OPERATIONAL CONCEPT FOR CONNECTED AND AUTONOMOUS VEHICLES IN AN URBAN ENVIRONMENT

A VAN STRATEN* and SJ ANDERSEN**

Stellenbosch University; Department of Civil Engineering, Private Bag X1,
Matieland 7602, Stellenbosch, South Africa
*Tel: 072 573 6692; Email: armvan3@gmail.com
**Tel: 021 808 2255; 082 550 1918; Email: jandersen@sun.ac.za

ABSTRACT

The emergence of Autonomous Vehicles (AVs) can significantly alter how people and goods are transported, as Connected and Autonomous Vehicles (CAVs) offer increased automation as well as improved connectivity between vehicles and roadside infrastructure. Although a future where all vehicles on the road are autonomous, which seems to be far-fetched, the rapid development of AV technologies worldwide is a clear indication that local readiness needs to be addressed sooner rather than later.

There are many uncertainties regarding how AVs would operate on the road network recognising that few studies have investigated how AVs would operate in an urban environment. This study attempts to provide insight as to how AVs and CAVs perform in such an environment, thus acting as a form of preparation for the future when AVs are eventually implemented.

Four levels of autonomous behaviour were evaluated with a microscopic model, developed in PTV VISSIM, to assess the relative improvements that each of these levels provides to the road network's performance at various penetration rates. The performance of the road network was evaluated by considering various performance indicators, including average network delays, network travel times, network travel speeds, queue lengths, and the average number of stops. Specific focus was also placed on the performance of CAVs and how robust they are to changes in traffic volumes.

AVs, and CAVs, were quite effective in improving the network's performance across all the performance indicators. Additionally, CAVs were quite robust when it came to handling changes in traffic volumes. However, the performance of the AVs were significantly dependent on their penetration rate. The findings in this study provided valuable insight into what the future would look like when AVs are implemented. This research provides a useful, albeit significant, first step in understanding the incremental introduction of CAVs and AVs in South Africa from a traffic engineering perspective.

1. INTRODUCTION

The emergence of Autonomous Vehicles (AVs) has significantly altered what the future of road transport looks like. As is the case with any new technological development, there are many uncertainties related to how these vehicles would operate on the roadway environment. As the name suggests, AVs require little to no input from a human driver to execute the driving task. AVs utilise many different existing sensory technologies, or combinations of these technologies, to perceive the necessary information from the surrounding environment to execute their actions safely and effectively on the roadway (Campbell *et al.*, 2018).

A main feature of AVs is that they can remove the often unpredictable behaviour of human drivers from the driving task. However, a further attractive but critical aspect of AVs is their capability to be connected, thus referred to as Connected and Autonomous Vehicles (CAVs). It is envisioned that CAVs will be able to communicate with all devices that are present on the roadway environment (Arena & Pau, 2019). These CAVs are considered essential for the development of future Smart Cities and future Intelligent Transport Systems (ITS) (Guanetti *et al.*, 2018).

Many studies have been conducted investigating how AVs and CAVs would perform in the roadway environment, identifying potential benefits, and challenges that arise with the implementation of AVs and CAVs (Jeong *et al.*, 2017; Kopelias *et al.*, 2020; Makridis *et al.*, 2018; Papadoulis *et al.*, 2019; Rezaei & Caulfield, 2021; Stanek *et al.*, 2018; Talebpour & Mahmassani, 2016; Ye & Yamamoto, 2019). These studies found that AVs and CAVs were able to provide many benefits in terms of increasing network capacity, reducing congestion, improving safety, and reducing pollution.

However, most of the studies conducted on AVs and CAVs focused on investigating the performance of AVs and CAVs in a freeway or highway environment. Fewer studies focused on the performance of AVs and CAVs in an urban environment. It is expected that, in the latter application, AVs and CAVs will be faced with much greater challenges than what can be found in a freeway or highway environment due to a more complex operational setting.

Using a microscopic simulation model developed in state-of-the-art software, this research aims to provide insight as to how AVs and CAVs would operate in this challenging urban environment. It investigates the potential benefits and challenges of AVs and CAVs as well as determining whether the added communication capability of CAVs does provide any additional benefits when compared to normal AVs.

