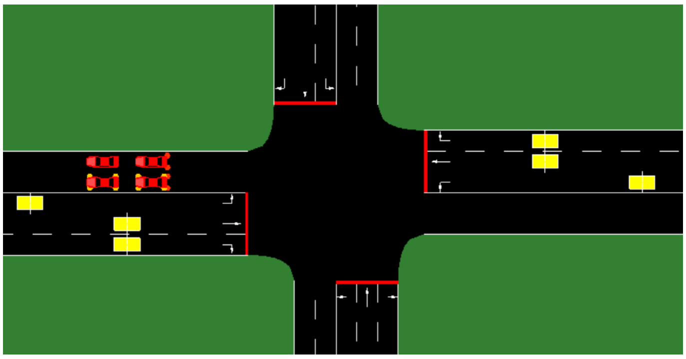


Figure 4.11: Collision intersection used in the simulation as seen in SUMO

and when this is done the intersection is referred to as "actuated" [35]. The system runs so that if there is a time gap of less than 2 seconds between one vehicle and the next, the maximum duration for that signal will be implemented.

Figure 4.12 illustrates the cycle length for the various lanes. Right turning lanes have a green diamond, indicating a filter arrow. What this means is that right turning vehicles are given 27 seconds in which they can proceed if the way is clear, otherwise they should pull out into the centre of the junction. Then they are given a 10 second filter arrow in which to proceed.

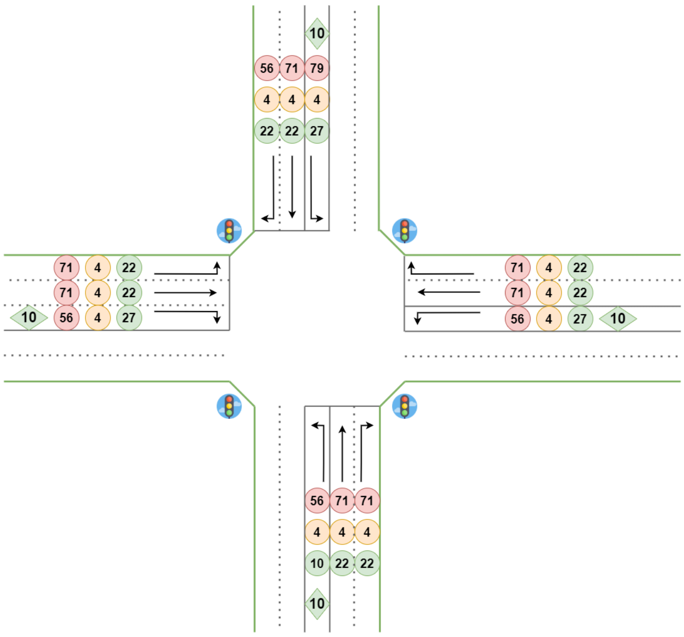


Figure 4.12: Illustrates the Traffic Light sequence used in the simulations

4.3.4 Road signs

The traffic signs in the network, serve two purposes.

1. They are used to add realism to the scenario.
2. Their positions are used to model when HDV and some automated vehicles will begin to detect situation ahead.

The road signs are placed with regard Irish Governments Department of Transport, Tourism and Sport [34]. The road sign images used for the project were sourced externally from the following sources:

- Traffic Lights Sign [36]
- Intersection Sign [37]
- Roadworks Sign [38]
- Left lane closed ahead Sign [39]
- RSI [40]

4.3.5 Intersection Overview

This section provides a detailed outline of the road networks used in Use Case A and B on a technical level.

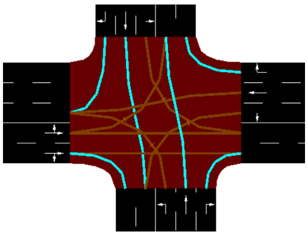
Use Case A Configuration

Table 4.6 shows the physical properties of Use Case A's intersection.

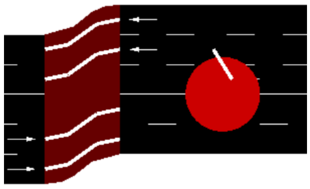
Use Case A	Settings	Notes
Road section length	Right arm: 500m Left arm: 500m Top arm: 500m Bottom arm: 500m	-
Road priority	Approach: 78 Exit: 46	-
Allowed road speed	Approach: 16.6667 m/s (60km/hr) Exit: 11.111 m/s (40km/hr)	-
Number of nodes	8	center left-node top-node right-node bottom-node blockage-end adjacent-end preparation
Number of edges	12	left-long-approaching preparation left-short-approaching closed-lane re-merging-lane left-exit top-approaching top-exit right-approaching right-exit bottom-approaching bottom-exit
Number of lanes	Approach adjacent to Roadworks: 2 Exit with Roadworks: 1 Other approach lanes: 3 Other exit lanes: 2	-
Work zone location	Center to blockage-end (closed lane)	50m
Disallowed vehicle classes	**closed-lane (L-2)**: custom1 **preparation (L-0 and 1)**: custom2 **left-short-approaching (L-1)**: custom2 **left-short-approaching (L-0)**: custom1 and custom2	Unless stated otherwise all vehicle classes allowed
Filenames	RoadworksIntersection.net.xml	-

Table 4.6: Use Case A network configuration

Connections
Figure 4.13, outline the lanes connections that exist inside the network.



(a) Lane connections at the intersection



(b) Lane Connections for vehicles moving around the closed lanes

Figure 4.13: Lane connections for the Use Case A

Intended Control of lane Usage

All vehicle approaching on the left arm of the intersection wishing to turn left (towards the top exit) are given a vClass of *custom2*. This ensures they occupy the left most lane and when they detect the situation or receive the TMS their vClass is changed to *custom1* so they can proceed in the middle lane and turn left.

AVs wishing to exit the intersection through the left exit have a vClass *custom1* while only *passenger* can exit through the affected lane. All HDV(SAE-L0) have vClass *passenger*. This means that when AVs approach they must either detect the situation/receive the TMS and convert their vClass to *passenger* or perform a ToC and become a L0-HDV.

AVs approaching on the left arm of the intersection and intending to continue straight are given a vClass *custom1*. If their path is impeded in continuing straight at the intersection, they have received the TMS, and there is space in the right turning lane they may change their vClass to *passenger* in order to change lane.

All vehicles approaching from the left and intending to turn right are given a vehicle class *passenger*.

Network Layout
Figure 4.14 illustrates the network and position of the lanes.
Road Segments

- Top arm of intersection
  - top-node to center is the *Top-Approaching* edge
  - center to top-node is the *Top-Exit* edge
- Right arm of intersection
  - right-node to center is the *Right-Approaching* edge

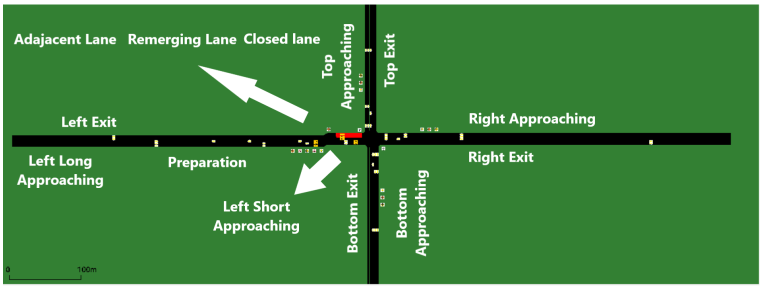


Figure 4.14: Roadworks network with names of the corresponding edges

  - center to right-node is the *Right-Exit* edge

- Bottom arm of intersection
  - bottom-node to center is the *Bottom-Approaching* edge
  - center to bottom-node is the *Bottom-Exit* edge
- Left arm of intersection
  - left-node to preparation is the *Left-Long-Approaching* edge
  - preparation to adjacent-end is the *Preparation* edge
  - adjacent-end to center is the *Left-Short-Approaching* edge
  - center to adjacent-end is the *Closed-Lane* edge
  - blockage-end to blockage-end is the *Re merging-Lane* edge
  - adjacent-end to left-node is the *Left-Exit*

Use Case B Configuration

Table 4.7 shows the physical properties of the Collision intersection.

Use Case B	Settings	Notes
Road section length	Right arm: 500m Left arm: 500m Top arm: 500m Bottom arm: 500m	-
Road priority	Approach: 78 Exit: 46	-
Allowed road speed	Approach: 16.6667 m/s (60km/hr) Exit: 11.111 m/s (40km/hr)	-
Number of nodes	6	center left-node top-node right-node bottom-node split-left
Number of edges	10	left-long-approaching left-short-approaching left-exit-blockage left-exit top-approaching top-exit right-approaching right-exit bottom-approaching bottom-exit
Number of lanes	All exits have 2 lanes All approaches have 3 lanes	-
Location	Left arm: 20m from center (in both lanes)	Length affected: 12m
Disallowed vehicle classes	**left-short-approaching (L-0)**: custom1 and custom2 **left-short-approaching (L-1)**: custom2 **left-short-approaching (L-2)**: custom1	Unless stated otherwise all vehicles allowed
Filenames (m/s^2)	CollisionIntersection.net.xml	-

Table 4.7: Use Case B network configuration

Connections
Figure 4.15, outline the lanes connections that exist inside the network.

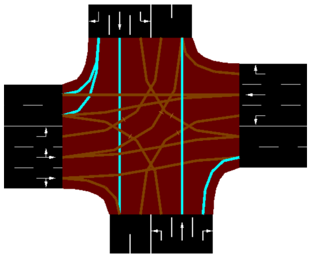


Figure 4.15: Lane connections for Use Case B

Intended Control of lane Usage
All vehicle approaching on the left arm of the intersection wishing to turn left (towards the top exit) are given a vClass of *custom2*. This ensures they occupy the left most lane. If an approaching cooperative vehicle receives the TMS it will be given a vClass of *custom1*, meaning it cannot proceed in the left-most lane and must perform a strategic lane change to the middle lane and turn from there.

Vehicles wishing to exit the intersection through the left exit have a vClass *custom1* or *passenger* depending on whether they are an AV or a HDV. However, when they encounter the collided vehicles their vClass will be converted to *emergency* to allow the vehicle overtake the collision and will revert back to their original class once this is completed.

The control of vehicles on the left arm going straight is the same as for Use Case A, see section 4.3.5.

Network Layout
Figure 4.16 illustrates the network and position of the lanes.

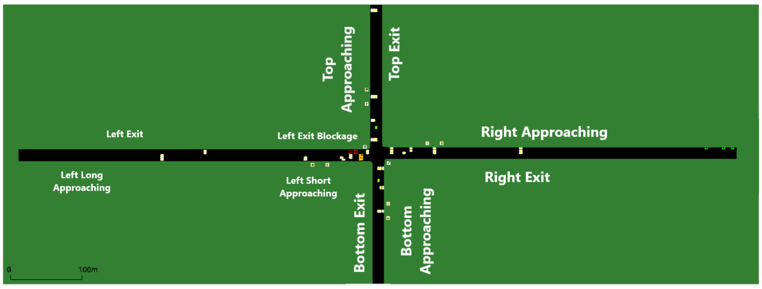


Figure 4.16: Collision network with names of the corresponding edges

Road Segments

- Top arm of intersection
  - top-node to center is the *Top-Approaching* edge

  - center to top-node is the *Top-Exit* edge

- Right arm of intersection
  - right-node to center is the *Right-Approaching* edge
  - center to right-node is the *Right-exit* edge

- Bottom arm of intersection
  - bottom-node to center is the *Bottom-Approaching* edge
  - center to bottom-node is the *Bottom-exit* edge

- Left arm of intersection
  - left-node to split-left is the *Left-Long-Approaching* edge
  - split-left to center is the *Left-Short-Approaching* edge
  - center to split-left is the *Left-Exit-Blockage* edge
  - split-left to left-node is the *Left-Exit* edge

4.3.6 Simulations

This section outlines the simulations that will be conducted in order to evaluate the proposed Use Cases.

Combating Congestion in Use Case B

When developing Use Case B, it was observed that while the TMS increased traffic efficiency, the intersection was still heavily congested. This congestion was happening even at LOS B and C. With so many vehicles present in the simulation, it made testing LOS D impossible due to the memory constraints on the CPU available. It also meant that vehicles wishing to use the blocked exit lane could be waiting 250m from the intersection for in excess of five minutes at a time before moving.

This shows how disruptive the unplanned closure of an exit lane can be, but does not represent how real vehicles would act in this situation. Vehicles waiting for excessive lengths of time would re-route and exit through a different lane. As a result it was decided two iterations of Use Case B would be simulated, once in which vehicles waited for their lane to clear and the other in which vehicles that were completely stationary for more than 140 seconds would consider re-rerouting. 40% of vehicles that considered re-routing would re-route.

Baselines

When developing a new system baselines need to be defined. The baselines are used to evaluate the experimental results. As Section 4.2.4 has 4 penetration rates with AVs, 4 baseline penetration rates are needed. The baselines run with the same vehicle quantities and penetrations but without the TMS. The reason the 100% HDV penetration rate won't be run with a baseline is that HDVs are unaffected by the TMS. The 100% HDV penetration rate is meant to display how the scenario would look on the roads today.

Number of iterations

Considering sections 4.2.4 and 4.2.4 there are four LOS, with 4 penetrations rates of AVs. Each with a baseline and finally a baseline with 100% HDVs. There are various elements of randomness in each run. Like:

- For each LOS the vehicle quantity could be +/-30 vehicles.
  - This feature was added to make the vehicle journeys more realistic
- The start times of each vehicles trip is randomly generated.
  - This is done using the randomTrips.py file discussed in section 4.2.5
- The TMS only affects 75% of vehicles.
  - This adds realism to the scenario as:
    - the TMS may not detect every approaching CV and therefore the CV may not receive the TMS
    - the CVs that receive the TMS may be unable to follow its guidance.

This means comparing the stats of any individual result against the baseline will not give a proper indication of how the system is actually performing. To ensure a degree of certainty each simulation will be run three times for each penetration rate at each LOS. Therefore for the entire project there will be 324 simulations:

$$Number\ of\ penetrations\ rates = HDV + Penetration\ rates + Baseline\ Penetration\ Rates$$

$$\begin{aligned} Number\ of\ Scenarios\ &= Use\ Case\ A\ + Use\ Case\ B \\ &+ Use\ Case\ B\ with\ Rerouting \end{aligned}$$

$$\begin{aligned} Total\ number\ of\ runs &= Number\ of\ Scenarios * Number\ of\ penetrations\ rates \\ &* Number\ of\ LOS * Number\ of\ Iterations \end{aligned}$$

$$Total\ number\ of\ runs = 3 * (1 + 4 + 4) * 4 * 3 = 324$$

5 Results and Discussion

This chapter will open by outlining the Key Performance Indicators (KPIs) that will be used to analyse and evaluate the proposed TMS for both Use Cases A and B. The results for Use Case A are reviewed, beginning with the safety metrics before moving to the efficiency metrics. In addition this section provides a discussion of what these results mean and some possible explanations. The process will then be repeated for Use Case B.

5.1 Key Performance Indicators (KPI)s

The KPIs for any traffic system are safety and efficiency.

5.1.1 Safety

The two safety metrics that will be used to measure the safety of the intersection are Time to Collision (TTC), and Post Encroachment Time (PET). These metrics are commonly used in the assessment of traffic safety and are used throughout other research in this area [5] [19].

Time to Collision (TTC) Incidents

TTC is the time to collision if two vehicles carry on their current path at their current speed [19], see Figure 5.1. The threshold time for what constitutes a safety incident varies for different automation levels. The thresholds being applied to the proposed Use Cases can be found in Table 5.2:

TTC time threshold for automation levels		
Automation Level	**TTC Threshold (s)**	**Notes**
HDV	1.5	A HDV with a TTC less than 1.5 seconds is marked as a conflict. The fewer conflicts the better
AV	0.75	AVs have a lower TTC threshold as they have faster reaction times

Table 5.1: TTC Thresholds for automation levels [6]

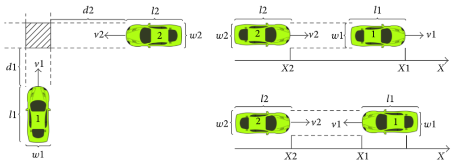


Figure 5.1: Incidents in which a TTC would occur [6]

Post Encroachment Time (PET) Incidents

PET is a safety metric for when vehicles are merging or crossing paths (e.g. an intersection) [41]. It is the difference between the lead vehicle exiting the conflict area and the following vehicle entering the conflict area. An example of a PET incident is shown in Figure 5.2. If the PET is below the threshold it is marked as safety incident. Various PET thresholds are recommended with Gettman et al.[42] proposing a 5 second value, however Qi et. al [8] pointed out that lower times will capture less incidents but the incidents that are flagged are "more dangerous". So Qi et. al recommended several thresholds depending on how serious an incident should be in order to be logged. As a result a value of 2 seconds will be used as it will capture "serious", "general" and "slight conflicts". The PET safety metric is constant for all vehicle types.

