The Managed Motorway: Studying the Effectiveness of a Dedicated Lane for Connected and Autonomous Vehicles on Motorways

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Master in Computer Science

Supervisor: Vinny Cahill

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Declaration

I, the undersigned, declare that this work has not previously been submitted as an exercise for a degree at this, or any other University, and that unless otherwise stated, is my own work.

Alex Kennedy

April 19, 2022
The Managed Motorway: Studying the Effectiveness of a Dedicated Lane for Connected and Autonomous Vehicles on Motorways

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University of Dublin, Trinity College, 2022
Supervisor: Vinny Cahill

Abstract
It is well known that motorways can suffer from congestion, especially during peak times. Connected and Autonomous Vehicles (CAVs) have the ability to synchronise driving due to communication between vehicles. Studies show that at high penetration rates of CAVs, improved travel rate and reduced road conflicts are seen. However, at lower penetration rates travel rate is worsened when human-driven vehicles (HDVs) and CAVs share the same road space. The number of conflicts also increases at lower CAV penetration rates. It is important that the transition period between HDVs and CAVs does not have a negative impact on travel rate and road safety. This project proposes a solution to this which is to utilise a dedicated lane for CAVs to travel on while they are on the motorway. This project aims to evaluate the effectiveness of a dedicated lane on a section of motorway by simulation. The implementation of this project is developed using Simulation of Urban MObility (SUMO), an open-source traffic simulation software and an API called Traffic Control Interface (TraCI) to directly manipulate vehicle’s lane changing behaviour. This project will build upon the work of (Guériau and Dusparic (2020)), using their work of a seven kilometre stretch of the M50 motorway network in Dublin containing two intersections with on-ramps and off-ramps. The dedicated lane on the M50 motorway will be simulated using induction loops (detectors) to identify vehicle types and using the TraCI API to perform the lane-changing behaviours on CAVs, directing them to the dedicated lane. The CAVs will spend as much time on this lane as possible. Another experiment looks at allowing heavy goods vehicles (HGVs) with CAV capabilities onto the dedicated lane in conjunction with passenger CAVs. The results obtained show that travel rate and conflicts worsen at low penetration and at high penetration rates. Compared to the baseline, 30% penetration rate showed similar results in travel rate, except in areas where CAVs were weaving back into regular lanes to exit through off-ramps. The number of conflicts was also higher in the dedicated lane simulation than the baseline at these junctions. Further work is needed to allow for smarter merging strategies for CAVs.
I would like to thank my project supervisor, Professor Vinny Cahill for the advice he provided to me throughout the project. The biweekly meetings with him really helped keep me on track with the project.

I would also like to thank my family for their continued support not only during my final year in college, but also throughout the entire five years I have been studying in Trinity College Dublin.

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Chapter 1

Introduction

This project aims to investigate the effects of reserving a dedicated lane for Connected and Autonomous Vehicles (CAV) on a motorway. Two metrics will be used to evaluate the effectiveness of these lanes:

- Travel rate, which refers to the time taken for a vehicle to travel a kilometre on different sections of the motorway.

- Time-to-collision (TTC) conflicts that occur on the motorway, a type of conflict which can be used for recording car-following collisions such as rear-end collisions (Naseralavi et al. (2013)).

The project is adapted from (Guériau and Dusparic (2020)), which models varying penetration rates of CAVs on a section of the M50 motorway during a 24 hour period and their effect on travel rate and conflicts created using SUMO. This project will investigate the performance of replacing the fast lane (right-hand lane) with a lane that is reserved for passenger CAVs by evaluating the travel rate and conflicts on the motorway over different periods of congestion such as during rush-hour and more quiet times.

1.1 Project Motivation

It seems that autonomous driving is becoming more and more popular, which can be seen with the increase in the number of these vehicles on the road like Teslas, which have been increasing year over year as seen in Figure 1.1.

Because of the unpredictability of human nature (Lieberman (2013)), humans’ driving behaviours can differ from one another. Different drivers may perform vastly different actions for the same scenario. These varying driving behaviours, in addition to increased
traffic volume at peak times, can lead to congestion, reducing traffic throughput as well as potentially increased risk of road incidences as seen in (Li et al. (2020)) which reports increased driver aggression after congestion periods. This is especially true on motorway road networks as there can be bottlenecks at off-ramps and on-ramps (Afrin and Yodo (2020)), causing congestion. Traffic performance may increase if driving behaviour was synchronised. This could be done through communication between vehicles.

Connected and Autonomous Vehicles (CAVs) are autonomous vehicles that are capable of communicating with each other. According to studies (Guériau and Dusparic (2020)) and (Papadoulis et al. (2019)), higher penetration rates of CAVs (> 20%) are shown to improve travel rate of vehicles and also reduce the number of conflicts, increasing road safety. (Guériau and Dusparic (2020)) also finds that the types of conflicts that are most prevalent in high penetration rates are conflicts between HDVs. This project proposes reserving a lane dedicated to passenger CAVs to test the effectiveness of this approach on a simulated motorway network. The reasoning behind this is to investigate if these vehicles will be able to travel faster along the motorway with as little human driver interference as possible, until CAVs need to leave the motorway through an off-ramp. Penetration rate refers to the percentage of CAVs on the road in relation to total vehicles.

\[
PenetrationRate = \frac{\text{numCAV}}{\text{totalVehicles}} \times 100
\] (1.1)
1.2 Research Question

While there is a transition period when HDVs and CAVs co-exist on the roads, using the results of Guériau and Dusparic (2020) as a baseline does implementing dedicated lanes for CAVs help to improve travel rate on motorways as well as helping to improve road safety by reducing the number of TTC conflicts on the road?

1.3 Overview of Project

This section gives a brief overview of the entire project, including the experiments performed. Another discussion is whether or not the the proposed solution of the project should be implemented in the real-world and if it should be implemented, what are the potential benefits it may have.

1.3.1 Research Approach

This project aims to evaluate the effectiveness of dedicated lanes for CAVs on motorways in terms of the average travel rate for vehicles and the number of conflicts recorded on the roads. The specific objectives of this project are as follows:

- Adapt the study (Guériau and Dusparic (2020)) on the performance of different levels of CAVs on the M50 motorway in Dublin, Ireland, to reserve a lane for passenger CAVs on the motorway i.e. replace the right-hand lane with a dedicated lane for CAVs.

- Implement these changes using SUMO traffic simulation software and TraCI (Traffic Control Interface).

- Plot and evaluate the results from the simulations using different volumes of CAVs on the motorway.

- Derive conclusions on the effectiveness of dedicated lanes for CAVs from the experiments performed.

1.3.2 Experiments Performed

The experiments performed in this project consist of applying different penetration rates of CAVs to utilise in the dedicated lane. The penetration rates used in the project are 10%, 20%, 30% and 70%. Another experiment performed is investigating the effects of allowing
heavy goods vehicles (HGVs) which have CAV capabilities (CATs) on the dedicated lane in conjunction with CAVs.

1.3.3 Potential Benefits of Research

If the research produces a positive result, a potential benefit if the research from this project were to be implemented is improving the travel rate on motorways for vehicles. This would have extended benefits such as reducing carbon emissions produced by vehicles as they will not be on the road for as long which can be seen in (Hamad and Alozi (2022)) which shows that high CAV penetration rates (> 40%) in dedicated lanes can reduce carbon emissions.

However, if the research produces some negative results compared to the baseline, this research can provide some insight into some of the concerns with dedicated lanes for CAVs on motorways.

1.3.4 Report Overview

The report is structured as follows: First, the report will discuss different aspects of related research about CAVs, levels of automation and the technologies utilised in the project. After this, the implementation of the dedicated lane will be described along with any challenges or issues that were encountered during the course of the project. The results and evaluation of the simulations of the dedicated lane for CAVs on motorways will then be discussed. The final section of the report will outline any future work which could be built on the work completed in this project.
Chapter 2

Background

This chapter discusses different areas of research which are related to the project. It first looks at relevant information regarding CAVs like level of automation, vehicular communication, car-following structures of CAVs and mixing trucks with CAV capabilities with passenger CAVs. It is important to go into detail about the technology behind CAVs to gain a better insight into the benefits of them. Then it looks at existing research in the sector of dedicated lanes for CAVs. The simulation software and third party tools used are also discussed.

2.1 Relevant Research

CAVs utilise both automation and connectivity in order to allow vehicles to drive with little to no human intervention. This section discusses some of the underlying technologies behind CAVs in terms of automation and communication.