This research was conducted using an urban road network located in South Africa, for twofold reasons: first, it is important that South Africa must prepare for the eventual arrival of AVs and CAVs. Although the substantial implementation of automated vehicles is unlikely in the near future, alignment with international current developments is imperative. Secondly, it is essential that a sense of urgency must prevail in preparing for increased automation. The readiness of road infrastructure as well as associated communications infrastructure needs to be identified and addressed timeously.

This paper is structured as follows: a literature review to provide background on the simulation of AVs is first presented. The methodology to investigate the performance of AVs and CAVs is then discussed, after which the major findings of this study is presented. Finally, the implications of the introduction of increased vehicle automation are discussed in terms of future research and recommendations.

2. LITERATURE REVIEW

2.1 Microscopic Simulation Models

Since it is not always possible to conduct real-life experiments, researchers have resorted to using simulations. Simulations can often be implemented more easily and are relatively accurate in representing the actual conditions. One of these frequently used types of simulation models used in transportation studies are microscopic simulation models.

Microscopic simulation models are used for investigating the individual behaviour of vehicles, which is governed by vehicle following, lane-changing and gap-acceptance algorithms (Ahmed *et al.*, 2021). Microscopic models are often used for modelling complex urban road networks, such as signalised traffic intersections and roundabouts.

PTV VISSIM is one of the well-known tools that transportation engineers and planners use to develop these highly detailed and complex microscopic models. This software makes use of many well-known algorithms such as the Wiedemann Model and the Rule-Based Lane-changing Method to define a vehicle's driving behaviour.

2.2 CoEXist Project

The CoEXist project was a project conducted quite recently to prepare for the eventual arrival of AVs on the road network (Rupprecht Consult - Forschung & Beratung GmbH, 2020). The CoEXist project is responsible for extending upon the features found in PTV VISSIM enabling it to be used for modelling AVs.

The CoEXist project conducted many studies investigating the impact of AVs and during those studies four levels of autonomous driving behaviour were identified (Rupprecht Consult - Forschung & Beratung GmbH, 2020). Figure 1 depicts the four AV driving behaviours identified during the CoEXist project.

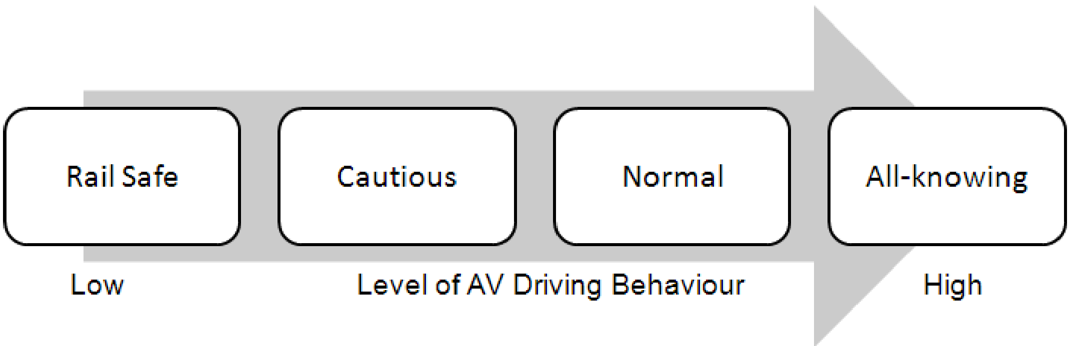


Figure 1: Levels of AV driving behaviour

Out of the various case studies conducted during the CoEXist project, two case studies stood out (Olstam *et al.*, 2020). These are a microscopic simulation model investigating the performance of AVs at a signalised intersection located in Helmond, Netherlands and a microscopic simulation model investigating the performance of AVs at multiple roundabouts located in Milton Keynes, UK. Using the different levels of AVs defined in Figure 1, microscopic simulations were conducted using PTV VISSIM. These studies found that ,initially AVs would worsen traffic conditions by increasing travel times and delays (Olstam *et al.*, 2020). As AVs become more prevalent on the road AVs do provide improvements in both travel times and delays (Olstam *et al.*, 2020). Furthermore, AVs were able to use much less space and provide significant improvement regarding safety.

2.3 Other AVs and CAVs Studies

Asadi et al. (2019) conducted a micro-simulation study, also using PTV VISSIM, investigating the impact that CAVs will have on the capacity of urban roads. Similar to the CoEXist project, Asadi et al. (2019) used Milton Keynes as the study area. However, the study area consisted of an entire section of the city, not just a single road section. The traffic flow data for the large-scale study area was collected through a SATURN macro-simulation. The traffic flow data obtained from the SATURN macro-simulation was used as input for the VISSIM micro-simulation.