TTC time threshold for automation levels		
Automation Level	**PET Threshold (s)**	**Notes**
All Vehicles	2	A vehicle with a PET less than 2 seconds is marked as a conflict. The fewer conflicts the better

Table 5.2: Values were obtained from Qi et. al [8]

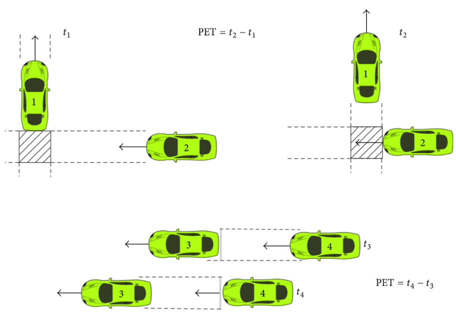


Figure 5.2: Incidents in which a PET would occur [6]

These metrics can be recorded in SUMO by adding a Surrogate Safety Measure (SSM) Device to vehicles and defining the metrics and thresholds required [41]. The metrics in this report will be the total number of incidents in each run of the simulation divided by the number of iterations of that simulation. Both the mean and standard deviation are reported.

5.1.2 Efficiency

For efficiency, a number of metrics will be used:

- Throughput (veh/hr)
- CO_2 Emissions (gr/Km)
- Mean Journey Duration (s)

Throughput (veh/hr)

Throughput of the intersection is how many vehicles per hour passed through the intersection. However, in the instance that one of the exits is blocked, it may not be true representation of the TMSs performance. As the three other exits could be completely unaffected and have a high throughput. While all the vehicles looking to exit through one of the affected exits may be stuck. Thus this metric alone will not reveal the success of the TMS. Throughput will be measured over the first hour of the intersection. This metric will be recorded like the safety incidents by gathering the throughput of all simulations and dividing by the number iterations.

CO_2 Emissions (mg)

The environmental impact of the intersection is represented by the average CO_2 emissions of every vehicle in the simulation. This is an interesting consideration as vehicles that pass through the network will no longer emit CO_2 but stationary (waiting) vehicles emit smaller amounts of CO_2 than moving vehicles. This metric will be recorded over the entire duration of the simulation. The total emissions of each iteration will be summed and averaged by the total number of vehicles to pass though the intersection across all iterations.

Mean Journey Duration (s)

Is the average length of time each vehicle spends traversing the network. This metric identifies if there are lengthy delays as a result of the blockage. The size of this metrics standard deviation will be large because initially vehicles will have a short journey time while vehicles later in the simulation may encounter congestion. This metric will be collected and reported like the CO_2 emissions.

Like the safety metrics the above efficiency metrics can be recorded by SUMO.

5.2 Use Case A

5.2.1 Safety

This section presents the safety results for Use Case A and examines the affect of the TMS on the intersection.

TTC

Figure 5.3 presents the average number of TTC incidents for each penetration rate at various LOS. The key finding here is the variance of incidents between 100% HDVs and 100% L4-CVs; this demonstrates that L4-CVs are significantly safer than HDVs. The TMS further decreases the TTC incidents across all LOS for all but one penetration rate (Penetration 1[1], LOS B).

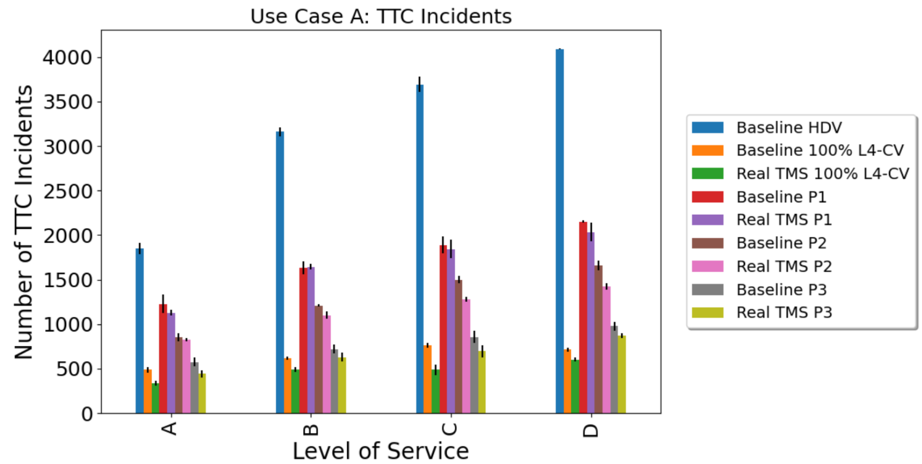


Figure 5.3: TTC incidents in Use Case A

For Penetration Rate 1 LOS B, it is observed that the number of incidents remains constant before and after the TMS. As Penetration 1 has the highest number of HDVs (excluding 100% HDV) and therefore the lowest number of CVs (vehicles that can receive the TMS), it is not surprising that this simulation is the one that experiences the least deviation from the baseline. Table 5.3 demonstrates that as the number of CVs rises the decrease in TTC incidents (because of the TMS) becomes more apparent.

For LOS A, it is noted that only at high CV penetration rates does the number of incidents vary. This reflects the findings of Maerivoet et. al [31] (Section 4.2.4), where it was noted that at LOS A, as so few vehicles inhabit the road network the TMS had little affect. Besides from LOS A the deviation in results for a given penetration in response to adding the TMS is consistent across all LOS.

PET

Figure 5.4, showcases the PET incidents. HDVs do not have the highest PET incidents rate, the baseline of 100% L4-CVs does. Another important observation is the magnitude of the incidents. For TTC, the HDV simulations were recording incidents in the 1,000s while in PET the incident rate is around 250. This change in magnitude is because of the low PET threshold, the SSM devices in the vehicles not detecting "potential conflicts" [8]. As a result when analysing these results it is important to consider that while all the deviations as a result of the TMS may only be 30 incidents

[1] It is important to remember the make up of the Penetration Rates that are given in Section 4.2.4, however to summarise as Penetration 1, 2, 3 rises, the number of AVs (both NCAV and CV) rise.

Penetration Rate	LOS A		
	Baseline	TMS	Change (%)
HDV	1850	-	-
L4-CV	488	335	-31
P1	1228	1127	-8
P2	856	825	-4
P3	574	442	-23

Penetration Rate	LOS B		
	Baseline	TMS	Change (%)
HDV	3159.0	-	-
L4-CV	614	490	-20
P1	1636	1644	0.5
P2	1209	1102	-9
P3	719	630	-12

Penetration Rate	LOS C		
	Baseline	TMS	Change (%)
HDV	3690	-	-
L4-CV	763	486	-36
P1	1890	1842	-2
P2	1500	1278	-15
P3	855	695	-18

Penetration Rate	LOS D		
	Baseline	TMS	Change (%)
HDV	4091	-	-
L4-CV	713	603	-15
P1	2152	2033	-5
P2	1658	1425	-14
P3	977	869	-11

Table 5.3: TTC Incidents Use Case A

they are serious more serious incidents. The standard deviations are also relatively larger, reflecting that different iterations were producing varying numbers of incidents.

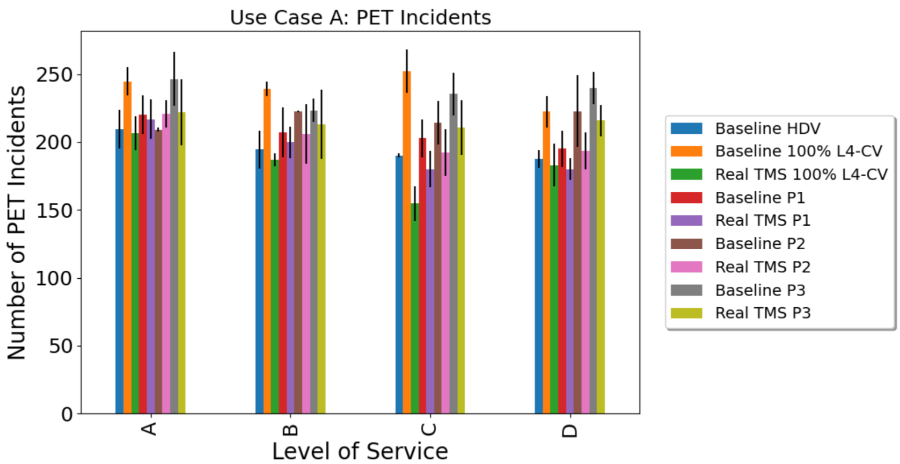
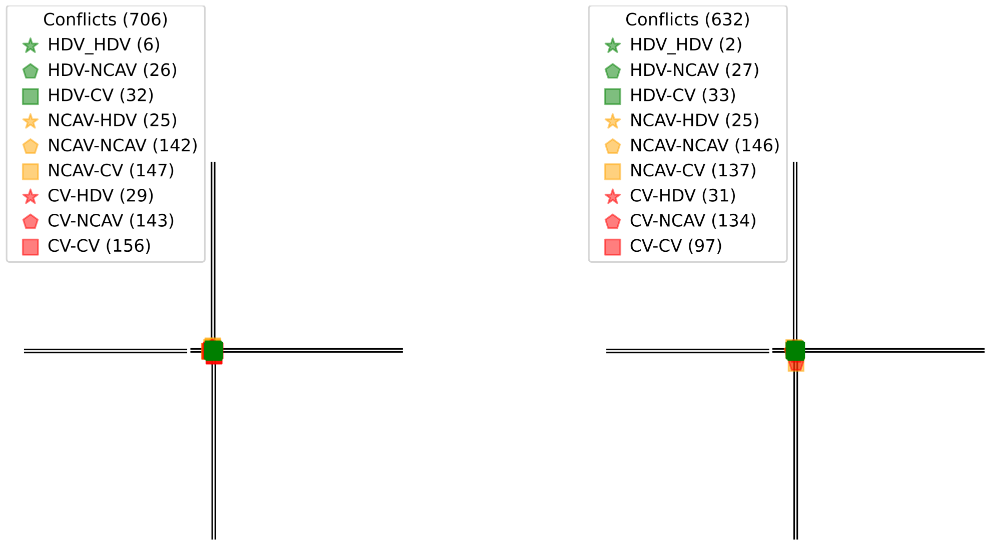


Figure 5.4: PET incidents in Use Case A

The TMS does have a negative effect on the number of PET incidents. But as the penetration penetration rate of AVs rise the number of PET incidents rise also. For further analysis of these incidents Penetration 3 at LOS C was chosen. Figure 5.5a and 5.5b indicate the position and vehicles involved in all of the incidents (in Penetration 3 at LOS C). It is clear the PET incidents occur in the center of the intersection. This is because CAVs(and NCAV) that miss the TMS, proceed into the center of the intersection while performing a ToC, shown in Figure 5.6. As a result the negative effects of the ToC occur in the center of the intersection.

This explains the incident reduction as the TMS prevents 75% of ToCs in CAVs. This is backed up by the data shown in Table 5.4, that shows the total number of incidents for P3 LOS C's baseline and TMS. It shows from the baseline to the TMS the total number of incidents falls by 74(10%), with incidents initiated by CVs decreases by 66 incidents which represents 89% of the decrease. The reason behind the incident rate being higher at P3 with the TMS than P2 without the TMS is that as the penetration of CVs rise so to does the penetration of AVs.



(a) Baseline (b) TMS

Figure 5.5: The PET incident location and vehicle involvements for Penetration at 3 LOS C

PET Incidents grouped by initiating vehicle				
Vehicles Type	**HDV**	**NCAV**	**CV**	**Total**
Baseline	74	314	328	706
TMS	62	308	262	632
Difference	-12	-6	-64	**74**
Difference (%)	-17	-2	-20	**-10**

Table 5.4: PET Incidents for Penetration 3 at LOS C

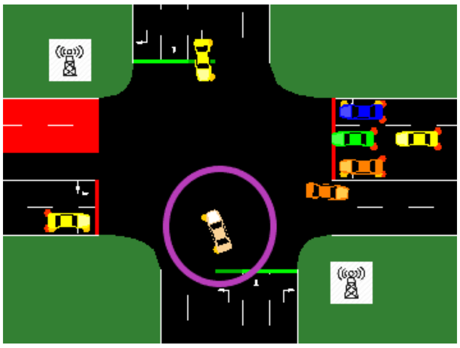


Figure 5.6: An incident in which a vehicle(white) performs a ToC in the center of the intersection

5.2.2 Efficiency

This section will present the efficiency results for Use Case A and explore the TMSs role in the results.

Throughput

Figure 5.7 contains the throughput of the intersection for the multiple simulations. Observe that the throughput of the network rises with the introduction of the TMS. This means that when the TMS is being applied more vehicles are passing through the intersection. At lower LOSs a smaller change in results is observed because the traffic is free flowing and there is no congestion. However, at higher LOSs the effects of the TMS are more evident especially during simulations with higher volumes of CVs because more vehicles are receiving the TMS.

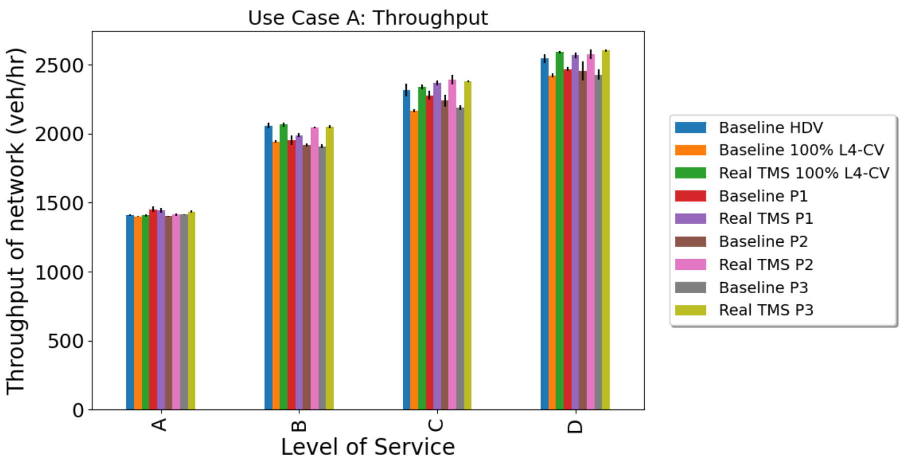


Figure 5.7: Throughput in Use Case A

Figure D.1a and D.1b (Appendix D) investigate Penetration 3 at LOS C in more detail, they show that intersection's throughput increase is because of the TMS improving the throughput of vehicles approaching and exiting on the left arm of the intersection(the arm with the work zone). This indicates that the TMS is equitably improving the intersections throughput, by tackling the worst affected routes.