2.1.1 Level of Automation in CAVs

When it comes to CAVs, studies tend to assume different levels of automation for their simulations. In general, there are six automation levels used in describing driving automation. Figure 2.1 showcases the different levels of automation.

It seems that the levels studies want to test with are level 2 and 4. This can be seen in (Guériau and Dusparic (2020)), which tests with level 2 and 4 CAVs. The reason for this is that achieving level 5, full automation of motor vehicles is still a very long way from becoming the norm on the roads. The reason for this is that level 5 refers to complete automation with no human interaction. These kinds of vehicles would need to be able to handle every edge case that could occur on the road to which a human may be able to
Figure 2.1: Different levels of driving automation (Synopsys (nd)). Level 2 still requires human interaction and attention on the road, whereas level 4 automation requires little to no human interaction.

react, even unlikely scenarios. According to Wang et al. (2021), there is little research on transferring human driving behaviours to high-level automation driving systems. Level 3 automated vehicles are also advised against due to the driver having to remain in control of a more advanced system, which could lead to drivers not monitoring their driving environments as well according to Seppelt and Victor (2016). However, more and more cars are becoming level 2, and organisations are beginning to develop prototypes of level 4 automated cars (Ramey (2021)). So it is more realistic to choose these kinds of CAVs to run simulations.

2.1.2 Inter Vehicle Communication

Inter-Vehicle Communication (IVC) refers to the ability of multiple vehicles to communicate with each other on the road by sending and receiving data. IVC would benefit many different vehicle applications, including collision avoidance, passing assistance, and platooning (Sichitiu and Kihl (2008)). According to Willke et al. (2009), IVC can potentially be supported by the use of vehicle ad hoc networks (VANETs). VANETS do not require fixed infrastructure and are more adaptable to ever-changing network structures (Willke et al. (2009)). VANETs are typically grouped based on their transmission distance between vehicles: short-range, medium-range and long-range.

(Ahangar et al. (2021)) describes in detail the different kinds of IVC technologies and
their applications when it comes to CAVs. Short-range VANETs have the benefits of having low latency but are hindered by the distance that data can be transmitted. So, the features which these low range technologies like UWB could be used for are forward-collision warning, toll-check and vehicle identification. However, for automated driving longer-range technologies are needed. The study suggests that medium-range VANETs like Wi-Fi and DSRC would ultimately not be suitable for use in automatic vehicles due to issues with congestion from an increase in communication load, which can degrade network performance in terms of packet loss. The study concludes that for any sort of automated driving and effective communication between vehicles, long-range communication methods which make use of 5G-based technology would be the most suitable.

(Zhong et al. (2021)) found that the DSRC communication density was lower on dedicated CAV lanes rather than on regular driving lanes. This was due to a lower traffic density in CAV platoons when separated from HDVs, causing V2V communication to break down less. This shows that congestion issues on medium-range communication systems could potentially be avoided if roads made use of dedicated CAV lanes.

2.1.3 Platooning

Platooning is a layout of interconnected CAVs (making use of IVC) in a single file position with a smaller safety distance between each other than regular human-driven cars. These
vehicles can constantly communicate with each other in order to improve road safety and traffic efficiency. The platoon is essentially a ‘Follow the Leader’ protocol where every vehicle behind the leading vehicle copies the actions of the leader vehicle. A general structure of platooning consists of four components, as described in Figure 2.3.

There has been quite a lot of work published on the performance and impact of platooning CAVs. Many of these studies are done with simulations. (Fernandes and Nunes (2010)) runs a SUMO simulation of a 5km stretch of road with eight cars in a platoon and looks at how communication delays affect the platoon. The leader of the platoon will inform the other vehicles of its next plan (e.g. lane change) and will not make a move until all other vehicles in the platoon are aware of the subsequent actuation. However, new approaches to this model are needed for dangerous situations like a sharp decline in the leading vehicle’s speed. The platoon leader’s decision may not be communicated to the rest of the platoon in time if the leading vehicle needs to make an emergency stop.

2.1.4 Cooperative Adaptive Cruise Control

Cooperative Adaptive Cruise Control (CACC) is another CAV following structure that is currently being researched and investigated. Like platooning, vehicles in a CACC formation will follow each other in a single file manner. However, there are some distinctions
between the two methods, which are showcased in Table 2.1.

A group of vehicles utilising CACC are said to be in a string rather than a platoon.

<table>
<thead>
<tr>
<th>Platooning</th>
<th>Cooperative Adaptive Cruise Control</th>
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<tbody>
<tr>
<td>Uses a constant distance gap strategy</td>
<td>Uses a constant time gap following strategy</td>
</tr>
<tr>
<td>Hierarchical control with a platoon leader</td>
<td>Uses <em>ad hoc string formation</em>, decentralised control</td>
</tr>
</tbody>
</table>

Table 2.1: Table showcasing the differences between platooning and CACC (Lu et al. (nd)).

This is because of the constant time gap strategy used by CACC, which makes the distance between vehicles proportional to their speed (Nowakowski et al. (2015)). CACC is seen to be an improvement to the already widely implemented Adaptive Cruise Control (ACC), which will change the vehicle’s speed depending on the distance of the vehicle in front of it. There is no IVC in ACC and so, the ability for vehicles to maintain a stable string is greatly hindered due to the fluctuations in speed due to acceleration and breaking of preceding vehicles, which the driver’s vehicle has no prior knowledge of without IVC. California PATH has done field studies investigating the differences in performance of ACC and CACC in trucks. (California PATH (nd)) contains videos of a field study testing out the viability of CACC using 5g communications. In a string of 5 cars of ACC, there were significant delays in the braking of the cars at the back of the string when the leading car in the string began to reduce speed, resulting in string instability. The vehicles were then equipped with CACC capabilities and were successfully able to travel at the same speed as the leading car through 5g communications.

2.1.5 Mixed Vehicle Types in Dedicated Lane (Cars and Trucks)

Cars and trucks (heavy goods vehicles) perform very differently on the road from each other. Trucks have slower acceleration and require more braking distance to stop completely than passenger cars. This is due to the power to weight ratio being lower than cars. Because of these differences, it may be challenging to provide a single dedicated lane for both CAVs and CATs. (Lu (2018)) shows in its field study that it is currently difficult to maintain a stable CACC string between trucks alone due to different braking distances from varying loads. Adding passenger CAVs into these lanes would most likely cause further issues. Therefore, it would most likely be more beneficial to restrict a dedicated lane for CAVs to passenger vehicles. This scenario is tested in this project where both CAVs and CATs will be directed to drive on the dedicated lane as an additional experiment.
2.2 State of the Art

Research on dedicated lanes for CAVs is essential as there will be a transition period where CAVs and human-driven vehicles (HDVs) will be on the road at different volumes. Current work studies the effectiveness of dedicated lanes for CAVs versus shared lanes for CAVs and HDVs. (Ye and Yamamoto (2018)) looks at studying the effects of traffic throughput with a CAV dedicated lane in a three-lane road compared to three shared lanes. This study found that at low penetration rates of CAVs (0% - 20%), traffic throughput worsened compared to 3 shared lanes. Another interesting point found in (Ye and Yamamoto (2018)) is that it found that an additional dedicated lane should be added when penetration rates reach > 50%. In this project, only one dedicated lane will be added so high penetration rates may lead to more congestion on the dedicated lane. The study also only looks at lane changes on straight lanes and does not take into account CAVs having to exit the dedicated lane to get to an off-ramp. This project looks at directing CAVs to off-ramps from the dedicated lane. (Ye and Yamamoto (2018)) also doesn’t investigate the effectiveness of dedicated lanes in terms of road conflicts. This project investigates how a dedicated lane can affect potential road conflicts.

However, traffic throughput improved when higher volumes of CAVs occupied the road (CAV penetration rate > 40%). (Hamad and Alozi (2022)) compares the performance of shared lanes for CAVs and HDVs and dedicated lanes for CAVs and found that traffic delays and throughput improve at a CAV penetration rate of >30% and continue to improve as volume increases. In terms of traffic throughput, the study also concludes that shared lanes perform better in low volume traffic while dedicated lanes perform better in high volume traffic. This could be due to unnecessary lane changes for CAVs to navigate to dedicated lanes as at low traffic volumes most vehicles will drive at free flow speeds.