Asadi et al. (2019) defined three generations of CAVs and predicted a market penetration forecast for the various for CAVs and were able to determine the impact of CAVs as they progress. Furthermore, they produced these different generations of CAVs in PTV VISSIM by adjusting the parameters of the Wiedemann 99 model and the lane-changing parameters. It was found that even though the number of vehicles on the road will increase, CAVs provide great benefits for reducing congestion and delays. Additionally, CAVs improved the road network’s ability to cope with the further increase in vehicles on the road.

Patella et al. (2019), conducted a simulation study using a traffic demand modelling software called EMMA, investigating the impact CAVs will have on urban mobility with the city of Rome (Italy) as the study area. They evaluated the effect CAVs will have by comparing a hypothetical scenario of a 100% penetration rate for CAVs, with the current situation found in the city of Rome. It was assumed that when CAVs reach a penetration rate of 100%, CAVs will be fully electric and connected.

It was found that CAVs will reduce travel time within the network by as much as 35%. Additionally, CAVs will substantially increase the average speed within the network by almost 50%. However, the focus of the study was to determine what effect CAVs will have on the environment at an urban mobility level. Using the output data obtained from the simulations, they were able to determine and compare the greenhouse gas emissions for the current situation in Rome with the hypothetical scenario. It was found that CAVs will greatly reduce the impact on the environment, through reduced greenhouse gas emissions, by approximately 60%.

3. METHODOLOGY

3.1 Study Area

The area identified as the focus of this research study is a section of the road network of the university town, Stellenbosch. Figure 2 depicts a view of the study area. As shown in Figure 2, the study area will be the section that stretches through sections of Merriman Ave., Marais Road, Victoria Street, and Ryneveld Street. This section of the road network has a variety of different traffic control systems, such as traffic circles, traffic signals, and a stop-controlled intersection which can be used to test the driving behaviour of the AVs. Furthermore, traffic count data was available in this section of the road network that could be used for calibration.

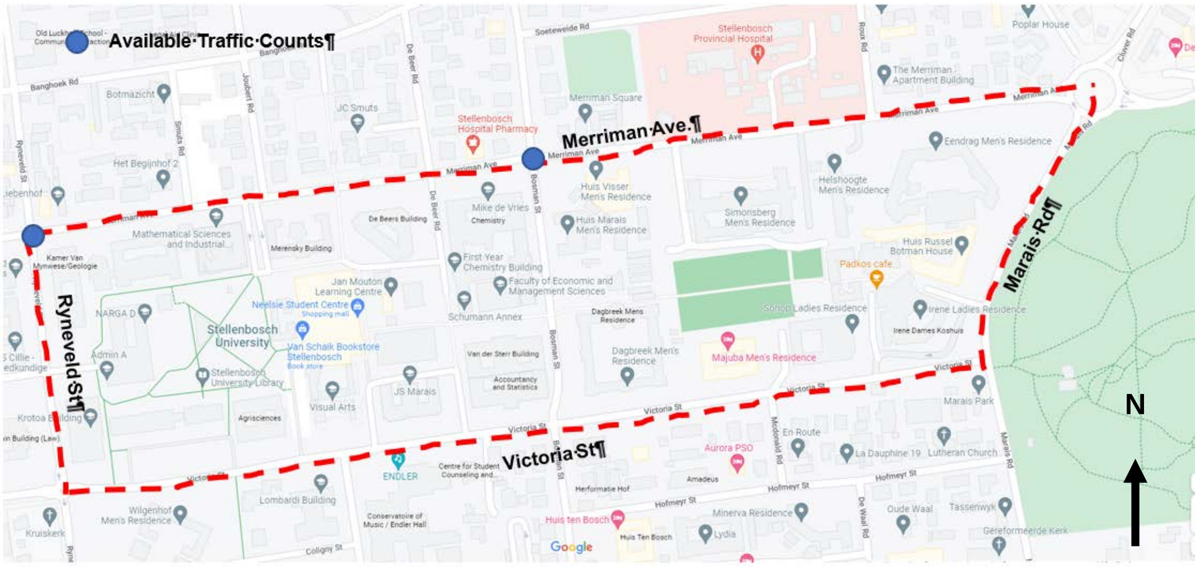


Figure 2: Section of network (Google Maps, 2022)

3.2 Model Development Approach

Figure 3 shows a graphical representation of the research approach taken for this study. The study approach was divided into three parts.