CO_2

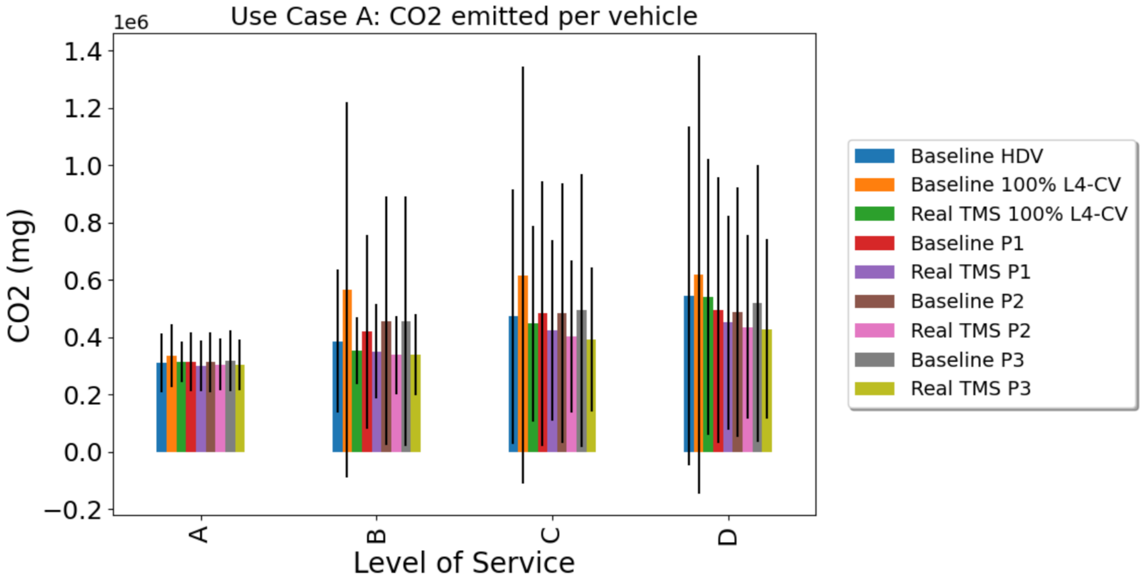


Figure 5.8: CO_2 in Use Case A

Figure 5.8 (average CO_2 emitted by each vehicle) shows that the use of the TMS reduces the CO_2 emitted by the vehicles. Interestingly the 100 % HDVs simulation emit less CO_2 than the baseline of L4-CVs. This may seem to contradict Section 2.1, where it is stated the introduction of AVs will increase efficiency, however at the TA which is being simulated it is clear HDVs are a greener option than AVs (or CAVs without a TMS). The reason for this is two-fold:

1. Human drivers are more likely to detect the roadworks early and will instinctively use the middle lane to turn right

2. Human driven vehicles do not perform ToCs or MRMs and therefore they disrupt the traffic less

Nevertheless, when the TMS is applied, the vehicles emit less CO_2 than when there is 100% HDVs. The CO_2 emissions behave similarly to the Throughput because as the penetration rate of CVs rise, there is an increased reduction in emissions from the baseline to the TMS.

Mean Trip Duration

Figure 5.9, illustrates again that the TMS is aiding traffic flow through the intersection. The trends are similar to the Throughput and CO_2 metrics. The graph demonstrates that when the TMS is applied the average journey time for the vehicles falls. The standout feature about Figure 5.9 is the standard deviations. The reason the standard deviations are so large is that the initial vehicles to approach the intersection, may get a green light and pass through without any delay. While later vehicles may be stuck at the traffic lights for several cycles. This means that there will be a discrepancy between the min and max values creating a large standard deviation. Very large standard deviations potentially indicate longer journeys at the end of the simulation. In Figure 5.9, when the TMS is applied the standard deviation decreases as well.

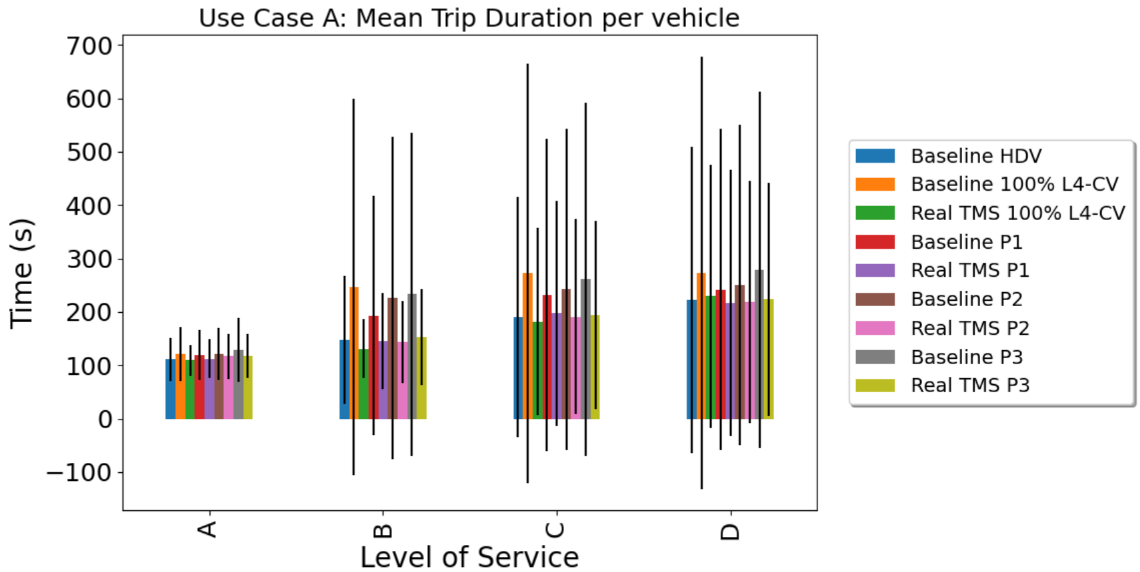


Figure 5.9: Mean Trip Duration in Use Case A

Figure D.2 (Appendix D) demonstrates again that the TMS is improving efficiency in the worst affected lanes. As it reduces the journey time for vehicles approaching and exiting on the left arm of the intersection.

5.2.3 Discussion

Examining the results of Use Case A, provides an insight into the impact of the TMS on the scenario. While it is clear that the TMS has a positive affect on the individual metrics, the behaviour of the metrics must be considered as a whole. This section first analyses the implications behind the safety results before moving to the efficiency results. It will conclude by examining the system as a whole.

Macro Results

Table 5.5 shows the overall change of the metrics as a result of adding the TMS.

Metric	Change from Baseline to TMS	Note
TTC	-11%	Decrease represents safety improvement
PET	-10%	Decrease represents safety improvement
Throughput	5%	Increase represents efficiency improvement
CO_2	-17%	Decrease represents efficiency improvement
Mean Trip Duration	-17%	Decrease represents efficiency improvement

Table 5.5: Macro Results for Use Case A

Safety

Judging by the safety metrics it is clear from the results in Section 5.2.1 and Table 5.5 that the TMS improves the safety of the intersection as the number of TTC and PET incidents fall on average by 11% and 10% respectively. While this data suggests that the TMS is making the intersection safer, there is another layer to the analysis. Excluding the penetration rate that consisted of 100% L4-CVs, it can be seen that as the percentage of AVs rises the number of TTC incidents falls and the number of PET incidents rises. This demonstrates there is a positive correlation between AV volumes on the intersection and the risk of a TTC incident. In contrast there is a negative correlation with PET incidents. It is necessary to point out that the TMS does reduce the PET incident but the trend of higher penetration rates of AVs increasing PET incidents is more prominent.

The issue is that the TMS attempts to mitigate ToCs in the vehicles it can contact. However, there is no system in place to handle the ToCs that do occur. The TMS's ability to only contact 75% of CVs is to make the simulations more realistic. Not all CVs will always receive the TMS whether through failed detection or communication errors. Additionally some vehicles may not be able to implement the TMS guidance. Therefore, there needs to be another layer added to the TMS, that prevents CVs entering the center of the intersection while performing a ToC. This change could be conducted by the OEMs or by the TMS. Nevertheless, the failure of the proposed TMS to offer an alternative strategy to prevent vehicles transitioning in to the intersection highlights that the system needs refining.

An alternative approach which could be used to manage the ToCs is demonstrated by the TransAID Project in Use Case 4 (discussed in Section 2.3). This use case involved the guiding of CVs into "safe spots" such as parking places or a vacancy in front of the work zone. This ensures the vehicles can safely transition and then proceed. This feature is key as AVs should improve traffic safety which is not the case here.

Efficiency

Moving to the efficiency results it is clear from the data shown in Section 5.2.2 that the TMS was highly effective. Across all three metrics the introduction of the TMS increased the efficiency. With the TMS (on average) 5% more vehicles passed through the intersection, spending less 17% time traversing it and emitting 17% less CO_2. While this points to a positive impact by the TMS it does not guarantee it, as the TMS may only serve to increase efficiency in lanes unaffected by the closure or by rerouting the effected vehicles. However, looking at Figures D.1 and D.2 it is clear that the TMSs primary function to improve efficiency in the routes impacted by the roadworks was achieved.

Overview

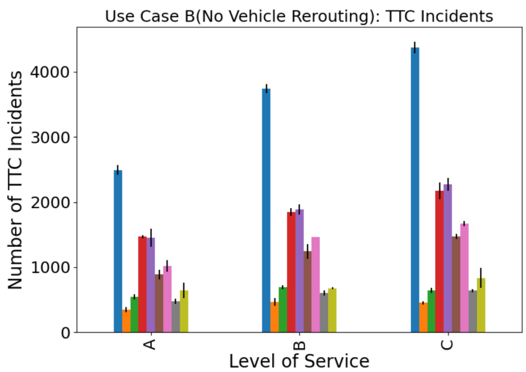
The results show the TMS improves the safety and efficiency of the intersection. Furthermore the results demonstrate that the more vehicles that are managed by the system the greater the improvements. It demonstrates that while the effect of the system might be small initially (low numbers of CVs) as CVs become more prevalent the system will perform better. Nevertheless, even at relatively low CV presence (Penetration 1) the system improves the KPIs. So while the TMS does not prevent all PET incidents it shows promise.

5.3 Use Case B

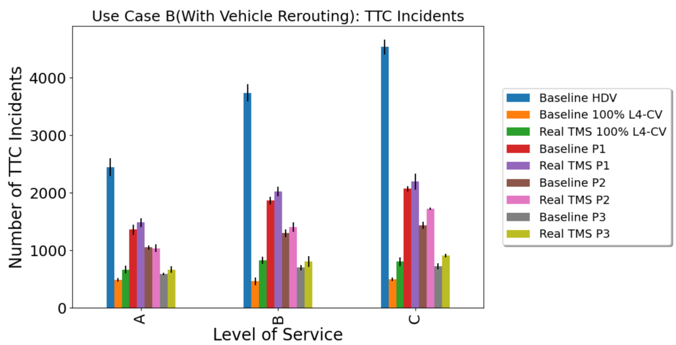
5.3.1 Safety

TTC

Figure 5.10a and 5.10b illustrate the TTC incidents that occur in Use Case B across all simulations with and without rerouting. Note that when vehicles experiencing delays alter their routes, there is 5% increase in the number of TTC incidents. Furthermore, when the TMS is applied the number of TTC incidents rises by 14% and 16% for with and without rerouting respectively. Meaning that the TMS is making the intersection more unsafe.



(a) Without Rerouting



(b) With Rerouting

Figure 5.10: TTC incidents in Use Case B with and without rerouting

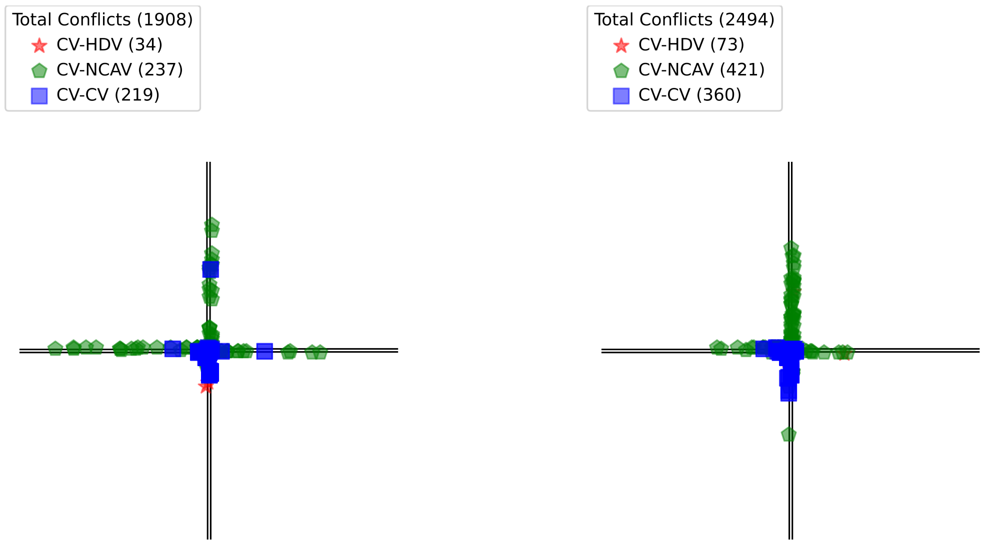
Digging deeper into the TTC incidents at Penetration rate 3 at LOS C, with vehicle rerouting, see Table 5.6 which displays the TTC per vehicle type. Note that the TMS increases the incidents caused by NCAVs and CVs by 52% and 74% respectively.

CVs experience the biggest rise in incidents increasing by 74%. Analysing these incidents in more detail (Figures 5.11a and 5.11b). It is noted that the incidents when the TMS scenario is applied are:

1. more densely packed around the center of the intersection
2. more evenly spread across the 4 arms

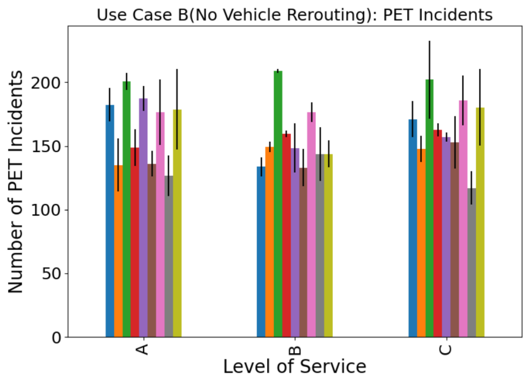
TTC Incidents grouped by initiating vehicle				
Vehicles Type	**HDV**	**NCAV**	**CV**	**Total**
Baseline	847	571	490	1908
TMS	772	868	854	2494
Difference	-75	297	364	586
Difference (%)	-9	52	74	30

Table 5.6: TTC Incidents for Penetration 3 at LOS C with vehicle rerouting

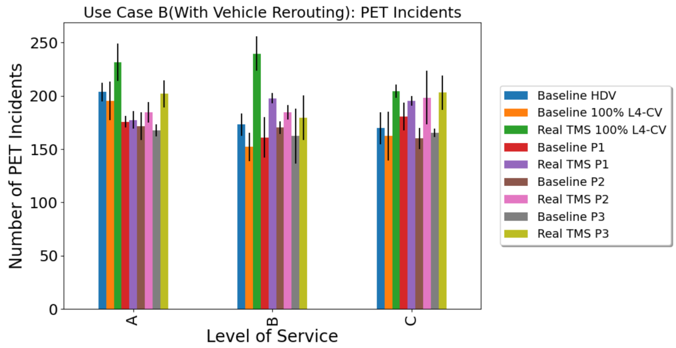


(a) Baseline (b) TMS

Figure 5.11: TTC incidents locations and vehicles involved for Penetration 3 LOS C.



(a) Without Rerouting

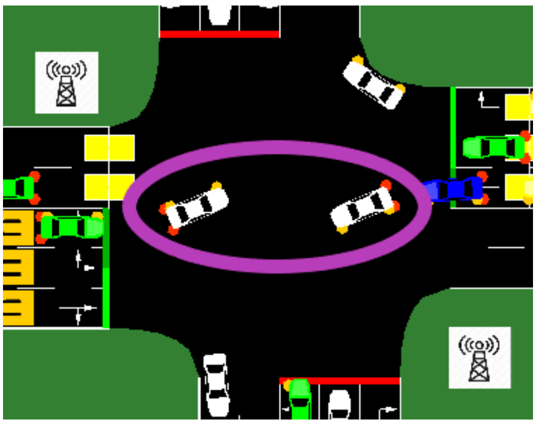


(b) With Rerouting

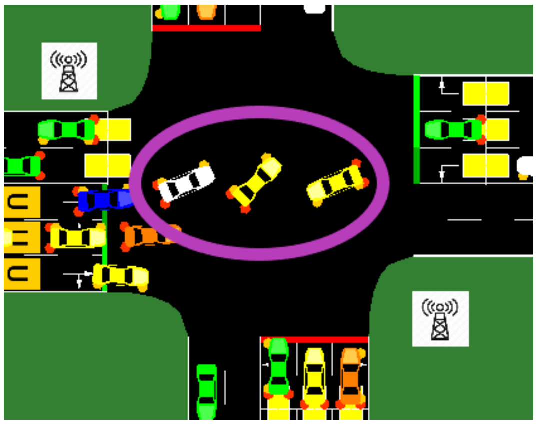
Figure 5.12: PET incidents in Use Case B with and without rerouting

PET

Figures 5.12a and 5.12b display the PET incidents for the scenario. PET incidents rise with the introduction of the TMS, furthermore when vehicles reroute the number of PET incidents rises by roughly 20%. PET incidents grow as the number of CVs increase.
Examining the intersection with/without the TMS in Figure 5.13, there is a key difference, CVs approaching on the left and exiting through the top will be in the middle lane, while non-CVs will be using the left lane. This means that two vehicles approaching on the left could be stopped in the middle waiting for a gap to turn, while one vehicle approaching on the right does the same. This increases the number of vehicles in the center of the intersection and as a result the vehicle interactions. Therefore leading to increased PET incidents.