Another question to ask is how dedicated lanes and regular lanes should be separated from each other. There are three main types of separation between dedicated lanes and regular lanes: A virtual barrier in the form of a paint stripe clearly indicating the two lanes, a buffer zone that would contain a varying amount of space between the two lanes and a physical barrier which would physically separate the two lanes with transition spaces when approaching different on/off ramps or exits (Razmi Rad et al. (2020)). A concern to look at when placing dedicated lanes with CAVs and regular lanes containing human drivers is whether the regular drivers’ behaviour is altered when in the presence of a high amount of CAVs. (Razmi Rad et al. (2020)) found that dedicated lanes for CAVs placed next to regular lanes with no physical barriers, regular drivers began to drive more closely
to the vehicles in front of them when in the lane adjacent to the dedicated lanes. Drivers were influenced by the actions of platooning CAVs adjacent to them.

2.3 Technologies Used

This section discusses some of the applications and third party tools used to develop this project.

2.3.1 SUMO

Simulation of Urban MObility (SUMO) is a microscopic (vehicle movement modelled off of car-following and lane-changing behaviours), multi-modal traffic flow simulation software that is open source. It is used to create models of road networks and run complex simulations of vehicle behaviour. The software can model many different vehicle classes (e.g. passenger cars and trucks), public transport, trains and pedestrians. The software allows for complex vehicle type customisation but also comes with a large number of predefined vehicles and car-following models. SUMO also comes with an easy to use GUI, which allows users to observe vehicle behaviour during different steps of simulations. The main objects and attributes in SUMO that are used in this project are as follows:

Vehicle Types

The vehicles within the simulation for this project are defined into two main types.

- Passenger vehicles. These represent the standard 5-7 passenger cars found on the road. These vehicles are named 'PKW' (personenkraftwagen - passenger vehicle).

- Trucks. These vehicles consist of large goods vehicles such as lorries. These vehicles are named 'LKW' (lastkraftwagen - heavy goods vehicle).

PKW and LKW are known as vehicle type distributions and describe a group of similar vehicles. In this case, each distribution contains three different vehicle types (HDV, level 2 CAV and level 4 CAV). The main attributes of a vehicle type are as follows:

- ID

  - An ID is a reference to the type of vehicle. For example, 'CAV4' is classed as a passenger CAV with level 4 automation and CAT4 is classed as a CAT with level 4 automation. 'HDC' is classed as a human-driven vehicle in the project.

SUMO docs: https://sumo.dlr.de/docs/index.html
• vClass
  - Describes a vehicle class defined by SUMO, which contains predefined parameters about the vehicle. Examples of vClass are ’passenger’ and ’truck.’

• speedDev
  - Speed deviation. A multiplier is applied to each vehicle’s top speed to simulate a more realistic driving scenario. Not all drivers will be driving at the exact same speed in the real world.

• carFollowModel
  - Describes the car-following model a vehicle has. Human-driven vehicles use the default car-follow model for SUMO, the Krauss model (Krauß (1998)). CAVs use the Intelligent Driver Model (IDM) (Treiber et al. (2000)) in this project.

• minGap
  - The minimum gap between a vehicle and the vehicle in front of it. This value is changed for CAVs as they will be able to drive with a smaller gap between vehicles. HDVs have the default 2.5m, CAV2 have 1.5m, and CAV4 have 1m for the simulations.

• tau
  - Tau is a parameter that affects car-following behaviour. It attempts to model a vehicle’s desired minimum time gap between a vehicle and its leader in front of it. By default, this value is 1.0 (used for HDVs). CAVs are given a smaller tau value.

• sigma
  - Sigma is another car-following parameter, a value between 0 and 1 used to describe driver imperfection. A value of 0 represents perfect driving. CAVs are assumed to be better drivers than HDVs so, they will have a lower sigma value.

• probability
  - The probability attribute denotes the likelihood of a vehicle type (HDV or CAV) from a specific vehicle distribution. It must be a value between 0 and 1 and the sum of the probabilities for that specific vehicle distribution must equal 1.0. This is used to define different penetration rates of CAVs.
Each vehicle is also attached with an SSM device. This device is used to record conflicts between vehicles. The SSM device can record different kinds of conflicts. In the case for this project, the TTC conflict is measured. This type of collision is widely used for recording rear-end collisions (Naseralavi et al. (2013)). Assigning each vehicle type an SSM device gives the option of setting different TTC thresholds for CAVs and HDVs. It is assumed that CAVs will be able to drive closer together on the road. For this project, CAVs are given a TTC threshold of 0.75 (s) and HDVs are given a TTC threshold of 1.5 (s).

**Vehicle**

Vehicles are the objects of the simulation, which represent real-world vehicles. They are extremely important as they are the actors of the simulation. Each vehicle is predefined in an emitters file which contains a list of all vehicles to be inserted in the simulation. As before, here are the essential attributes associated with each vehicle.

- **ID**
  - A unique identifier associated with the vehicle.

- **type**
  - The vehicle type distribution that is associated with the vehicle. Either 'PKW' or 'LKW'.

- **depart**
  - This parameter denotes the time that the vehicle will be inserted into the simulation.

- **departLane**
  - The lane at which the vehicle will be inserted into the simulation. The parameter used in this project is 'best'. This value will insert the vehicle into the lane which will allow the vehicle to drive the longest without changing lane.

- **departPos**
  - The departing position of the vehicle on the first edge in its route. For this project, every vehicle is given the value 'random_free'. This value will try to place the vehicle at a random position on their departing edge ten times. If these random choices are not suitable (i.e. a vehicle is already driving on the position), then it will place the vehicle on any position that is currently free.
• departSpeed
  – The speed the vehicle will be travelling at when it is inserted into the simulation. Here, the departing speed of the vehicle will be its max as it is being inserted into the middle of the M50 motorway. So it is assumed the vehicle would have been at a high speed when it entered the simulation.

• arrivalPos
  – The position where the vehicle will leave the road network and will be removed from the simulation. The value set for this parameter in this project is set as ‘max’, which will force the vehicle to drive to the very end of its destination edge.

• route
  – This is the id of the route that each vehicle will drive along. The route object is described later.

Edges & Lanes

Edges in SUMO act as a section of road and are created by connecting two nodes together. Each edge can have a different number of lanes assigned to it. Edges are essentially roads in the network. Vehicles are able to switch between lanes on an edge freely. Edges are used to create the routes that vehicles will drive on while in the road network. Figure 2.4 shows the general layout of an edge in SUMO.

Lanes are nested within an edge tag. Here are the crucial attributes associated with lanes.

• ID
  – Unique identifier for each lane. Typically, each lane will have the same name as its edge with the addition of an index at the end. For example, a lane in the edge ‘testEdge’ will have an ID of ‘testEdge_0’.

• index
  – The index of the lane inside an edge. The first lane in an edge will have an index of 0, and the final lane will have an index of n-1 where n is the number of lanes in an edge.

• speed
Figure 2.4: General Layout of an edge in SUMO. Two connecting nodes create the edge. The lanes on each edge will typically be uni-directional.

- The speed in m/s that is permitted on the specified lane.

- length
  - The length of the lane in metres.

Routes

Routes in SUMO connect edges to form a path that a given vehicle will drive along during the simulation. Routes of a simulation are stored in a '.rou.xml' file. It is important to note that routes must be connected. If the current edge is not directly attached to the next edge, an error will be thrown. The important attributes of a route are as follows:

- ID
  - A unique identifier is given to each route in a route file.

- edges
  - The edges that are contained within a route. They are listed according to their ids. These are the edges that a vehicle will drive along.
2.3.2 TraCI

_Traffic Control Interface_ (TraCI) allows for access to a currently running SUMO simulation. It uses a client/server architecture using TCP to give access to SUMO. SUMO essentially acts as a server. This allows TraCI to take over the simulation and makes it possible to retrieve values about many different objects such as vehicle data, road network data and route data. The states of objects can also be changed from their defined states. For example, TraCI can direct vehicle lane changes. Many different programming interfaces have been developed for TraCI. In this project, the python library is used. Figure 2.5 shows a basic diagram on how TraCI communicates with a SUMO simulation.

![Diagram of TraCI communication](image)

Figure 2.5: The client will transmit a command to SUMO to influence a vehicle’s behaviour or to extract details. SUMO will return a status code response with the required information from the command. (German Aerospace Center (DLR) (nda)).
Chapter 3

Implementation of Dedicated Lane

This chapter describes how the dedicated lane for CAVs was created for the project. It takes a deeper look into how the Traffic Control Interface (TraCI) python API in SUMO is used to dynamically alter the behaviour of vehicles during simulation runtime and using induction loops to allow TraCI to extract information about vehicles that pass over these induction loops to check what kind of vehicle it is. The chapter will also detail the limitations of the solution and any challenges encountered while developing.