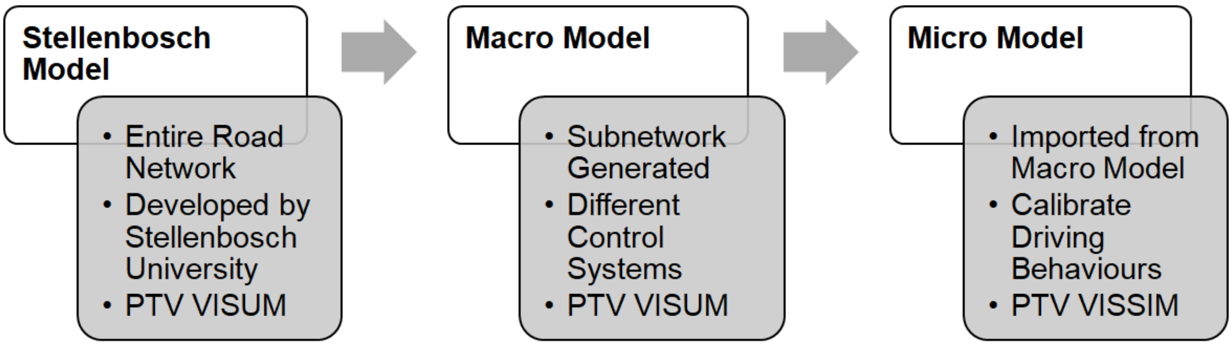


Figure 3: Research approach components

The first component used for the model development was a regional PTV VISUM macroscopic model of the city of Stellenbosch. This model was developed, by Stellenbosch University, as a demand model using the Four-Step Method. The Stellenbosch Model required a large amount of data collection, which includes zonal information and land use patterns, traffic counts at intersections recording specific turning movements, free flow speeds, and road classifications. The data was provided by the local municipality of Stellenbosch.

The second component involved the extraction of a sub-model from the larger Stellenbosch Model generated in PTV VISUM. The sub-model generated included the origin-destination data and traffic volumes that would travel through the road network section defined as the study area (Figure 2). This Macro Model also included information regarding intersection geometry and signal phases. Signal phase plans were provided by the local municipality of Stellenbosch. Most of the alterations to the network were done during this stage of the model development process.

Finally, the Macro Model was imported into PTV VISSIM to create the Micro Model. At this stage the Micro Model was ready for simulation, i.e., all the major links, nodal structure and geometry had been refined. Only slight alterations to the road network were made during this stage of the model, which did not affect the simulation outcomes. After the alterations were made the Micro Model was calibrated and was ready to generate results. Most notably, setting the driving behaviour parameters for the four levels of autonomous driving behaviour in the Micro Model namely, Cautious AVs, Normal AVs, All-knowing AVs and CAVs, where CAVs were the only AV type that could receive signal information from traffic signals. The driving behaviour settings for the different levels of autonomous driving behaviours were done using the CoEXist project as guidance.

Table 1 shows some of the key parameters for the following behaviour for the different driving behaviours. As shown in Table 1, AVs can maintain a closer following distance between each other compared to Conventional Vehicles and as AVs become more advanced the following distance between the vehicles become smaller. Furthermore, AVs can maintain constant following distances, consequently, the Multiplicative Part of Safety Distance and Following Distance Oscillation parameters were set to zero. Also shown in Table 1, only CAVs were able to Receive Signal Information. This enables CAVs to maintain an optimal speed to reach an intersection as soon as the signal turns green. The behaviour for Receiving Signal Information was programmed using an external Python script.