(a) Baseline



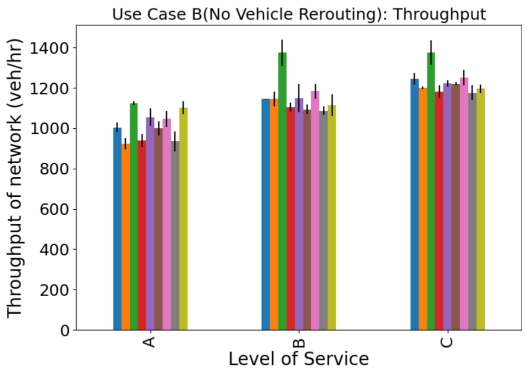
(b) TMS

Figure 5.13: Increased vehicle presence in the intersection, as the circled vehicles wait for an opportunity to turn left

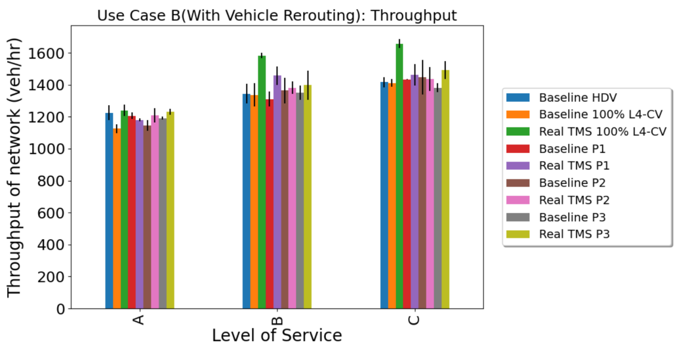
5.3.2 Efficiency

Throughput

Figures 5.14a and 5.14b, show the effect of the TMS on the Throughput for this scenario. There is a roughly 17% increase in the throughput when heavily delayed vehicles reroute. This is as expected, as rerouting does increase the Throughput. However, note that when vehicles reroute after a significant delay it is far more effective than the TMS in increasing throughput. The TMSs greatest influence is seen when there is no rerouting and a lower number of vehicles are present (LOS A). An important note is that the throughput never rises beyond 1600 vehicles, so while the TMS does improve the results the scenario's throughput is significantly lower than is seen in Use Case A.



(a) Baseline

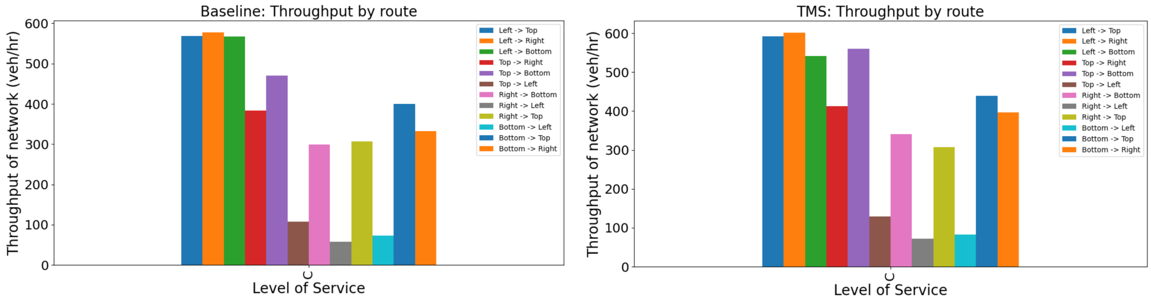


(b) TMS

Figure 5.14: Throughput of the intersection with and without rerouting

Looking in more detail at Penetration 3 at LOS C with rerouting (see Figure 5.15) there is an increase in Throughput when the TMS is applied. Observe that the rise in Throughput is not due to an increase in vehicles using the left exit but rather that other exits are receiving more traffic. Most notably top to bottom which increased by nearly 100 vehicles, which is a 20% increase of the pre-TMS value.

In contrast, looking to Tables 5.7 and 5.8, which contain the throughput for the number of vehicles that pass through the left exit and their route for LOS A, no rerouting at Penetration 100% L4-CV and Penetration 3 respectively. The results demonstrate that while the intersections throughput does increase at Penetration 3 this is only marginally because of improved throughput in the affected lanes. Nevertheless, it should be acknowledged that at higher CV rates the TMS does increase the throughput through the blocked exits even at high traffic levels. This can be seen in Figure D.3 in Appendix D which demonstrate 100% L4-CV at LOS C. Where the number of vehicles exiting through the left exits increases.



(a) Baseline (b) TMS

Figure 5.15: Total throughput per route. For Penetration 3, with rerouting at LOS C across all iterations.

Throughput by route			
Route	**Bottom to Left**	**Top to Left**	**Right to Left**
Baseline	73	107	58
TMS	82	129	72
Difference	9	22	14
Difference (%)	12	20	24

Table 5.7: Throughput by route. For Penetration 3 at LOS A without Rerouting

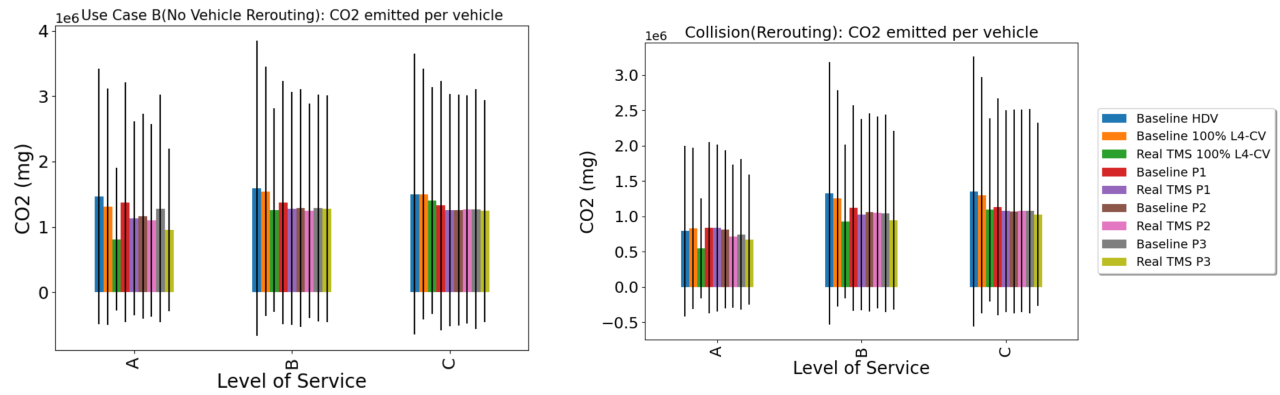
Throughput by route			
Route	**Bottom to Left**	**Top to Left**	**Right to Left**
Baseline	81	77	45
TMS	123	219	122
Difference	42	142	77
Difference (%)	52	180	170

Table 5.8: Throughput by route. For 100% L4-CV at LOS A without Rerouting

CO_2

Figures 5.17a and 5.17b, show the mean CO_2 emissions of the intersection. Again, there is a significant decrease in the CO_2 emissions as a result of the rerouting as vehicles experiencing delays are now using alternative routes. Looking at the effect of the TMS on the rerouting simulation, there is a decrease in emissions with greatest decrease observed at high CV penetration rates and the largest difference happening when there are only CVs showing that the TMS is effective. However, when the CVs only make up a small proportion of the vehicles the effects are only marginal as seen at LOS C in Penetration 1 and 2.

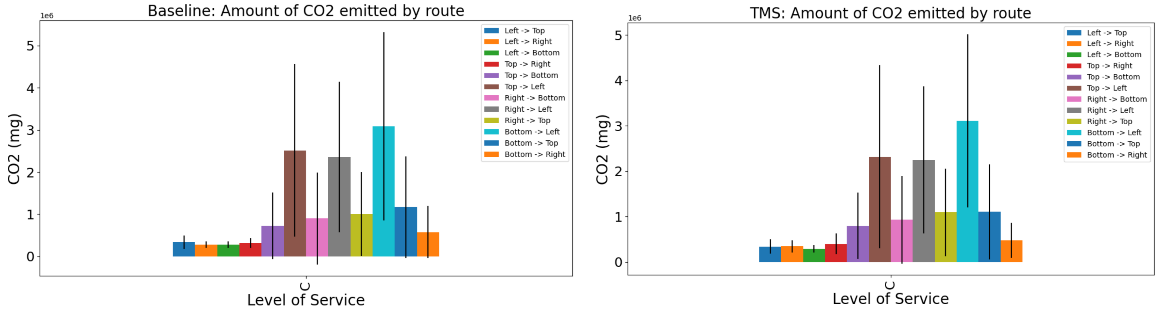
Figures 5.17a and 5.17b show LOS C Penetration 3 with rerouting in more detail. It illustrates the $CO2$ emitted per route. It shows that the TMS has little affect on the emissions of vehicles using the left exit. In Appendix D in Figure D.4a and D.4b it is again seen that at higher CV penetration rates the TMS is more effective and will decrease the emissions of vehicles using the left lanes.



(a) No Rerouting

(b) Rerouting

Figure 5.16: The CO_2 emitted by the vehicles in the intersection with and without rerouting



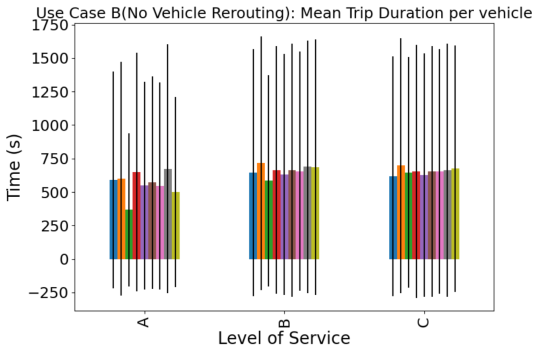
(a) Baseline

(b) TMS

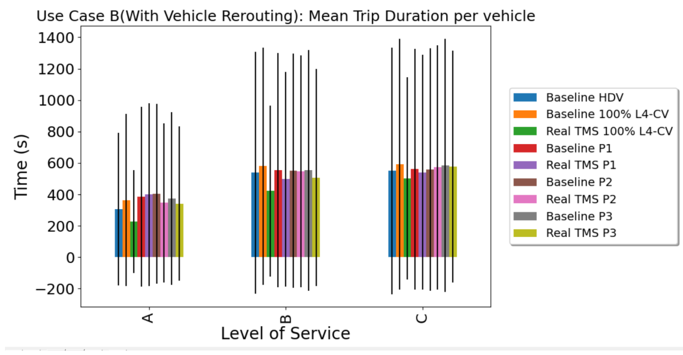
Figure 5.17: The average CO_2 emitted by vehicles separated by the route taken. For Penetration 3 with rerouting at LOS C

Mean Trip Duration

Figures 5.18a and 5.18b show the duration of the vehicles journeys through the intersection. The reason behind the mean trip duration's being constant at LOS B and C, is because vehicles that are stationary at the traffic lights for 5 minutes straight, teleport to the other side of the intersection. This is a feature of the simulator SUMO to avoid grid lock and to ensure the simulations end. Hence when looking at the results the only penetration rate that the TMS has any effect in was the 100% L4-CV. At lower CV penetration rates the vehicles could not overtake in the left lane and therefore some were teleported. The reason for the large standard deviations is that vehicles using other exit lanes would have short trips. Meaning the values were in two clusters of those grid locked trying to exit through the left and those not grid locked using the other exits. Figures 5.19a and 5.19b, show the route breakdown.

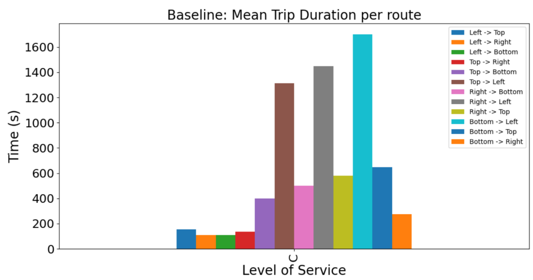


(a) No Rerouting

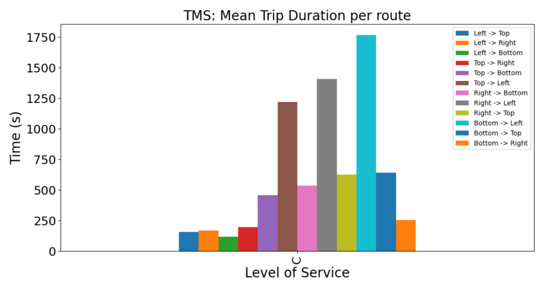


(b) Rerouting

Figure 5.18: Mean trip duration by the vehicles in the the intersection with and without rerouting



(a) Baseline



(b) TMS

Figure 5.19: Mean Trip Duration separated by route taken for Penetration 3 with Rerouting at LOS C

5.3.3 Discussion

Use Case B differs significantly with Use Case A, in that the individual metrics vary when the TMS is applied. It also differs in that the impact of the TMS on the results is less evident. Looking at the data presented in Section 5.3.2, it is evident that vehicles rerouting and using alternative exits is far more effective than the TMS.

Macro Results

Tables 5.9 and 5.10 show the overall change of the metrics as a result of adding the TMS for when vehicles do not reroute and when they do reroute respectively.

Safety

Examining the safety metrics for Use Case B in Section 5.3.1, the TMS appears to decrease the safety of the intersection. with TTC and PET incidents rising (on average) by 14% and 25% respectively when there is no rerouting[2]. There are two primary factors for the decrease in safety

[2]16% and 20% with Rerouting

Metric	Change from Baseline to TMS	Note
TTC	14%	Increase represents safety reduction
PET	25%	Increase represents safety reduction
Throughput	0%	Represents no change in efficiency
CO_2	-11%	Decrease represents efficiency improvement
Mean Trip Duration	-10%	Decrease represents efficiency improvement

Table 5.9: Macro Results for Use Case B - without rerouting

Metric	Change from Baseline to TMS	Note
TTC	16%	Increase represents safety reduction
PET	20%	Increase represents safety reduction
Throughput	6%	Increase represents efficiency improvement
CO_2	-11%	Decrease represents efficiency improvement
Mean Trip Duration	-10%	Decrease represents efficiency improvement

Table 5.10: Macro Results for Use Case B - with rerouting

1. The center of the intersection is becoming more congested as a result of the TMS instructing CVs to turn left using the middle lane.
2. The throughput of the intersection rises as the TMS is applied, meaning there are more vehicles moving throughout the intersection. This increases the incidents because stationary vehicles awaiting traffic lights are not at risk of having a collision, while moving vehicles are. Moreover, it provides insight into the distribution of the collisions as vehicles approaching from the bottom are no longer grid-locked. Hence the expansion of the incident positions along the bottom arm.

As congestion rises, the presence of up to 3 stationary vehicles in the intersection, awaiting an opportunity to turn will increase the vehicle interactions. Thus, increasing the possibility of incidents. This means that as the system becomes more effective (i.e. high rates of CVs) the number of incidents will rise.
Furthermore, if the TMS was implemented on a road in reality, the increased presence of vehicles in the intersection, will block other vehicle's view of the intersection and create blind spots. This could lead to vehicles attempting to turn when there is oncoming vehicles creating further incidents. This issue could be especially troublesome when there is a high percentage of human driven vehicles whose detection capabilities are inferior.

Nevertheless, looking at the positions of the TTC incidents in Figure 5.11, it is observed that in the absence of the TMS there are very few incidents on the bottom arm of the intersection, this rises when the TMS is introduced. This is because of the increased traffic flow through the bottom arm of the intersection observed in Figure 5.15.

Efficiency

The efficiency results do not bode well for the TMS. Looking at the contrast between when no vehicles alter their route and when 40% of vehicles that experience a 140 second delay do alter their route yields an increase efficiency. There is a roughly 17% increase in throughput and decreases of 23% and 11% in both mean trip duration and CO_2 emissions respectively. The rerouting of vehicles manages to improve the efficiency of the network significantly more than the TMS. The issue with these improvements are that they do not represent the increased trip duration a road user would have to undertake in order to arrive at the destination. The rerouting statistic in this sense only provide coverage of the throughput of the intersection as it demonstrates how many vehicles the intersection can process.