3.1 High-level Overview of Project

The implementation of the project makes use of TraCI to dynamically alter vehicle behaviour during simulation runtime. In order to decide which kinds of vehicles to direct to the dedicated lane, induction loops are used as detectors to give TraCI the necessary information to perform these lane changes. Different induction loops are looking to detect different vehicle types. The first kind of induction loop is checking whether a vehicle that has entered the motorway is a CAV. If it is, then TraCI will direct that vehicle to the dedicated lane. CAVs need to be directed back to a regular lane if they need to exit through an off-ramp. This is done by TraCI listening on induction loops placed near these exits. It will then check to see if a vehicle’s end edge in its route is on that exit and if it is, the vehicle will be directed off.

Sometimes, especially at the beginning of the simulation, HDVs will be on the dedicated lane. Induction loops have been placed periodically along the dedicated lane which are used by TraCI to check for HDVs. If there is a HDV that passes over one of these induction loops, TraCI will then redirect that vehicle off the dedicated lane to the lane next to it.
3.2 Simulation Process

All data used to create network simulations are composed of XML files, with each entity having a large number of editable attributes to alter the behaviours of these entities. The simulation is created by a '.sumocfg' file, an XML file that references all the necessary data files for the simulation, such as the network and route files. Additional files may also be referenced. These additional files may include other entities like detectors on the road. The 'sumo.cfg' file can also write to output files, giving statistics about the simulation. This output file is typically named 'tripinfo.out.xml' and contains information about a vehicle’s average speed, departure and arrival time, and vehicle type. TraCI is an API that uses a TCP based client/server system to allow direct access to running SUMO simulations. It allows for the retrieval of values and direct manipulation of vehicles during simulation run-time. TraCI is used in this project to identify CAVs and direct them to change to the dedicated lane and direct them back when they need to exit the motorway. The following figure shows the high-level file architecture of how SUMO runs the simulations for this project.

Figure 3.1: High-Level Overview of the simulation architecture. The initial XML files generate the simulation 'sumocfg' file. A TraCI python script is called to run the simulation on a server and will dynamically check attributes within the simulation. Once the simulation has finished, various output files are created to be used to visualise the results of the simulation.
3.3 Car Following Models

Varying vehicle types that are in the simulation make use of different car-following models that are implemented in SUMO. These models have default values given to them, which are slightly altered depending on the kind of vehicle. In general, car-following models are based on acceleration which determines how aggressive a vehicle will accelerate and decelerate in relation to vehicles in front of them (Treiber et al. (2000)). The two car-following models used in this project are the Krauss Car-following model (Krauß (1998)), created by Stefan Krauß and the Intelligent Driver Model (Treiber et al. (2000)) created by Martin Treiber.

3.3.1 Krauss Car-Following Model

The Krauss car-following model is described in (Krauß (1998)). The general approach that was taken to create this model was to model for two scenarios. The first was that when a vehicle is in free motion (i.e. not interacting with any other vehicle), it is constrained by some maximum velocity of

\[ v \leq v_{\text{max}} \] (3.1)

The other scenario is when a vehicle is interacting with other vehicles, the velocity of a vehicle should not exceed the maximum safety velocity given by

\[ v \leq v_{\text{safe}} \] (3.2)

The safe speed of a vehicle is calculated using the following equation (Song et al. (2014))

\[ v_{\text{safe}} = v_l(t) + \frac{g(t) - v_l(t)t_r}{v_l + v_f(t)} t_r + t_r \] (3.3)

\( v_l(t) \) is the speed of the leader vehicle during time \( t \). \( g(t) \) is the distance of the leader vehicle during time \( t \). \( t_r \) is described as the reaction time of the driver, and \( b \) is the deceleration of the vehicle. This model describes perfect driving behaviour, although that is not entirely realistic for human drivers as it is unrealistic for strings of human-driven vehicles to drive perfectly. SUMO contains the \( \text{sigma} \) parameter, which is used to model driving imperfections. This value is between 0 and 1, where 0 denotes perfect driving. Human-driven vehicles for this project are given a value of 0.5 while CAVs are given a value of 0.05.
3.3.2 Intelligent Driver Model

The acceleration of the Intelligent Driver Model (IDM) is calculated using two different equations. One compares the current speed of the vehicle to the desired speed and the other equation compares distance to the desired distance (Treiber and Kesting (2013)), the equations are written as follows:

$$\dot{v} = a [1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s}\right)^2] \quad (3.4)$$

$$s^*(v, \Delta v) = s_0 + \max(0, vT + \frac{s^* (v \Delta v)^2}{2 \sqrt{ab}}) \quad (3.5)$$

The parameters in these equations are described as follows: $a$ is the vehicle’s acceleration. $v$ is the vehicle’s current speed and $v_0$ is the desired speed. $s$ is the current distance of a vehicle from its leading vehicle, $s^*$ is the desired distance. $s_0$ is the minimum gap between the vehicle and the leading vehicle (bumper-to-bumper). $T$ refers to the time gap to the leading vehicle. $\delta$ is the acceleration exponent and $b$ refers to deceleration (Treiber and Kesting (2013)). In SUMO, the $\tau$ parameter for vehicle types is used to adjust the minimum gap for the IDM model that is integrated in SUMO itself.

<table>
<thead>
<tr>
<th>Krauss Car-Following Model</th>
<th>Intelligent Driver Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$</td>
<td>$v$ Current speed</td>
</tr>
<tr>
<td>$v_l(t)$</td>
<td>Velocity of leading vehicle in $t$</td>
</tr>
<tr>
<td>$g(t)$</td>
<td>distance of leading vehicle in $t$</td>
</tr>
<tr>
<td>$t_r$</td>
<td>Reaction time of driver</td>
</tr>
<tr>
<td>$b$</td>
<td>Deceleration</td>
</tr>
<tr>
<td>$s^*$</td>
<td>Desired distance</td>
</tr>
<tr>
<td>$s_0$</td>
<td>Minimum gap between vehicle and leading vehicle</td>
</tr>
<tr>
<td>$T$</td>
<td>Time gap to leading vehicle</td>
</tr>
<tr>
<td>$b$</td>
<td>Deceleration</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Acceleration exponent</td>
</tr>
</tbody>
</table>

Table 3.1: Table showcasing model parameters for Krauss (Song et al. (2014)) and IDM (Treiber and Kesting (2013))

3.4 Vehicles in the Simulation

3.4.1 Vehicle Types

There are a number of different vehicles used in this simulation adapted from (Guérin and Dusparic (2020)). The project uses both passenger vehicles and heavy goods vehicles.
Both vehicle types have three different vehicles (HDV, CAV level 2, CAV level 4) which have varying driving behaviours. HDVs make use of the Krauss Car-Following model (Krauß (1998)), simulating human driving behaviour (level 0 automation). Both CAV levels: level 2 automation and level 4 automation use the Intelligent Driver Model (Treiber et al. (2000)). Both CAV levels are assumed to be modelled with vehicle-to-vehicle (V2V) communication through parameters that have been tweaked on the CAVs. Although no V2V communication was implemented in SUMO as part of this project. Figure 3.2 shows how each vehicle looks when the simulation is run in the GUI. This is to allow observers to easily distinguish vehicles from each other when running the simulations.

Figure 3.2: The appearance of vehicle that is included in the simulation. HGVs are modelled to be larger than CAVs. This is useful to observe the types of vehicles entering the dedicated lane in the simulation.