Table 1: Following behaviour key parameters

Wiedemann 74				
Driving Behaviour	Average Standstill Distance (m)	Additive part of Safety Distance	Multiplicative Part of Safety Distance	Receive Signal Information
Conventional Vehicles	1.5	2	3	OFF
CAVs	1	1.5	0	ON
Wiedemann 99				
Driving Behaviour	Standstill Distance (m)	Gap Time Distribution (s)	Following Distance Oscillation (m)	Receive Signal Information
Cautious AVs	1.5	1.5	0	OFF
Normal AVs	1.5	0.9	0	OFF
All-knowing AVs	1	0.6	0	OFF

Table 2 shows some of the key parameters for the lane-changing behaviour for the different driving behaviours. The aggressiveness of the lane changes manoeuvre is governed by the Safety Distance Reduction Factor, the smaller the value implies a more aggressive behaviour. As shown in Table 2, Cautious AVs behave more cautiously than

Conventional Vehicles driven by a human. Higher levels of AVs such as, Normal AVs, All-knowing Avs, and CAVs, behave on a somewhat similar level of aggressiveness as Conventional Vehicles. However, these AVs can execute Cooperative Lane Changes creating the cooperative and connected driving environment expected from higher levels of AVs.

Table 2: Lane-changing behaviour key parameters

Driving Behaviour	Cooperative Lane Change	Safety Distance Reduction Factor	Minimum Clearance (m)
Conventional Vehicles	OFF	0.6	0.5
Cautious AVs	OFF	1	0.5
Normal AVs	ON	0.6	0.5
All-knowing AVs	ON	0.75	0.5
CAV	ON	0.75	0.5

The development of the microsimulation model was made easier by following this research approach. Note that the Micro Model only included private vehicles as a mode of transport. Furthermore, this model only considers the morning peak hour that occurs in this section of the road network.

4. RESULTS

Each simulation was repeated 10 times, each time with a different random seed. Additionally, each simulation run consisted of a 15-minute warmup period and an hour simulation period. The warmup period was used to fill the model with vehicles before any results were recorded. Executing each simulation this way ensured the results were adequately averaged, well-balanced, and reflected reality.

The performance of AVs and CAVs was evaluated at three levels: a network level, a nodal level, and a link level. The results that were of interest included the following: network delays, total travel times, average travel speeds, queue lengths at intersections, and travel times along key streets or avenues. Results were furthermore reported for different AV penetration rates.

4.1 Performance of Different Driving Behaviours

Figure 4 depicts the performance of the various levels of driving behaviour across all the performance indicators measured in this study. As shown in Figure 4 AVs and CAVs were able to provide noticeable improvements across all the performance indicators. Also, as a general trend, as driving behaviour becomes more advanced it increased the overall improvement provided. The performance indicators showing the highest improvement where the average queue lengths at the key nodes followed by the average delay experienced throughout the network.

The connectivity capability of CAVs provided clear improvement in the average delays experienced in the network, the average queue lengths, and the number of stops at key nodes. This could largely be attributed to CAVs having the Receive Signal Information parameter enabled, allowing CAVs to receive information on the next green phase at traffic signals. Thus, CAVs can adjust their speeds to reach the intersection during a green phase.

CAVs were not able to provide any significant improvements for other performance indicators such as travel times, average travel speeds, and were mostly outperformed by Normal AVs and All-knowing AVs. Thus, the additional connectivity capability added to CAVs does not imply that all the aspects of a network's performance would be improved.