The results indicate that the proposed TMS does not function well with low CV penetration rates. While the network does experience marginally better efficiency it is not because of the TMS managing the situation. The TMS was designed to aid vehicles pass through the left exit, but this only happens when there is 100% L4-CVs. However, 100% L4-CVs penetration rate was mainly included in the simulations to emulate an ideal situation while Penetration 1, 2 and 3 were added to reflect more realistic scenarios. So the TMS is not improving the efficiency enough to be deemed effective.

Overall

Considering the failure of the TMS to increase either safety or efficiency in this use case, it should not be considered for use on public roads in the future. The reality of the TMS is that it increased the efficiency of the unaffected routes. An alternative approach of advising vehicles to reroute around the blockage may be a more optimum way to solve this potential TA. Although this will need to be balanced with the distance that vehicles may need to travel in order to reach their new destination.

6 Conclusion

This section opens by summarising the work completed in this project. It then examines the strengths and weaknesses of the experimental approach outlined in this report. It evaluates the realism of the simulations and discusses the reliance on one piece of research. Next, it discuses the key findings for Use Case A and B and the TMS provided. It covers issues with the design approach and what changes to the experiment should be made if the experiments were to be repeated. It concludes by discussing the next steps, in the development of the TMSs proposed.

6.1 Summary of Work Completed

This research highlighted two future transition areas that had not previously been researched and proposed two TMS to prevent approaching CAVs performing a ToC. In doing so the road networks for the scenarios were created in SUMO with realistic traffic simulation. The results of these traffic management systems were analysed with the system for Use Case A showing promise as it reduces the number of TTC incidents by 11% and decreased the mean trip duration by 17%. While Use Case B, didn't perform to the same standard as Use Case A it provided insight into the effectiveness of rerouting vehicles around the transition area. This insight can be used in further research in this area.

6.2 Strengths and Weaknesses in approach

6.2.1 Realism

It is key to assess how well the model maps to the real world. As these systems will be implemented on public roads there is a lot that could vary hour to hour that would not change in a simulation. The systems proposed builds on the TransAID 2020 Horizon project in this respect: initially only 25% of the CAVs could detect the scenario with this rising to 75% in the presence of the TMS. This 75% adds realism to the scenario, especially in the early development because when these systems are deployed they may not be as reliable at detecting and communicating with CVs. The system could be over run by heavy traffic congestion and only able to reach a proportion of the vehicles within its scope.

As the safety and efficiency of the public roads is being managed by this system, it is wiser to underestimate the detection ability in the simulations than to over-estimate. For Use Case A, it was seen that as the penetration of CVs rose the performance rose, meaning that if the communication ability of the TMS was higher than the pre-determined 75%, the performance could have risen even further. However, underestimating the ability has highlighted limitations in the system that may not have been observed at higher TMS communication.

Another strength of the simulations is the pseudo-random element of the vehicle simulations, both in driving performance and the vehicle journeys. This represents reality, where not all AVs will behave the same. The vehicle journeys and start times are also random and no two simulations are the same. The benefit of this randomness is that the simulation results for two iterations of the same scenario can differ. This adds to the reality of the experiment. The intersections behave differently depending on the vehicle parameters and journeys as it would in real life. It ensures that the results reflect real traffic flows, this leads to certainty that the results would be replicated if applied to a real intersection.

The weakness in the randomness of varying the vehicle models is in the lack of reliability. As the vehicles in the iterations of the project could differ in both route and driving parameters, the results may not be conclusive in their coverage of the scenarios. Running more iterations of the project at each penetration rate and Level of Service will provide more confidence in the results. Due to limited time available, this research only considers 3 iterations of the model.

6.2.2 TransAID

Another weakness in the approach presented is in the over-reliance on one piece of research. As previously mentioned the TransAID project was the first research operation conducted in the development of a Traffic Management System to prevent/manage CAVs performing a ToC or MRM. However, it seems to be the only major research done into this area. While there are other papers on this area, a lot of their Use Cases are derived from those originally shown in the TransAID project.

They all reference TransAID project's vehicle models, penetration rates and simulation software. While they do make minor tweaks to increase performance, they have very similar methods just to different problems. The issue is, that there is only really one approach to follow. There is no cross referencing against other vehicle parameters or driving models.

However, the popularity of the TransAID project in the community does have its advantages: the reasons for its popularity is its professionalism and results. As countless papers have built upon the Use Cases referenced by the TransAID project, there are lots of resources in how to conduct the simulations and other key findings as other research papers built on TransAID's process. So while the reliance on the TransAID project is a limitation it is the best starting point to build on.

6.3 Key Findings

This section summarises the key findings of each scenario

6.3.1 Use Case A

The system proposed did increase the safety (reducing the incident rate for TTC and PET by 11% and 10% respectively) and efficiency (increasing throughput by 5%, while decreasing both the mean trip duration and CO_2 emissions by 17%) of the intersection and therefore should be considered a success. The system will provide a good stepping stone towards future development in the management of this transition area.

However, in Use Case A, the system failed to manage or consider AVs that failed to detect the situation and missed the TMS. This only became apparent when analysing the PET results. TransAID have already developed the system of instructing vehicles that require an MRM to instead enter a Safe Zone, so the implementation is all that is required. It would involve adding a safe spot to the front of the roadworks and adding parking spots along the side of the street for these vehicles to use. The addition of this layer to the TMS will decrease the number of PET incidents and therefore increase safety.

6.3.2 Use Case B

The system did increase the efficiency when 100% of the vehicles were CV, this doesn't reflect a realistic scenario within the next 20-30 years, it is expected mixed traffic will dominate. However, the biggest drawback to this system was that the design was inherently flawed as it increased the number of vehicles stationary in the intersection, which increased the vehicle interactions and safety incidents (by 14% and 25% for TTC and PET without rerouting) as a result. In reality the system would perform worse than in the simulations, as the presence of these vehicles in the center of the intersection creates blind spots which would become extremely hazardous especially with high numbers of HDVs.

The other issue with the results from Use Case B, arise from analysing the results from the efficiency metrics, they present the illusion that re-routing vehicles was making the intersection more efficient. However, the reality behind the situation is that these vehicles were taking a less optimum route to reach their destination and therefore in the long run may have experienced longer journey duration or emitted more CO_2. So while the intersections throughput rose (by 17%) the re-routing does not indicate greener and more efficient roads as a whole. To correct this issue, the road network being simulated should be increased so that when vehicles exit the intersection the journey does not end, rather they continue on through the network to a certain destination. By doing this it will indicate more clearly just how effective the rerouting is on the intersection.

6.4 Future work

This project adds two new future transition areas and traffic management systems to the research area of managing transitions of control. In doing so it highlights the need for future research to be conducted on these areas and suggests improvements to the proposed traffic management systems.

Looking ahead to further research being done, Use Case B needs to be re-evaluated. The system of instructing vehicles to turn left using the middle lane serves to make the intersection more unsafe and while there is a low number of CVs on the road it is not practical. The system needs further work to assess the validity of rerouting vehicles. As rerouting may prove to be a better approach than a TMS.

For Use Case A, as mentioned above research needs to be done in order to prevent rising PET incidents with the number of AVs. On top of this further development of the system could be done to ensure that the same TMS works for intersections with different formats such as T and Y junctions. While the TMS may work for the given scenario, experimenting with the proposed solution on other scenarios to ensure its versatility would be useful so that in future the approach could be standardised for intersections and become more familiar to road users.

To further increase the safety of the differing types of intersection, the system then needs to be evaluated while simulating V2X communication. As the project assumes the communication is happening, the next step is to model that communication. This step is outlined in the TransAID project [43]. It would involve finalising the exact positions of the RSI based on communication range and would be carried out in the iTetris Framework. It would involve the coupling of the traffic simulation shown in this report with a communication simulation. It will allow for the refining of the TMS communication and provide a more definite value of what proportion of CVs receive the TMS. If the results for this part of this research continued on the trend seen in this report, the next step would be to deploy the system with real vehicles in a private center.

6.5 Summary

The TMS proposed to solve Use Case B is not a viable solution to the problem but it does highlight the issue with the scenario. So while the solution is not applicable, it should be noted that HDVs currently have no solution to the unplanned closure of an exit lane at an intersection. Use Case A does improve the performance of the intersection both in safety and efficiency and therefore contributes to the area of research as the TMS is a good starting point for future work on this transition area.

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A Appendix A

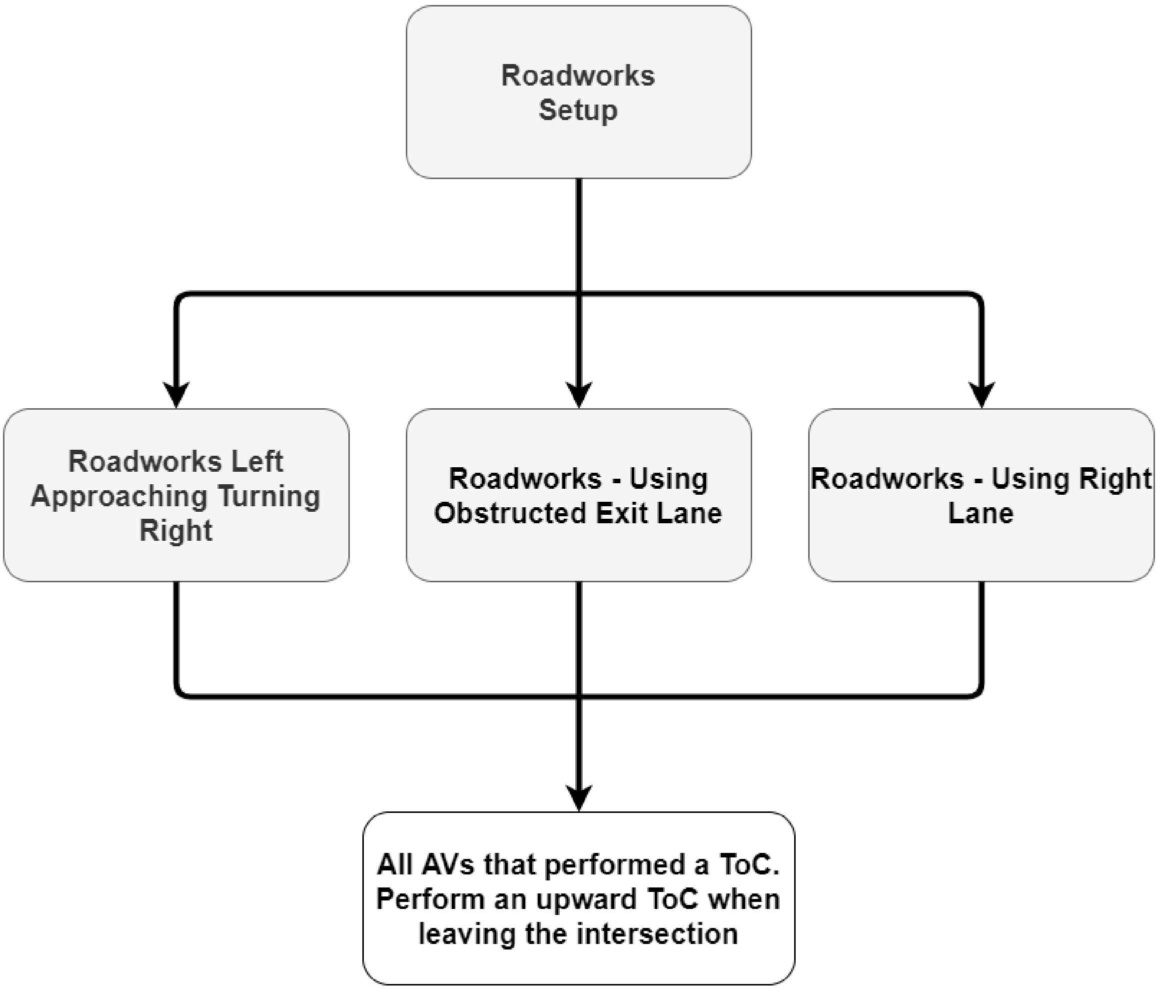


Figure A.1: The grey elements in this Figure refer to Figure A.2, A.3, A.4 and A.5

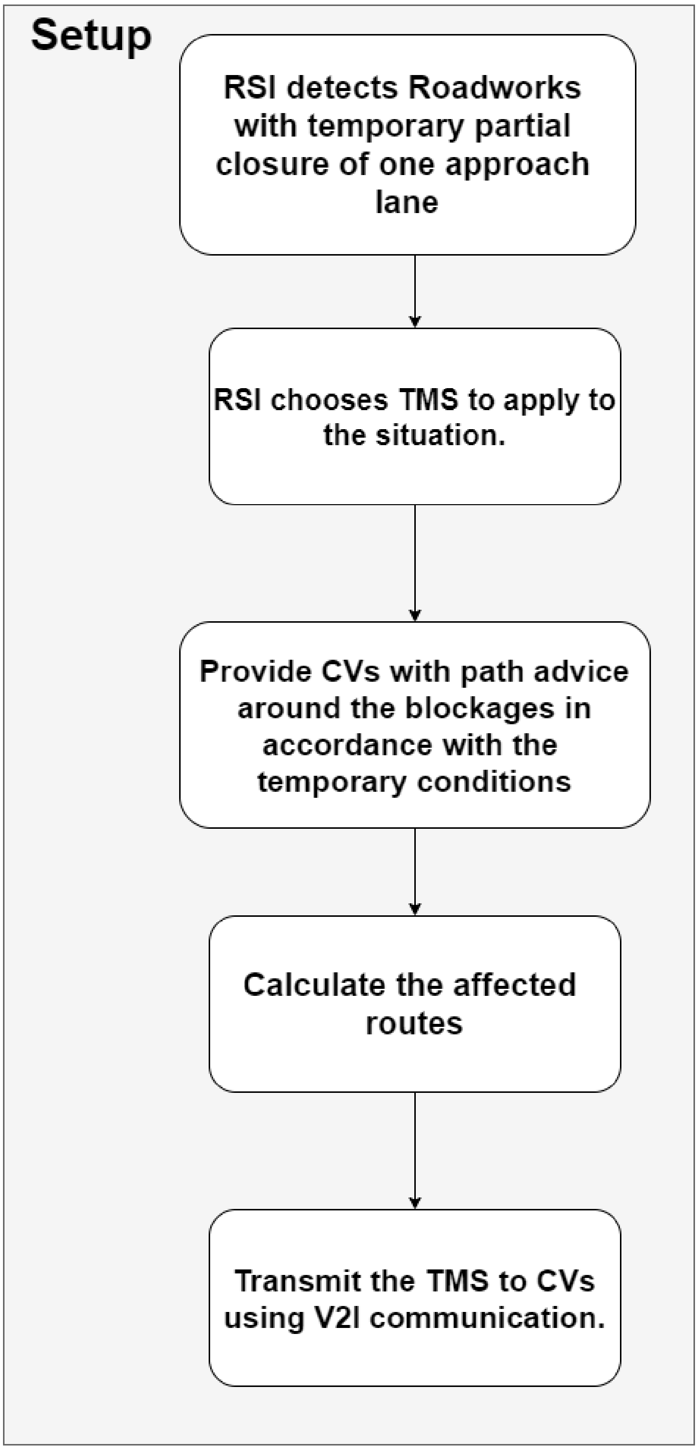


Figure A.2: The actions of the RSI

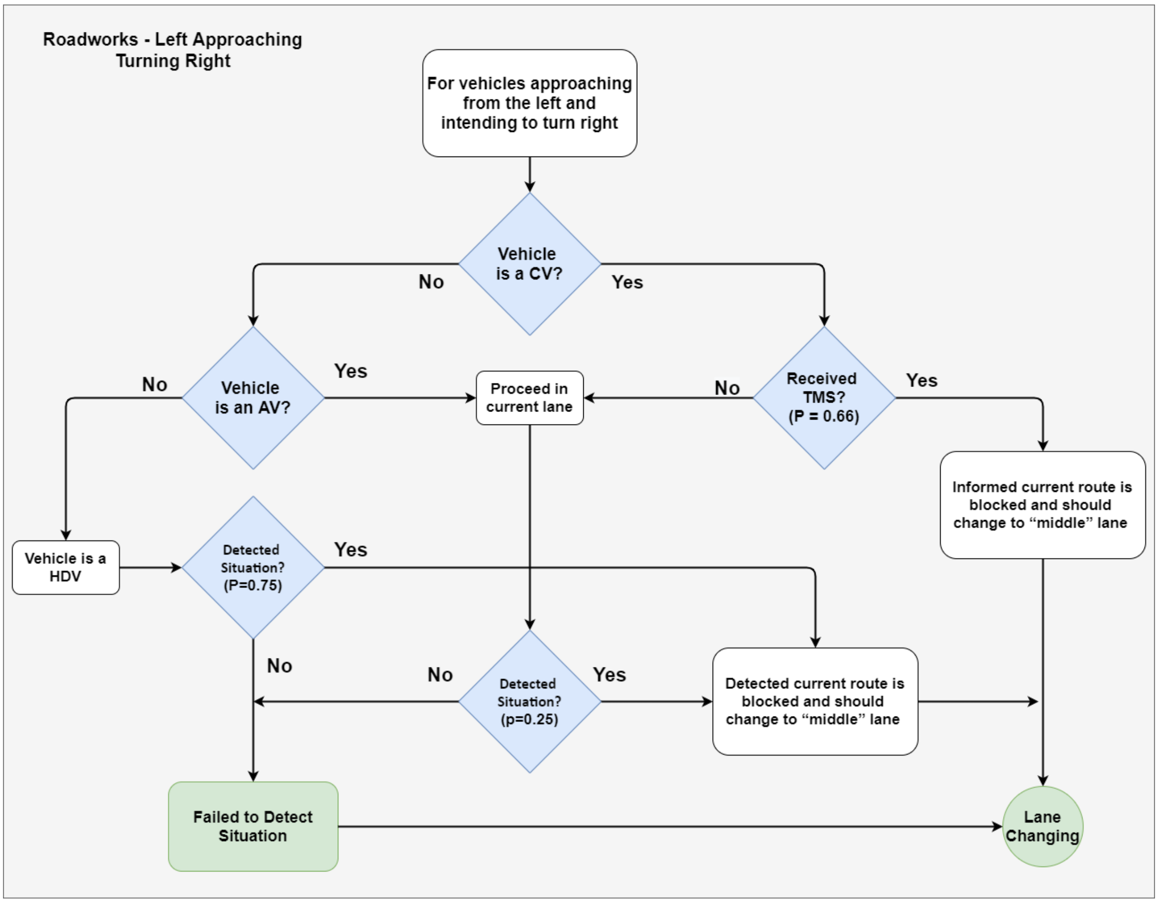


Figure A.3: The behaviour of vehicles approaching from the left and intending to turn right. The green elements refer to A.6 and A.7