### 3.4.2 Parameters of Vehicles

The vehicles in the simulation are created using microscopic modelling, which refers to the movement of the vehicles being controlled by car-following models and lane-changing
models. While these models have already been implemented in SUMO, parameters for both levels of automation have been tweaked so as to assume that level 4 automation is a safer and more efficient driver than level 2 automation. Because every CAV’s lane-changing model is effectively being manipulated to direct them to the dedicated lane, the CAV’s car-following model is the primary controller of the vehicle. Table 3.2 shows the different parameters values given to each vehicle which were described in Section 2.3, adapted from (Guériau and Dusparic (2020)).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HDV (car)</th>
<th>CAV2 (car)</th>
<th>CAV4 (car)</th>
<th>HDV (HGV)</th>
<th>CAT2 (HGV)</th>
<th>CAT4 (HGV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car-following model</td>
<td>Krauss</td>
<td>IDM</td>
<td>IDM</td>
<td>Krauss</td>
<td>IDM</td>
<td>IDM</td>
</tr>
<tr>
<td>Minimum Gap (m)</td>
<td>2.5</td>
<td>1.5</td>
<td>1</td>
<td>2.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Time Headway (s)</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
<td>1.5</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Max Acceleration (m/s²)</td>
<td>2.6</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Deceleration (m/s²)</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Emergency Deceleration (m/s²)</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Sigma (driver imperfection)</td>
<td>0.5</td>
<td>0.05</td>
<td>0.05</td>
<td>0.5</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Tau (minimum headway multiplier)</td>
<td>1.2</td>
<td>0.8</td>
<td>0.5</td>
<td>1</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3.2: Table displaying each vehicle type’s parameters (Guériau and Dusparic (2020))

3.5 Motorway Network

The motorway network used in this project is from (Guériau and Dusparic (2020)). The network was generated from OpenStreetMap (OSM) using OSM Web Wizard. OSM Web Wizard is a tool installed by default with the SUMO package that can use OpenStreetMap Data and convert it to an XML network file to be used in netedit, a network editor with a graphical user interface. Users can essentially cut out a section of an area; in this case, it is a section of the M50 motorway in Dublin. After a site is selected, OSM Web Wizard gives the user control over the types of vehicles and roads to be in the simulation (demand generation). Once the user generates the scenario, a temporary folder will be created locally, containing all of the necessary XML data files and the ‘.sumocfg’ simulation file. The main file to look at for this project is the ‘.net.xml’ file which contains all the data to create the M50 road network. This file can then be opened in netedit to clean up the road network. The resources provided by (Guériau and Dusparic (2020)) and used for this project are as follows:

- network file containing the xml to build the network.
• route file to denote all the different vehicle routes.
• emitters file containing all the vehicles to be used in the simulation.

The road network features a seven-kilometre stretch of the M50 motorway in Dublin, Ireland, with both northbound and southbound directions. Each direction contains two intersections consisting of both off-ramps and on-ramps. These intersections lead vehicles to other national roads (the N7 and N9). The number of lanes differs depending on each section of the network, but the large stretch between intersections consists of four lanes. Any additional lanes are used as either transition lanes to off-ramps or transition lanes from on-ramps when vehicles enter the motorway from the intersections. Figure 3.3 shows one of the intersections in the road network used for the simulation in the SUMO-GUI. In order to test scenarios involving different volumes of traffic, traffic data was collected.

Figure 3.3: Image showing one of the intersections used in the M50 motorway network. The centre roads are the main northbound (left) and southbound (right) roads. On-ramps and off-ramps can be seen to the left and right. These exits lead to national roads.
from Transport Infrastructure Ireland. This data contains flows of traffic on each lane aggregated every 5 minutes. Low volume and high volume traffic are represented by different times of day (Guériau and Dusparic (2020)). For the motorway, high volume traffic (congestion) was selected for between 7am and 8am and low volume traffic (allowing the free flow of vehicles) was selected for between 1pm and 2pm. These are the two situations that will be evaluated for each penetration rate scenario in this project.

3.6 The Dedicated Lane Solution

This section describes how the dedicated lane for the M50 motorway was developed using TraCI. Because the road network was already generated from (Guériau and Dusparic (2020)), changing any of the configurations with the network XML files would be an arduous task, and so the more efficient method of simulating a dedicated lane on the motorway would be to directly manipulate the vehicle’s behaviour. This was done using the TraCI python library and through induction loops (detectors). The default solution is that only passenger CAVs will be directed to the dedicated lane. Another experiment is performed that allows both passenger CAVs and CATs onto the dedicated lane. The solution is similar to a sorting machine. When a vehicle passes over an induction loop, the system will check what kind of vehicle it is. If the selected vehicle is a passenger CAV, that vehicle will be directed to the right-hand lane and will drive on the dedicated lane until it either exits the simulation, or the predefined route of the vehicle requires it to exit the motorway through an off-ramp. This solution consists of many induction loops, which TraCI listens to during every simulation step. TraCI performs different tasks depending on the induction loop a vehicle passed over in the simulation, e.g. directing a vehicle to the dedicated lane or directing a CAV to an off-ramp. Figure 3.4 shows a flow chart describing the decision of TraCI to direct a CAV to the dedicated lane.

3.6.1 Induction Loops

Induction loops are detectors placed on an edge that can extract information about any vehicle that passes over them. TraCI can then use this information to perform actions on these vehicles, in this case change a vehicle’s lane. An output XML file can also be written for each induction loop to give information about the vehicles that have driven over it during the simulation. Here are some of the main attributes associated with induction loops.

- ID
Figure 3.4: Flow chart showcasing TraCI whether or not to direct a CAV to change lane.

- Unique identifier for each induction loop. In this project, each id is typically prefixed with ‘northBound’ or ‘southBound’ to denote which side the induction loop is on.

- lane
  - The id of the lane on which the induction loop sits.

- pos
  - Float value, which denotes the position of the induction loop along a given lane.

- freq
  - The values collected by the induction loop during a given aggregation period in steps. These values will then be written to an output file.

- file
the path to write to an output file with the aggregated data. In this project, it is not needed and so, the value 'NUL' denotes that an output file will not be created.

In this project, there are a total of eighty induction loops used in the entire motorway network to ensure good coverage and that CAVs get to the dedicated lane as soon as possible and to remove HDVs off the lane. These are in a file named 'M50.add.xml' using the parameters listed above. This file is then added to the 'M50_simulation.sumo.cfg' file to be used as an additional file as input whenever the simulation configuration is loaded. Each induction loop is named and grouped appropriately in order for easier reading and to identify the function of the induction loop. Figure 3.5 shows how induction loops appear in the SUMO-GUI.

![Figure 3.5: How induction loops look in the SUMO GUI.](image)

3.6.2 The Functionality of TraCI Depending on Induction Loop

Directing CAVs to dedicated lane

Because of the base configuration of the project, CAVs are not inserted into the dedicated lane when they enter the simulation. Because each vehicle has the 'random_free' depart-Lane attribute, each vehicle will be inserted at any position along the first edge in its route. To help get CAVs onto the dedicated lane as quickly as possible, there are multiple
induction loops placed on the first edge on the southbound direction of the network. This is to ensure that a CAV will not be on a regular lane for long before it is directed onto the dedicated lane. These induction loops are also placed at each on-ramp. This allows TraCI to direct CAVs as soon as they enter the motorway network through an on-ramp.

Induction loops are accessed in TraCI by the ‘inductionloop’ python class. This class contains many functions used to extract information from induction loops. In the case of this project, the function `getLastStepVehicleIDs(string detectorID)` takes in the id of the induction loop and will return the vehicle that passed over that particular induction loop in the last time step. Only one vehicle will pass over the induction loop in each time step as the step-length value is quite small at 0.5. This function will return a string consisting of the vehicle’s id. In order to validate whether a given vehicle is a CAV or a HDV, the ‘vehicle’ class needs to be called, and the function `getTypeID(string vehicleID)` is invoked. This will return the type of vehicle that is associated with a given vehicle id. If the vehicle is a CAV (passenger), the vehicle’s state is changed using the function `changeLane(string vehicleID, string laneID, float duration)` from the ‘vehicle’ class and the vehicle changes to the right-most lane on the edge. The duration is set to a high number to keep the vehicle in the dedicated lane for as long as possible. Figure 3.6 shows how a CAV and HDV react to an induction loop that puts CAVs onto the dedicated lane.

Leaving the Dedicated Lane

While some CAVs’ routes are to travel the entire length of the motorway network, some of them need to exit the network through off-ramps. These occur at the two intersections in the road network. In order to redirect these vehicles back into a suitable lane so they can exit the network through an off-ramp, more induction loops need to be used. To give CAVs ample time to merge back into regular lanes, induction loops were placed around 700 metres from each off-ramp. This is particularly important in high volume traffic as it may be difficult for CAVs to merge back into the appropriate lane to exit the network. 700 metres was chosen for these induction loops because of high volume traffic situations. When vehicles were being directed to change lanes at closer distances during congested times, they would not be able to make the successful lane change as the lanes were filled with HDVs.