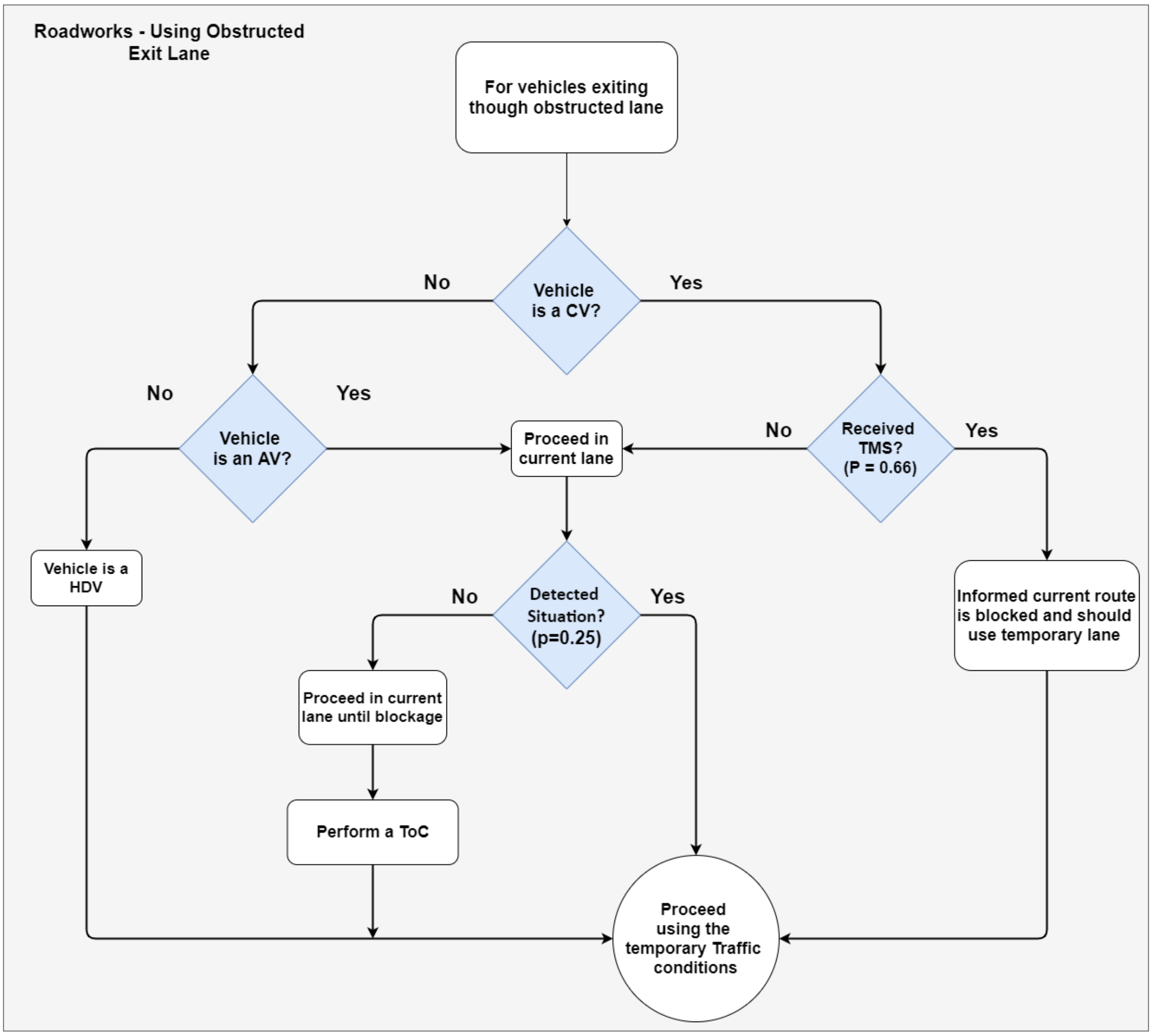


Figure A.4: The behaviour of vehicles intending to use the obstructed lane

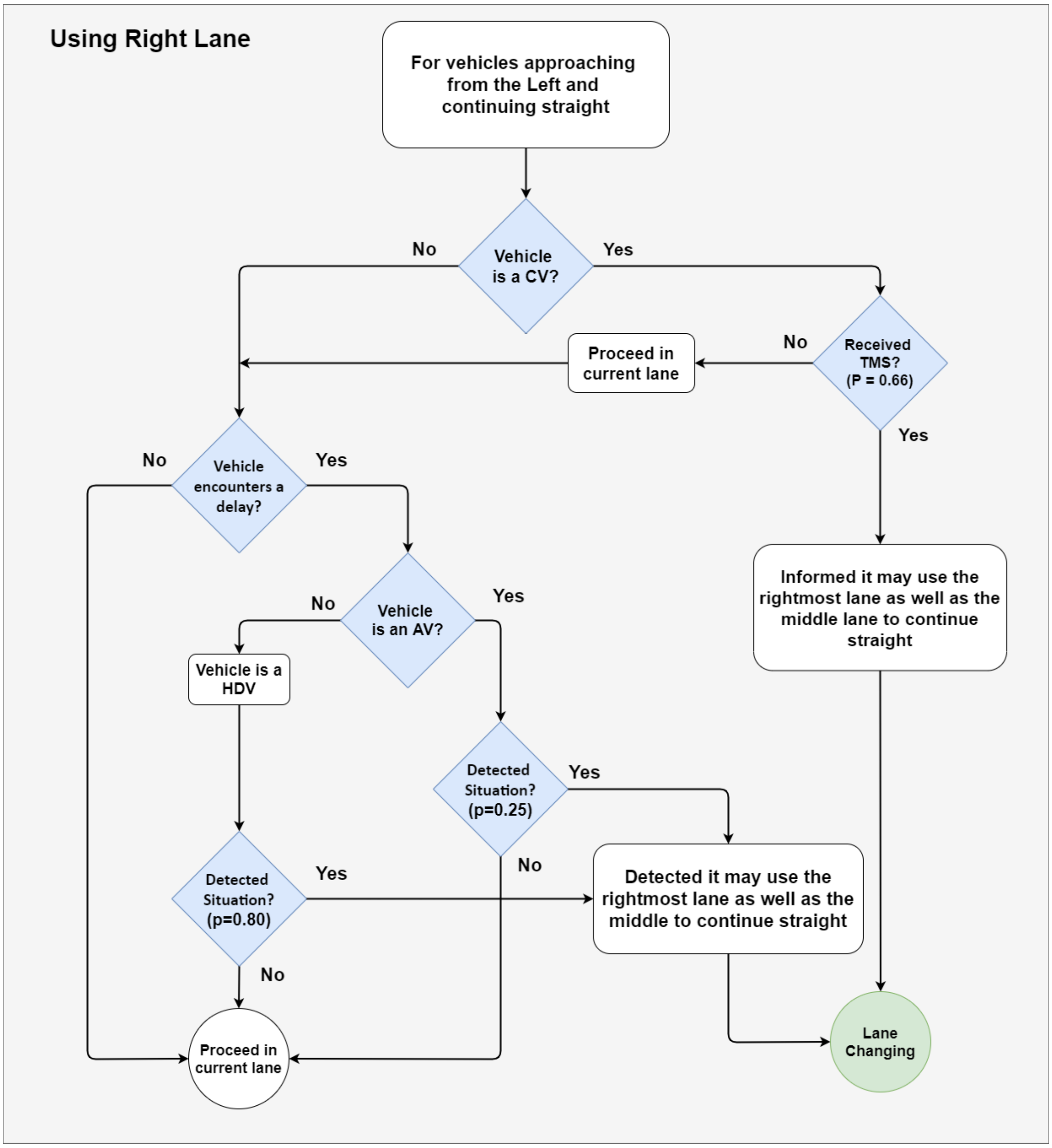


Figure A.5: The behaviour of vehicles approaching on the left and intending to go straight. The green elements refer to A.7