A python function was created to check the end edge in a vehicle’s route. TraCI’s ‘vehicle’ class contains the function `getRoute(string vehicleID)` which returns a vehicle’s route
Figure 3.6: The scenario on the left shows a CAV2 passing over an induction loop. The induction loop reads that it is a CAV, and so the vehicle will attempt to move into the dedicated lane (indicated by the strong red dividing line. The scenario on the right shows a HDV passing over the induction loop. Because it is not a CAV, TraCI will not perform any actions on the vehicle, and so the vehicle will continue to travel along its predefined route.
as a list of strings of the edges for a vehicle’s route. If the vehicle passes over a particular induction loop and their end edge requires them to enter the off-ramp, then the vehicle is directed off the dedicated lane using the `changeLane()` function mentioned previously. The duration parameter is set to a small number here to ensure that the vehicle’s lane-changing behaviour is returned to its pre-configured behaviour once the lane change is successful. It is important to note that the `changeLane()` function will not override the vehicle’s safety behaviour, i.e. the vehicle will not change lane until it is safe to do so. Figure 3.7 shows how a CAV that needs to leave the network through an off-ramp behaves versus one that does not need to leave at that particular off-ramp.

![Figure 3.7: CAVs exiting the motorway network through an off-ramp. The scenario on the left shows a CAV that needs to exit through the off-ramp. This is checked by the induction loop and then TraCI will direct the vehicle to perform a lane change. The scenario on the right shows a CAV that stays on the stretch of motorway. TraCI will check the end edge of the vehicle that passed over the induction loop and will perform no action on it if it does not need to leave through the off-ramp. For illustration purposes, the induction loops are placed close to the off-ramp. These induction loops are placed much further back in the actual simulation.](image)
Removing HDVs From Dedicated Lane

Because the vehicles in the network are configured to be inserted onto a random lane on the first edge of their route, sometimes HDVs will begin on the dedicated lane. This is a consequence of the implementation of the project. Vehicle’s behaviour can only be manipulated once they are inserted into the simulation. To fix this, there are induction loops placed periodically on the dedicated lane which will check if the vehicle is a HDV or a HGV. These vehicles will then be directed back onto the regular lanes (lane next to the dedicated lane). This reduces the amount of time a CAV is exposed to a HDV in the lane. The functionality behind these induction loops are effectively the same as moving CAVs from the dedicated lane when they need to exit the motorway through an off-ramp. Figure 3.8 shows the functionality behind these induction loops.

![HDV being directed off the dedicated lane. This typically occurs when vehicles are inserted at the beginning of the simulation.](image-url)
3.6.3 Challenges Faced

CAVs Halting on Dedicated Lane

One challenge that was encountered during early development of the project was in regards to the functionality of the `changeLane()` function. One of the required parameters for the function is a float duration value to tell the vehicle how long it should drive in the dedicated lane. If this value was too small, the CAV would return to its predefined route and would no longer be utilising the dedicated lane. If the value was too large, the vehicle would become stuck on the dedicated lane, unable to move to a lane that would allow them to leave the motorway network through an off-ramp. This would cause CAVs to halt on the dedicated lane, causing a jam on the dedicated lane. An example of this can be seen in Figure 3.9.

![Figure 3.9: Example of a halt on the dedicated lane in the SUMO-GUI because a CAV is stuck on the dedicated lane when it needs to leave through an off-ramp.](image)

The solution to this was to add some induction loops on the dedicated lane before each off-ramp and check for each CAV’s end edge in its route to check if the end edge was connected to the given off-ramp. If it was, then the CAV would be directed back to a lane which was connected to the off-ramp so the vehicle could exit the motorway network properly. These induction loops are placed around 700 metres back from each of...
the off-ramps in order to give the CAVs a suitable amount of time to get back into the appropriate lane.

3.6.4 Limitations of Solution

There are some limitations of the project when it comes to the dedicated lane solution implemented. Because TraCI can only dynamically alter vehicle behaviour once the vehicle is inserted into the simulation and the project is using predefined routing of vehicles from \cite{Guériaud and Dusparic 2020}, HDVs sometimes enter the dedicated lane when they are inserted into the simulation or enter the motorway network through an on-ramp. Because of this, the results obtained from the simulation may contain some inaccuracies due the implementation of the dedicated lane and the structure of the project.

Another limitation of the solution is that due to time constraints, only 4 penetration rates could be tested as each simulation required a large amount of resources and time to complete and in general, only one simulation could be run at a time. In total, 10 different simulations were run.
Chapter 4

Evaluation

This chapter examines the effectiveness of the dedicated lane for CAVs in the SUMO simulation. These experiments were performed against a baseline simulation adapted from (Guériau and Dusparic (2020)) which utilises the same motorway network, but contains no dedicated lane. The experiments were performed with a number of different penetration rates of CAVs which can be seen in table 4.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>HDV (cars and trucks)</th>
<th>CAV2 (cars and trucks)</th>
<th>CAV4 (cars and trucks)</th>
<th>CAV2 + CAV4 (cars and trucks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>90%</td>
<td>7.5%</td>
<td>2.5%</td>
<td>10%</td>
</tr>
<tr>
<td>B</td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>C</td>
<td>70%</td>
<td>20%</td>
<td>10%</td>
<td>30%</td>
</tr>
<tr>
<td>D</td>
<td>30%</td>
<td>50%</td>
<td>20%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table 4.1: Table showing different penetration rates of CAVs used for each scenario. The sections in the table show the aggregated total for both vehicle types of passenger cars and trucks.

Successive scenarios represent increased penetration rates until the final scenario which represent the majority of vehicles on the network being CAVs (70%). Two levels of traffic will be evaluated which will be represented by the time of the day (1pm-2pm consists of low volume traffic, 7am-8am consists of high volume traffic). The motorway network generated in SUMO consists of a seven kilometre stretch of road travelling in both the northbound and southbound directions with two intersections to exit the motorway which lead to two national roads. The default scenario is that only passenger CAVs can utilise the dedicated lane. The other scenario that is investigated is allowing CATs to also utilise the dedicated lane in conjunction with passenger CAVs.
4.1 Testing Metrics

Both traffic flow and traffic safety utilising dedicated lanes are evaluated in this project. The two metrics that are used to reflect these conditions are travel rate and the number of conflicts recorded (conflict metric is time-to-collision (TTC)) which are both used in (Guériau and Dusparic (2020)). These metrics are described as follows:

- **Travel Rate**
  - Travel rate of vehicles refers to the time it takes a vehicle in the simulation to travel in different sections of the motorway a kilometre. This metric is measured in \text{min/km}. The main sections of the motorway that will include an average travel rate are before intersections, off-ramps, on-ramps and the long stretch of road between the two intersections. The plots produced show a heat map of the average travel rate in different sections of the motorway.

- **Rate of conflicts in terms of TTC**
  - TTC refers to the time it will take a vehicle to collide with another vehicle. This type of conflict measurement is typically used for rear-end collisions (Naseralavi et al. (2013)). For this project, the TTC threshold is 1.5 seconds for HDVs and 0.75 seconds for CAVs i.e. a conflict is recorded when a vehicle is 1.5 or 0.75 seconds or less from colliding with the vehicle in front of them depending on the speed they are travelling at. A conflict does not mean that two vehicles have collided with each other.

4.2 Results of Baseline

The simulations for the baseline were all run with the different penetration rates from the above table. The SUMO-GUI was not used to run the simulations in order to reduce computational load, although simulation run times still exceeded 4 hours with massive resource drain in terms of memory needed for each simulation. This limited the number of penetration rates tested due to time constraints with the project.

4.2.1 Travel Rate

Figure 4.1 shows the average travel rate of vehicles on the motorway network for each scenario for the morning rush hour (high volume traffic) and Figure 4.2 shows the scenarios for the afternoon (low volume traffic).
Figure 4.1: Average travel rates on different sections of the motorway with various penetration rates of CAVs in high volume traffic. These results are recreated from the work of Guériau and Dusparic (2020).
Figure 4.2: Average travel rates on different sections of the motorway with different penetration rates of CAVs during low volume traffic. These results are recreated from the work of Guériau and Dusparic (2020).
For the low volume traffic scenario, there is not really any discernible difference in the
travel rate on the motorway with different penetration rates of CAVs. The travel rate on
the majority of the motorway is quite high. The only areas with low travel rates are when
vehicles exit the off ramp and need to drive slower to navigate the curve. The suspected
reason for the good travel rate across the entire network is the fact that at low volume
traffic, vehicles are typically always in free flow. So they will typically have no issue in
exiting the network at off-ramps, where congestion of traffic usually occurs.