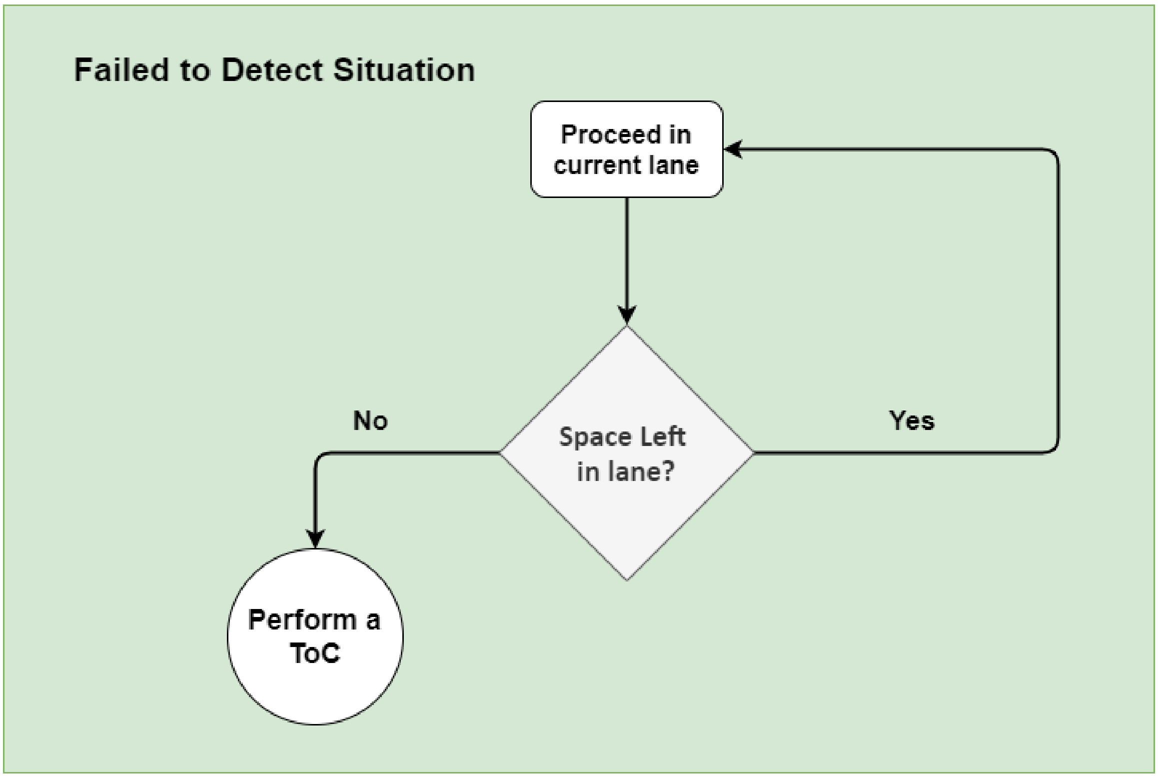


Figure A.6: The behaviour of vehicles that fail to detect the scenario

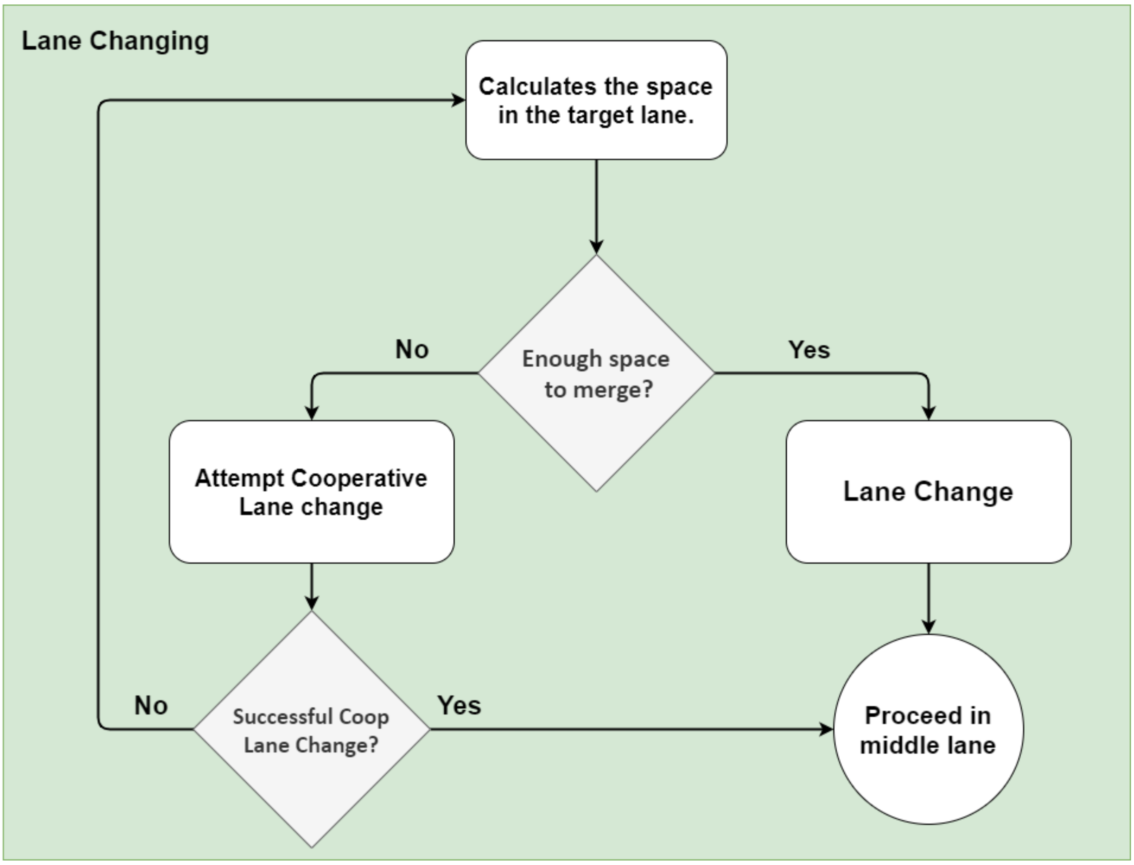


Figure A.7: The behaviour of vehicles when lane changing

B Appendix B

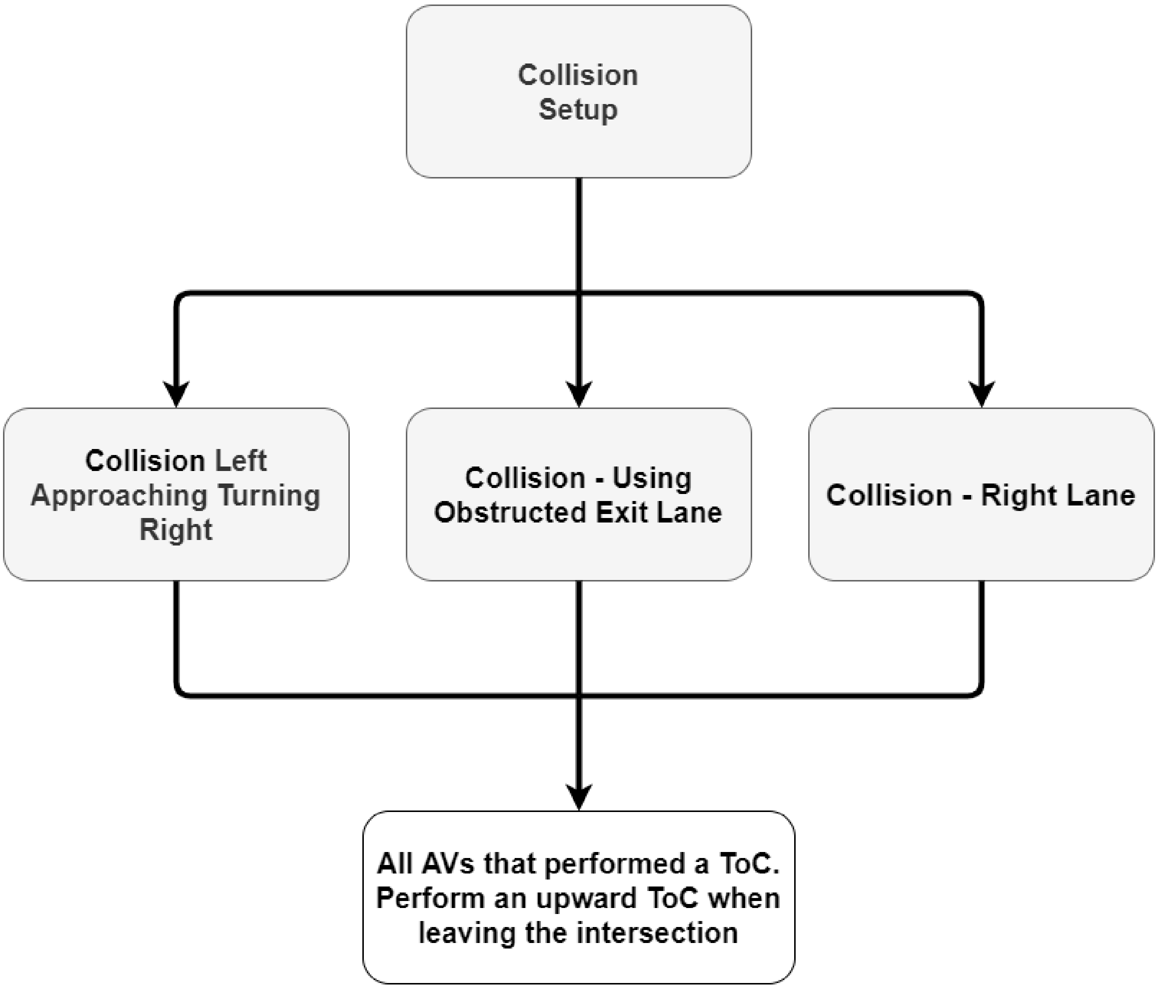


Figure B.1: Supplies an overview of the TMS. The grey elements in this Figure refer to Figure B.2, B.3, B.4 and B.5

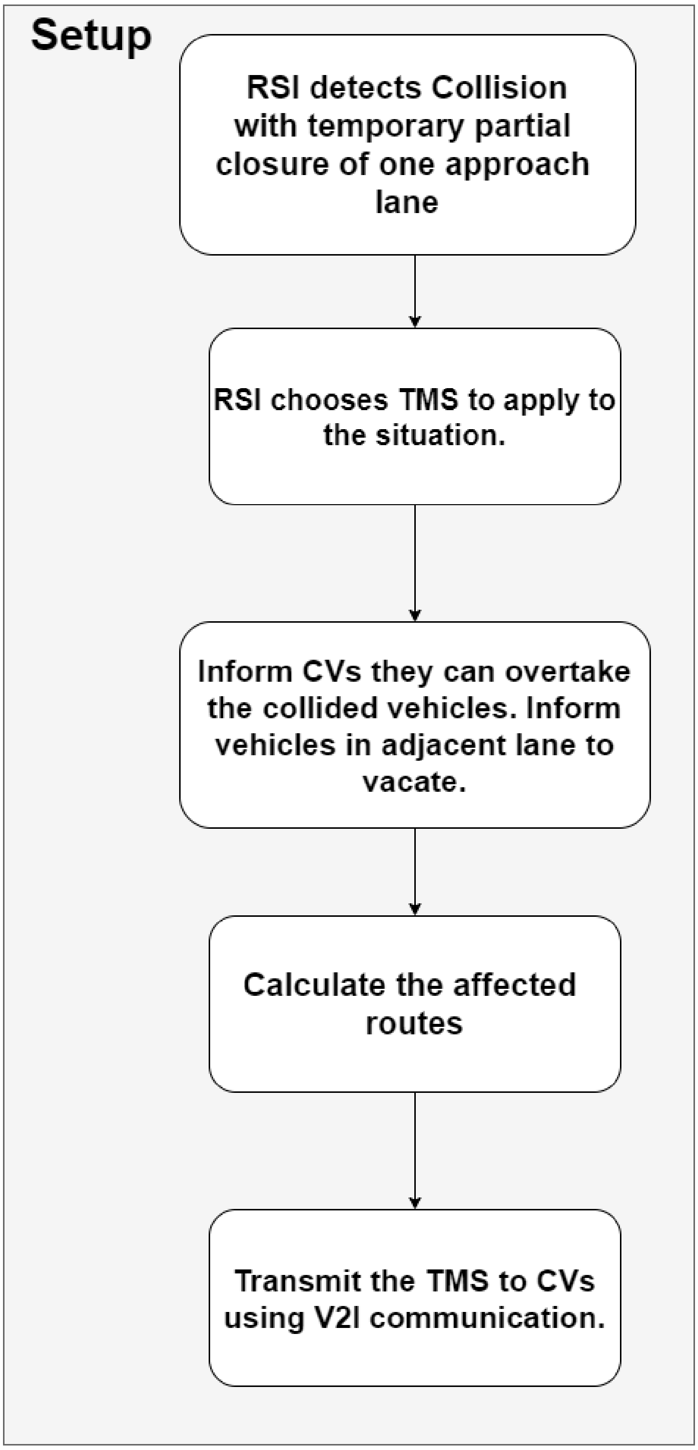


Figure B.2: The actions of the RSI

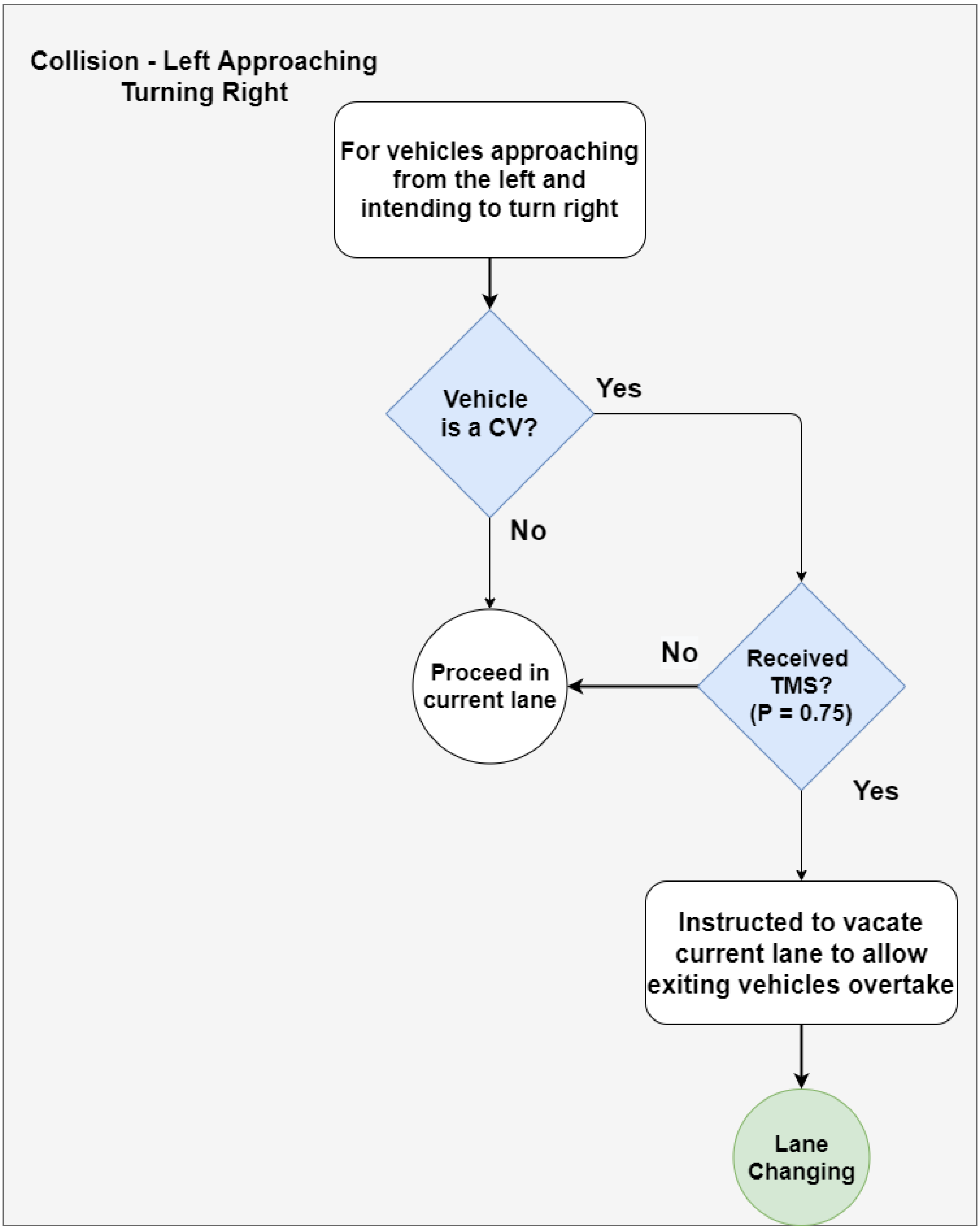


Figure B.3: The behaviour of vehicles approaching from the left and intending to turn right. The green element refers Figure A.7

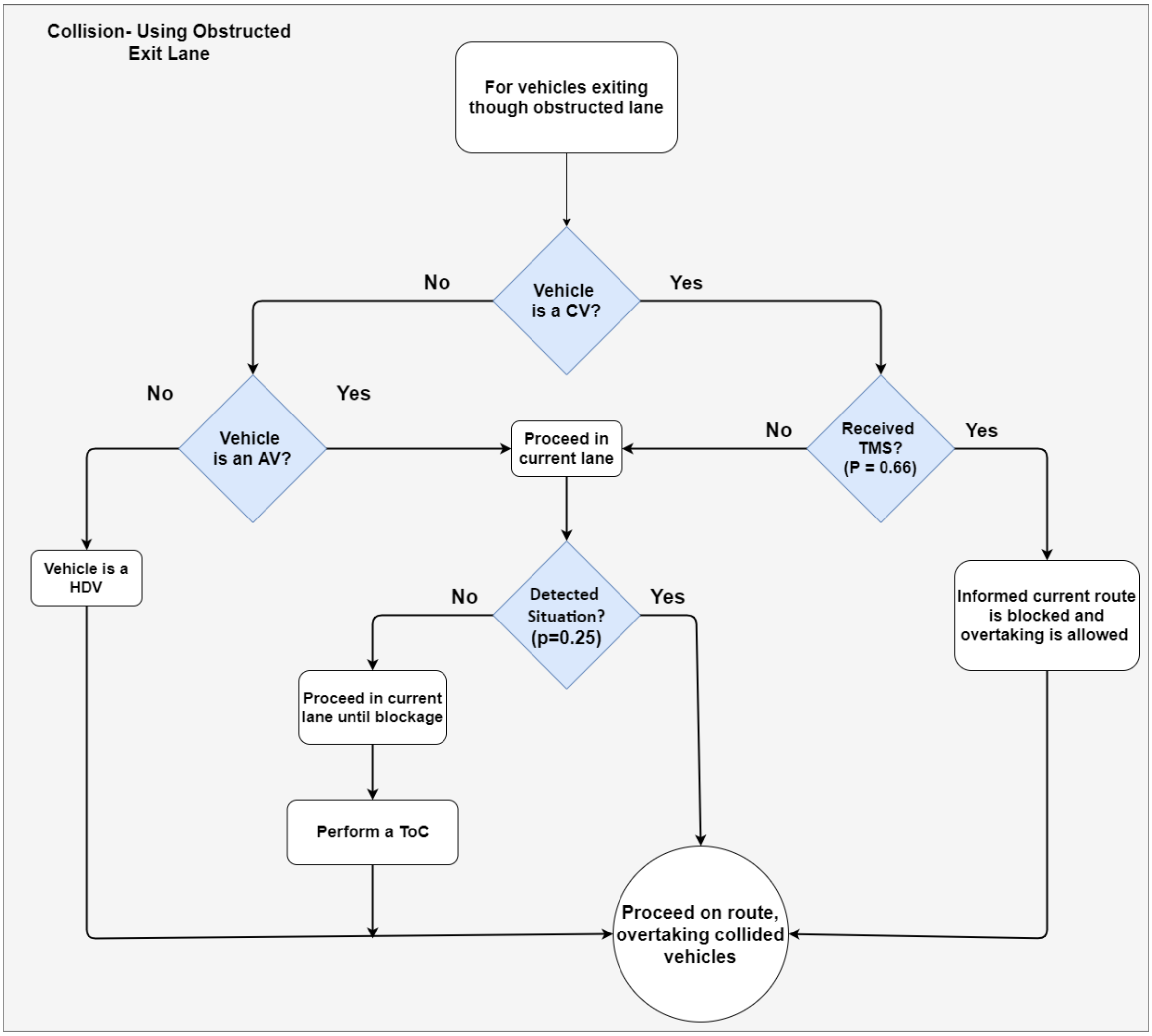


Figure B.4: The behaviour of vehicles intending to use the obstructed lane

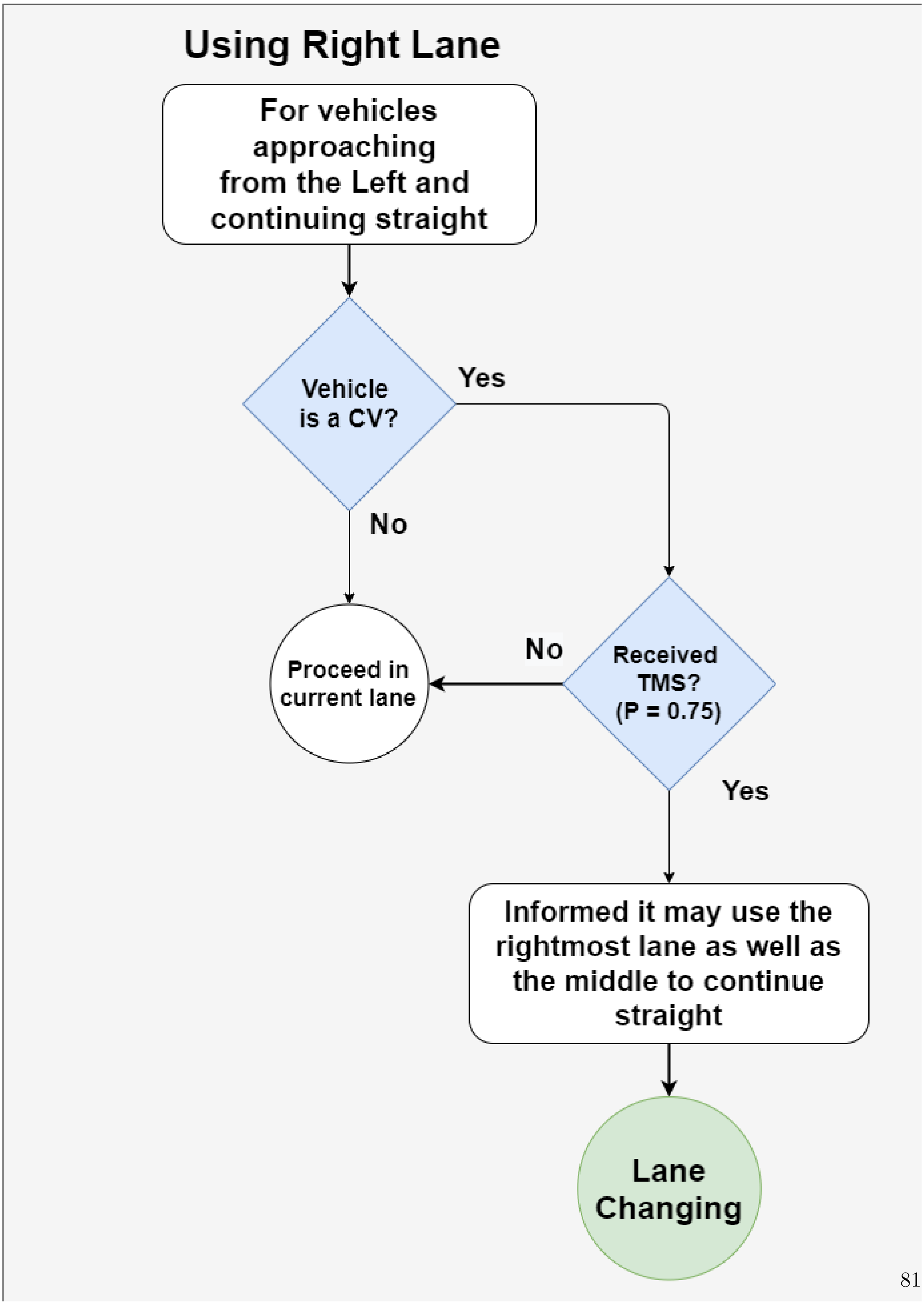


Figure B.5: The behaviour of vehicles using the right lane. The green element refers to Figure A.7

C Appendix C

Parameter	Definition	SAE-L0
length (m)	Length of the vehicle	5
width (m)	Width of the vehicle	1.8
vClass	SUMO Vehicle class	passenger
carFollowModel	Controls vehicles headway and speed fluctuations	Krauss
decel(m/s^2)	Standard deceleration of the vehicle	normal(3.5, 1.0); [2.0, 4.5]
accel(m/s^2)	Standard acceleration of the vehicle	normal(2.0, 1.0); [1.0, 3.5]
sigma	Driver's faults	normal(0.2, 0.5); [0.0, 1.0]
speedFactor	The vehicles expected multiplicator for lane speed limits	normal(1.1, 0.2); [0.8, 1.2]
emergencyDecel (m/s^2)	Max acceleration of the vehicle	9.0
lcAssertive	Tolerance of taking lower front and rear gaps	normal(1.2, 0.05); [1.1, 1.3]
tau (s)	normal(0.6, 0.5); [0.5, 1.6]%	0.6%
actionStepLength (s)	The length of time taken for the vehicle to perform its decision logic i.e., acceleration and lane changing	0.1
emissionClass	Time taken for the driver to gain control of the vehicle after a TOR	HBEFA3/PC$_{GE}U4$

Table C.1: The driving parameters used by SAE Level 0 vehicles. Values were obtained from Mintsis et al. [7]

Parameter	Definition	SAE-L2
length (m)	Length of the vehicle	5
width (m)	Width of the vehicle	1.8
vClass	SUMO Vehicle class	custom1
carFollowModel	Controls vehicles headway and speed fluctuations	(C)ACC*
decel(m/s^2)	Standard deceleration of the vehicle	normal(3.0, 1.0); [2.0, 4.0]
accel(m/s^2)	Standard acceleration of the vehicle	normal(2.0, 1.0); [1.0, 3.5]
emergencyDecel (m/s^2)	Max acceleration of the vehicle	9.0
lcAssertive	Tolerance of taking lower front and rear gaps	normal(1.2, 0.05); [1.1, 1.3]
tau (s)	Minimum time headway%	0.6%
actionStepLength (s)	The length of time taken for the vehicle to perform its decision logic i.e., acceleration and lane changing	0.1
emissionClass	Time taken for the driver to gain control of the vehicle after a TOR	HBEFA3/PC$_{GE}U4$
initialAwareness	The drivers awareness after a ToC	normal(0.7, 0.2); [0.6, 1.0]
responseTime (s)	Time taken for the driver to gain control of the vehicle after a TOR	1.5
tauCACCToACC	Minimum time headway when switching from CACC to ACC	normal(1.5,0.2); [1.1,2.0]
mrmDecel(m/s^2)	Deceleration of the vehicle during an MRM	3.0
dynamicToC-Threshold (s)	The time a vehicle can remain in its current lane before before performing a ToC	normal(9.0, 0.5); [8.0, 10.0]
Manual Driving mode	Vehicle type after performing a ToC	L0-HDV

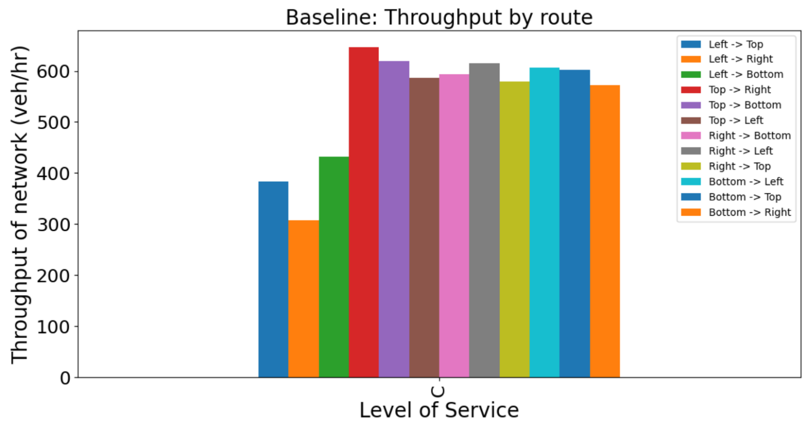
Table C.2: The driving parameters used by SAE Level 2 vehicles. Values were obtained from Mintsis et al. [7]

Parameter	Definition	SAE-L4
length (m)	Length of the vehicle	5
width (m)	Width of the vehicle	1.8
vClass	SUMO Vehicle class	custom1
carFollowModel	Controls vehicles headway and speed fluctuations	CACC
decel(m/s^2)	Standard deceleration of the vehicle	normal(3.0, 1.0); [2.0, 4.0]
accel(m/s^2)	Standard acceleration of the vehicle	normal(2.0, 1.0); [1.0, 3.5]
emergencyDecel (m/s^2)	Max acceleration of the vehicle	9.0
lcAssertive	Tolerance of taking lower front and rear gaps	normal(0.85, 0.02); [0.8, 0.9]
tau (s)	Minimum time headway%	0.6%
actionStepLength (s)	The length of time taken for the vehicle to perform its decision logic i.e., acceleration and lane changing	0.1
emissionClass	Time taken for the driver to gain control of the vehicle after a TOR	HBEFA3/PC$_{GE}U4$
initialAwareness	The drivers awareness after a ToC	normal(0.6, 0.2); [0.3, 1.0]
responseTime (s)	Time taken for the driver to gain control of the vehicle after a TOR	normal(4, 2.0); [2, 15]
tauCACCToACC	Minimum time headway when switching from CACC to ACC	normal(1.5,0.2); [1.1,2.0]
mrmDecel(m/s^2)	Deceleration of the vehicle during an MRM	3.0
dynamicToC-Threshold (s)	The time a vehicle can remain in its current lane before before performing a ToC	normal(9.0, 0.5); [8.0, 10.0]
Manual Driving mode	Vehicle type after performing a ToC	L0-HDV

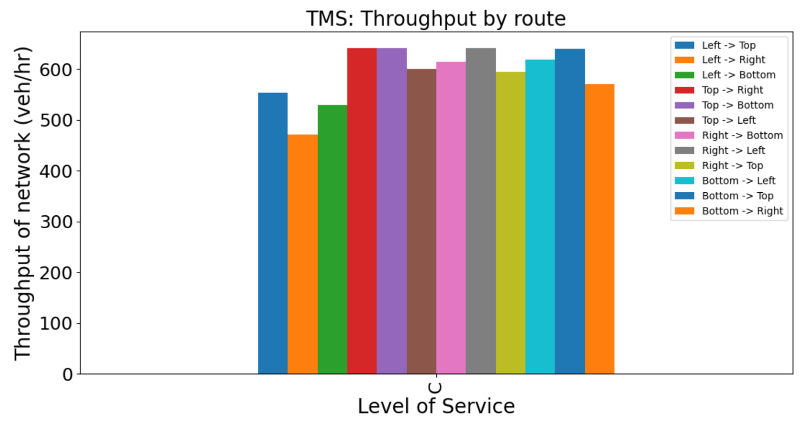
Table C.3: The driving parameters used by SAE Level 4 vehicles. Values were obtained from Mintsis et al. [7]

D Appendix D

D.1 Use Case A

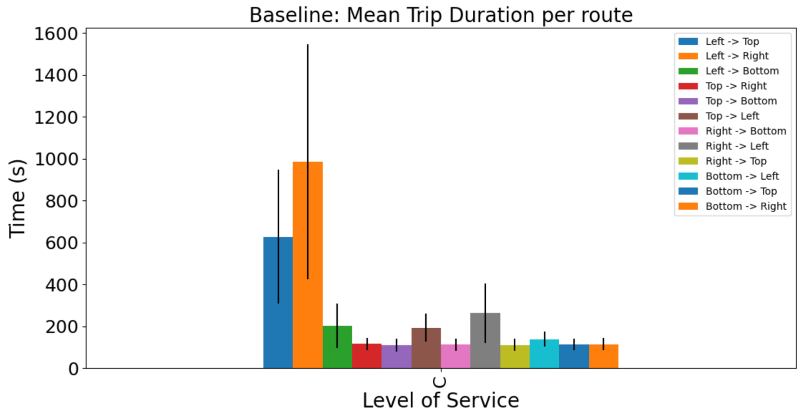


(a) Baseline

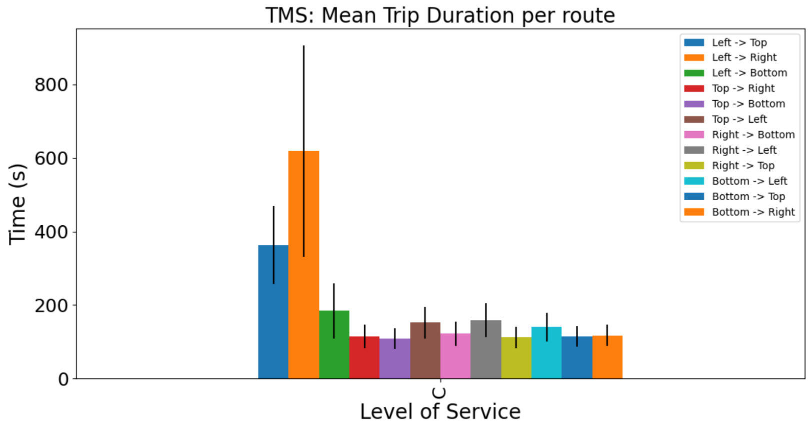


(b) TMS

Figure D.1: The total Throughput of the intersection separated by the routes the vehicles took for Penetration 3, LOS C across all iterations



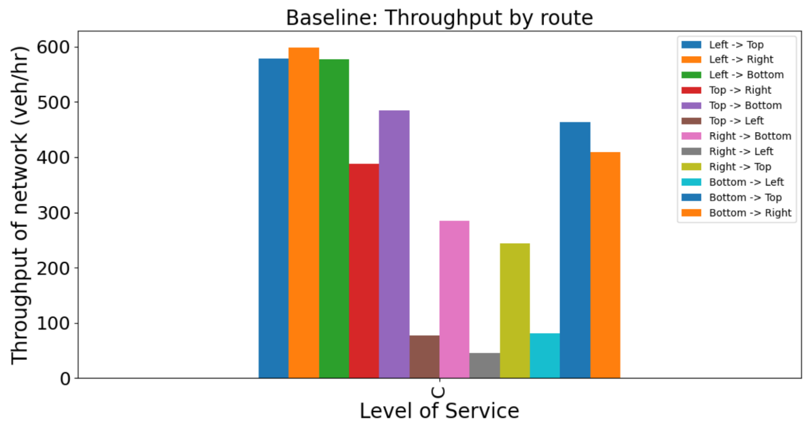
(a) Baseline



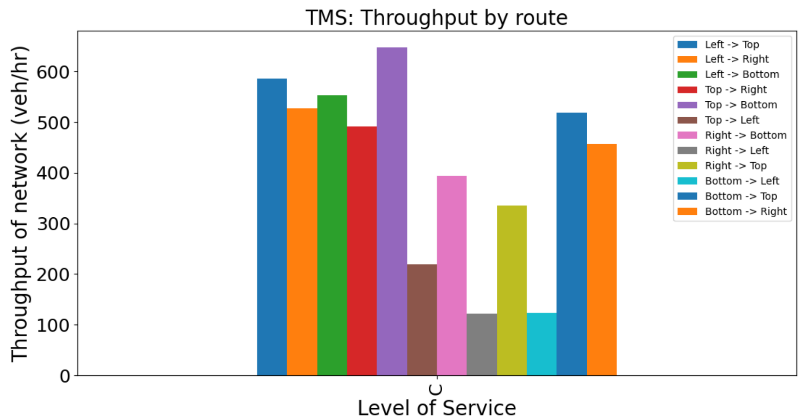
(b) TMS

Figure D.2: The mean trip duration of the intersection separated by the routes the vehicles took for Penetration 3 at LOS C

D.2 Use Case B

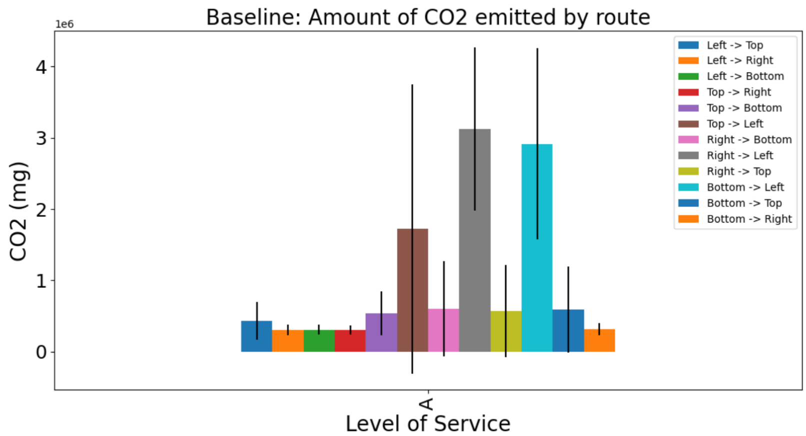


(a) Baseline

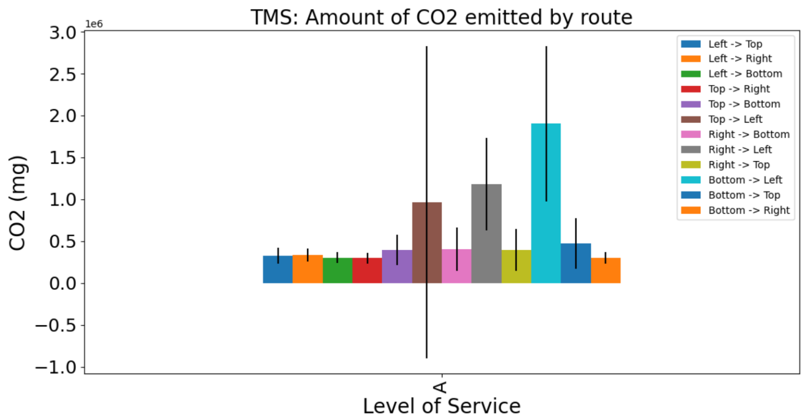


(b) TMS

Figure D.3: The total Throughput of the intersection separated by the routes the vehicles took for Penetration 100% L4-CV at LOS C across all iterations



(a) Baseline



(b) TMS

Figure D.4: The average CO_2 emitted by vehicles separated by the route taken. For Penetration 100% L4-CV with rerouting at LOS A