For the high volume traffic scenario there are many sections of the motorway network
that now have slower average travel rates. The high congestion areas occur around exits
to off-ramps. The beginning of the southbound road shows a large amount of congestion of
traffic. However, as penetration rates of CAVs increase the travel rate begins to improve.
Scenario A (10%) shows the worst travel rates out of all the scenarios tested. Scenario B
(20%) shows slight improvements to the travel rate. This can be seen at the beginning of
the northbound road. Travel rate begins to improve greatly at higher penetration rates.
Scenario C (30%) and Scenario D (70%) show a drastic improvement to the travel rate
across the entire network. Scenario C shows that congestion is almost fully cleared on
the northbound road and congestion on the southbound road. At 70% penetration rate of
CAVs, congestion is almost fully cleared in the entire network with just a small amount
on the north junction. The results gathered here match the results found in (Guériau and
Dusparic (2020)). Increasing penetration rates of CAVs will help to improve the overall
travel rate of vehicles on motorways.

4.2.2 TTC Conflicts

Figure 4.3 shows the number of TTC conflicts and the location of each conflict on the
network during high volume traffic. Figure 4.4 shows the TTC conflicts that occurred
during low volume traffic. From the figures, it seems that increasing the penetration
rate of CAVs will increase the number of TTC conflicts that occur. The majority of TTC
conflicts occur near junctions as this is where vehicle’s speed are more likely to change
rapidly and more lane changes will take place. Although an interesting point to note is
that the conflicts that are caused by CAVs only increase marginally as the penetration
rate increases. This can be seen in the low volume traffic scenario, where CAV conflicts
increase slightly over each scenario. HDV conflicts remain high even as the total number
of HDVs on the road is reduced when the penetration rate of CAVs increase. In scenario
C (30%) and Scenario D (70%), the number of CAV caused conflicts reduces from 16 in
C to 10 in D, but the HDV caused conflicts remain high even after their relative total
Figure 4.3: TTC conflicts occurred during high volume traffic of baseline. Each dot on the network indicates a TTC conflict that has occurred. The total number of conflicts as well as the how many CAVs (cars and trucks) and HDVs (cars and trucks) caused the conflict are displayed.
Figure 4.4: TTC conflicts occurred during low volume traffic of baseline. Each dot on the network indicates a TTC conflict that has occurred. The total number of conflicts as well as the how many CAVs (cars and trucks) and HDVs (cars and trucks) caused the conflict are displayed.
number is reduced.

In terms of the high volume traffic scenario, many more conflicts take place on the network in comparison to the low volume traffic scenario, occurring near junctions where a rapid change in speed is more common. The number of CAV caused conflicts has a much sharper increase than in the low volume scenario. Scenario A (10%) has just 4 CAV conflicts while D (70%) has 45 (52% of total conflicts in Scenario D). Scenario C (30%) has a very high number of conflicts at 123, with the majority of the conflicts being caused by HDVs. This number gets reduced by half in Scenario D where there are many more CAVs. This suggests that HDVs may struggle to keep a safe distance away from CAVs, especially during lane changes.

The results obtained from this experiment differ quite significantly from the results obtained in (Guériau and Dusparic (2020)) in terms of conflicts. That study found that TTC conflicts reduced as penetration rates of CAVs increased. The suspected reason for this is that the SUMO configurations for recording conflicts were not provided by the study, and so the methods for recording TTC conflicts in this project were most likely different to the method used in (Guériau and Dusparic (2020)).

4.3 Results of Dedicated Lane for Passenger CAVs

The following section presents the results obtained by running simulations using the dedicated lane solution described in the previous chapter. The penetration rates used for these simulations are the same that were used for the baseline model.

4.3.1 Travel Rate

The average travel rate of different sections of the motorway with varying penetration rates and volumes of traffic can be seen in Figures 4.5 and 4.6. For the low volume scenario (Figure 4.6), large amounts of congestion occur on the network at the lower penetration rates in A (10%) and B (20%). This congestion is especially prevalent on the southbound road, but can also be seen on the long stretch of road between the junctions in both road directions (northbound and southbound). The majority of vehicles (HDVs, HDTs, CAT2, CAT4) on the road are losing a portion of their driving space on the motorway which is causing further congestion. Travel rate begins to improve when penetration rates increase. This can be observed in C (30%) and D (70%) although in D, travel rate is still substantially reduced when vehicles are inserted into the simulation.
Figure 4.5: Average travel rates on different sections of the motorway with various penetration rates of CAVs in high volume traffic while CAVs are directed to the dedicated lane.
Figure 4.6: Average travel rates on different sections of the motorway with various penetration rates of CAVs in low volume traffic while CAVs are directed to the dedicated lane.
on the southbound road. The suspected reason for this is the fact that 70% of passenger vehicles are attempting to enter the dedicated lane. There is simply not enough capacity for the majority of vehicles to utilise the dedicated lane. This jam could be observed while the simulation was running. The simulation began requiring a massive amount of memory (approximately 10GB) due to the large amount of objects being rendered while only a few were leaving the simulation.

Similar findings can be seen in the high volume traffic scenario. Travel rates when CAVs are directed to the dedicated lane and when they are merged back into regular lanes are quite high. The northbound road seems to be affected more also. The combination of reduced road space for HDVs and CAVs attempting to move in and out of the dedicated lane hinders travel rate quite significantly at lower penetration rates (A and B). Scenario C (30%) does show a significant improvement to travel rate over the previous scenarios. Scenario D (70%) shows similar results to the low volume traffic scenario where massive jams occur when CAVs attempt to enter the dedicated lane. From the results, it is clear that if a dedicated lane were to be implemented, travel rates begin to improve while there are a moderate amount of CAVs (in this case 30%)

4.3.2 TTC Conflicts

TTC conflicts recorded for the dedicated lane simulation in high volume and low volume traffic scenarios can be seen in Figures 4.7 and 4.8 respectively.

TTC rates in the high volume traffic scenario remain quite stable throughout each penetration rate, only increasing moderately in scenario D (70%), although CAV conflicts do see a sharp increase from B to C (16 vs 32). The majority of conflicts occur where CAVs are merging back into regular lanes to exit through off-ramps and also occur at the off-ramps themselves. This could be due to the rapid changes in speed that is typically seen in these areas. HDVs are involved in more conflicts than CAVs in A, B and C. But CAVs are involved in more conflicts in D (71 vs 54), once they become the majority vehicle on the road.

The low volume traffic scenario produces extremely sporadic results. Massive numbers of conflicts occur in A, B and C. Unlike in the high volume traffic scenario, many of the conflicts seem to occur at the beginning of the simulation on the southbound side, in addition to junctions. The conflicts occurring seem to be correlated with where large amounts of congestion are occurring in the network. This can be seen in the long stretch
Figure 4.7: TTC conflicts occurred during high volume traffic when CAVs are directed to the dedicated lane. Each dot on the network indicates a TTC conflict that has occurred. The total number of conflicts as well as the how many CAVs (cars and trucks) and HDVs (cars and trucks) caused the conflict are displayed.
Figure 4.8: TTC conflicts occurred during low volume traffic when CAVs are directed to the dedicated lane. Each dot on the network indicates a TTC conflict that has occurred. The total number of conflicts as well as the how many CAVs (cars and trucks) and HDVs (cars and trucks) caused the conflict are displayed.
road in A and B where there are large congregations of conflicts occurring. Slower travel rates can also be observed in those sections.

4.3.3 Comparison to Baseline

Overall, it seems that replacing the right hand lane on the network to be used as a dedicated lane negatively impacts performance in terms of both travel rate and TTC conflicts. At lower penetration rates (10%, 20%), the baseline has better average travel rates on many of the sections of the motorway than the dedicated lane experiment because there is more road space for any vehicle to use. At 30%, performance of the dedicated lane improves, showing similar results to the baseline scenario (no dedicated lane) at 30% penetration rate. Although travel rate does seem to be reduced in areas where CAVs attempt to merge back into regular lanes, especially in high volumes of traffic. This suggests that CAVs need to be more intuitive to upcoming traffic to be able to make decisions to change lanes where traffic volume is low. A single dedicated lane for high penetration rates (70%) results in extremely slow travel rates before junctions, it was observed that traffic jams were occurring here in comparison to the baseline, where excellent travel rates were observed. A second dedicated lane for CAVs could be a solution to this issue as suggested in Ye and Yamamoto (2018).

In terms of traffic conflicts, the baseline achieves lower total conflicts than in the dedicated lane scenario. The conflicts on the dedicated lane appear in similar spots to the baseline, but can also be observed at locations where CAVs are attempting to move into the dedicated lane and where they are merging back into regular lanes to exit through off-ramps. This once again suggests that with this implementation, CAVs are having difficulty moving back into regular lanes safely and effectively.

4.4 CAT Encroachment on Dedicated Lane

This experiment investigates the effect that CATs have on the dedicated lane if they are permitted to use it along with passenger CAVs. Only scenarios A (10%) and C (30%) as well as high traffic volume were tested. This was due to time constraints as each simulation requires a high amount of resources and time to complete.

4.4.1 Travel Rate

Average travel rates of sections of the motorway if CATs are also permitted to use the dedicated lane can be seen in Figure 4.9. At low penetration rates (10%), it is observed
that there are many areas of the motorway which suffer from low travel rates, the number of HGVs on the road are extremely small relative to the number of passenger vehicles, and so the majority of vehicles on the road now have less road space to drive on (as seen previously). As penetration rates increase (30%), Travel rates improve dramatically, especially during the long stretch between the two junctions. Although there is some congestion build up where CAVs and CATs need to exit through the off-ramp at the south junction.

4.4.2 TTC Conflicts

TTC conflicts for the CAT encroachment of the dedicated lane can be seen in Figure 4.10. The number of conflicts in the low penetration rate is quite low, matching similar numbers to the baseline scenario of low penetration rate in terms of both CAV caused conflicts and HDV caused conflicts. In scenario C (30%), higher conflicts arise. This can be seen in particular before off-ramps at the north junction on both the southbound and northbound road, where CAVs and CATs need to leave the dedicated lane to exit the network. This shows that CAVs and CATs may be changing lanes quite aggressively, causing some HDV conflicts.

4.4.3 Comparison to Dedicated Lane

Overall, it seems that allowing CATs to utilise the dedicated lane in conjunction with CAVs has a negative impact on performance in terms of travel rate and conflicts. Although there are lower conflicts to be seen when CATs are using the dedicated lane, the travel rate at low penetration rates (10%) is quite long which shows large amounts of congestion. At 30% penetration rate the travel rate for CAT encroachment does improve over 10% penetration rate but it seems to be worsened in comparison to a passenger CAV exclusive dedicated lane. There are higher levels of congestion at exits to off-ramps. This could potentially be due to CATs having a more difficult time merging back into other lanes due to their size.
Figure 4.9: Average travel rates on different sections of the motorway with various penetration rates of CAVs in high volume traffic while CAVs and CATs are directed to the dedicated lane.
Figure 4.10: TTC conflicts occurred during high volume traffic when CAVs and CATs are directed to the dedicated lane. Each dot on the network indicates a TTC conflict that has occurred. The total number of conflicts as well as the how many CAVs (cars and trucks) and HDVs (cars and trucks) caused the conflict are displayed.
4.5 Summary

Overall, it seems that replacing the right-hand lane in the M50 motorway network with a lane dedicated to CAVs worsens travel rate and increases the number of conflicts between vehicles when using the solution that was implemented in this project compared to the baseline of results found from performing the experiments of (Guériaud and Dusparic (2020)). At low penetration rates, travel rate was reduced. This matches the findings of (Ye and Yamamoto (2018)) as the reduced road space for the HDVs increases congestion, especially during times of high volume traffic. Similar results occur when the majority of the vehicles on the road are CAVs. At 70%, large traffic jams occur as there are massive amounts of vehicles trying to enter the dedicated lane. At 30% penetration rate, travel rate is improved over other penetration rates but in comparison to the baseline, some congestion occurs in locations where CAVs need to weave back into regular lanes to exit through an off-ramp. This is reflected in the location of conflicts that occur in the dedicated lane scenario.

A potential reason for a difference in the findings are some of the limitations and parameters that were set in the project. Slight HDV encroachment onto the dedicated lane may have contributed to the worsened travel rate, particularly towards the beginning of the road networks. CAVs also changed lanes with 100% compliance after passing each induction loop so while the vehicles would not cause any collisions, the aggressive lane changes may have required other vehicles to slow down increasing the amount of congestion and TTC conflicts. Therefore, it is important to ensure that CAVs have good anticipation when it comes to weaving back into regular lanes to exit through off-ramps for any future work done on dedicated lanes.

When it comes to allowing CATs to drive on the dedicated lanes also, it was observed that both travel rate and conflicts were worsened at the optimal penetration rate of 30%. The suspected reason for this is the fact that HGVs are slower to perform lane changes than passenger vehicles. There was increased congestion and conflicts where CATs were directed to exit the dedicated lane through off-ramps.
Chapter 5

Conclusion

The aim of this project was to build upon the work of (Guériau and Dusparic (2020)) and develop an experiment to investigate the effects of replacing the right-hand lane of the M50 motorway network with a dedicated lane which only passenger CAVs were able to use. Another experiment was performed where HGVs with CAV capabilities were also able to utilise the dedicated lane. The metrics used to evaluate the effectiveness of the dedicated lane were the average travel rate of vehicles along different sections of the motorway and the number and location of TTC conflicts which occurred on the network.

SUMO was used to create the simulation and the dedicated lane solution was implemented using induction loops in SUMO to identify vehicles in the network, then making use of TraCI to directly manipulate the behaviour of CAVs to move into the dedicated lane as soon as they were inserted into the simulation.

The final results gathered from running the various simulations were that adding a dedicated lane to the motorway at low penetration rates of 10% and 20% and high penetration rates of 70% resulted in reduced travel rate as a result of increased congestion from the majority vehicle having a lower amount of driving space. Penetration rates of 30% showed improvements in travel rate in comparison to the other penetration rates. However, compared to the baseline of no dedicated lane on the motorway, some areas of the motorway suffered from increased congestion and an increase in the number of conflicts, in particular areas located before off-ramps at junctions where CAVs needed to weave back into the regular lanes to exit through these off-ramps. Lower travel rates and higher conflicts were recorded at 30% penetration rate when CATs were also permitted to drive on the dedicated lane in comparison to a passenger CAV exclusive dedicated lane, due to HGVs having slower lane change times when merging back into regular lanes to exit through
off-ramps.

From the results gathered in this project, some potential can be seen with CAV dedicated lanes at moderate penetration rates. Although more work is needed to be done on CAVs with more anticipation when it comes to merging back into regular lanes, merging when it is the safest and most efficient to do so. There are many different avenues through which this project could be built upon which are discussed in the final chapter of this report.
Chapter 6

Future Work

While this project provides a comprehensive study into the effectiveness of dedicated lanes for CAVs on a motorway network, there are some limitations involved with the implementation of the solution. Because the road network and vehicle routing were predefined, there are some inaccuracies in the performance of the dedicated lane due to the encroachment of some HDVs onto the lane, in particular towards the beginning of the simulation where vehicles are inserted directly onto the motorway. This project could be adapted to redefine the road network to specifically set the right-hand lanes in the network to not allow HDVs onto the lane at all. This can be done within the XML files of the network file, or the motorway network could be extracted from OSM Web Wizard and configurations for not allowing HDVs on the dedicated lane could be set up there.

This project assumes that a CAV will change lane as soon as it passes an induction loop. Another potential piece of work would be to implement real-time V2V communication between CAVs and implement road-side sensors that could relay traffic information that is occurring further up the network. This could allow for CAVs to make smarter decisions when merging back into the regular lanes to exit through off-ramps. For example, if the road network is not currently busy, the CAV could merge into the regular lanes closer to the off-ramp. If the road network is highly congested (during peak times), the CAV could attempt to merge into regular lanes a further distance away from the off-ramp.

This project could also be extended to study if dedicated lanes for CAVs perform better when CAVs are travelling for much longer distances, and so another extension of the project would be to look at extending the distance of the road network, potentially covering the entire M50 motorway. This could be achieved by utilising the OSM Web Wizard tool to extract a larger amount of the M50 motorway out. This work could also
be extended to using OSM data to create network for other real-world motorways. Traffic
data for each particular motorway would need to be collected, so it may be a challenge
to source that information.
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Appendix

Figure 1: Example of induction loop configuration data for SUMO.

Figure 2: Example of a vehicle type in SUMO (CAV4 in this case).

Figure 3: Example of TTC conflicts generated during simulation.
Figure 4: Example of an edge in the network in SUMO generated by Guériau and Dusparic (2020).

Figure 5: Example of the dedicated lane in action in SUMO. CAVs (blue and red) can be seen on the right-hand lane, while HDVs remain in the other lanes.