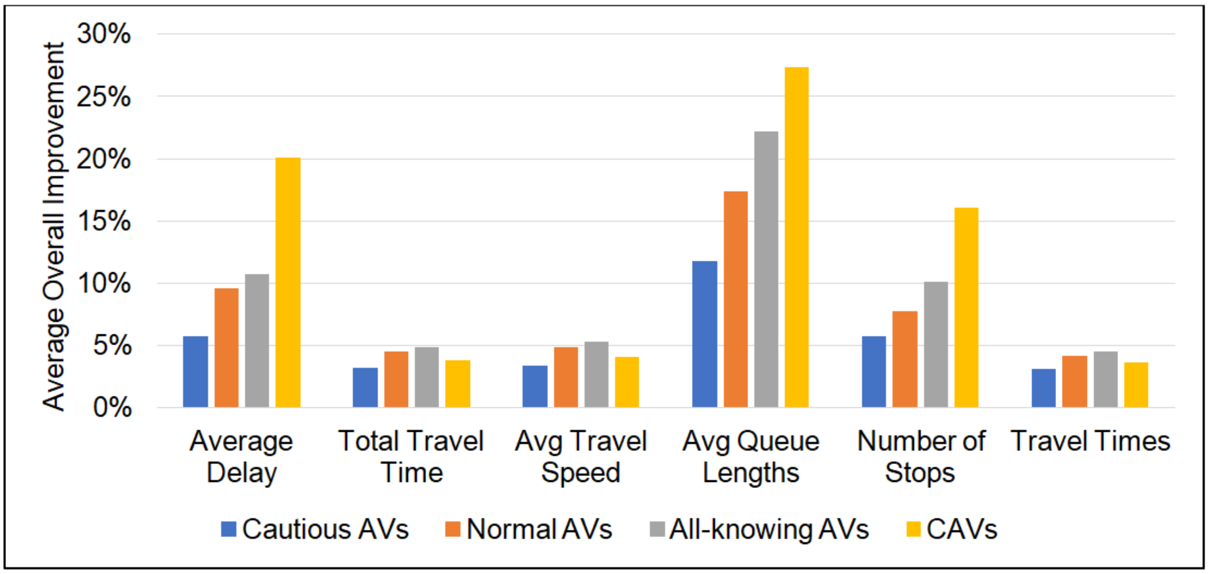


Figure 4: Performance of different driving behaviours

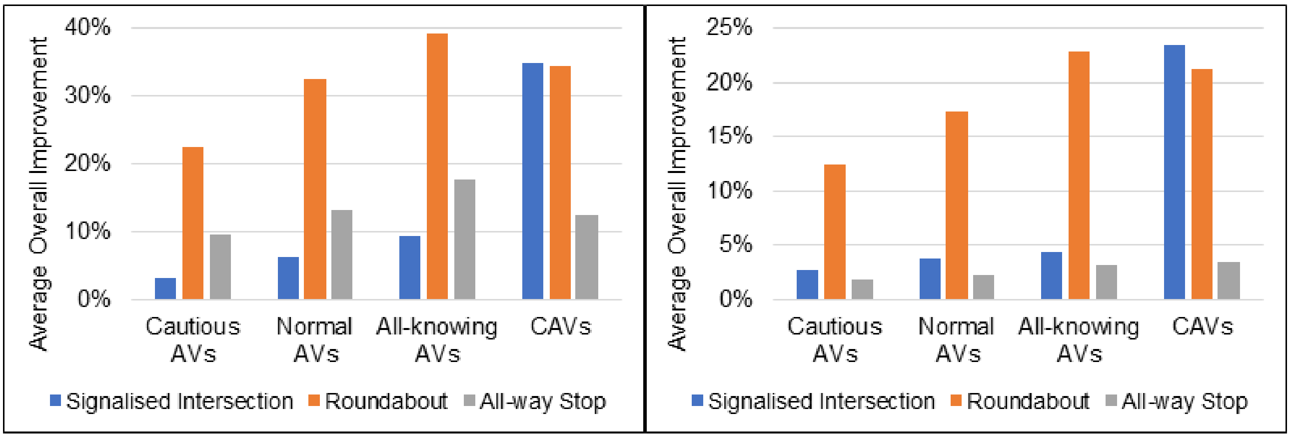
These findings are supported through discoveries by other studies (Olstam *et al.*, 2020; Patella *et al.*, 2019). Olstam *et al.* (2020) found that AVs can decrease delays and travel times, such improvements will also increase as the autonomous behaviour becomes more advanced. Patella *et al.* (2019) found in their study that CAVs were able to decrease travel time and average speed by as much as 35% and 50% respectively, supporting the findings of this study which is, that CAVs were able to provide improvement to the average speed and travel time through the network, however not to such an extent as the cited study.

4.2 Performance at Different Traffic Control Systems

Figure 5 (a) and (b) shows the overall average improvement in the average queue lengths and the number of stops provided by the different autonomous driving behaviours at the various traffic control systems, respectively. As shown in Figure 5 (a) and (b), similar to the other performance indicators, as the autonomous driving behaviour became more advanced it generally resulted in larger improvements in the traffic conditions at the intersections. However, there is a clear differentiation in the performance of the AVs depending on the traffic control systems being used at the intersection.

As shown in Figure 5 (a) and (b), Cautious, Normal, and All-knowing AVs were not very effective in improving the traffic conditions either at signalised intersections or at the all-way stops. However, AVs were found to be quite effective in providing improvements to the traffic conditions at the roundabout. This was evident even at the lowest level of autonomous driving behaviour.

As was the case for AVs, CAVs were also quite effective in improving the traffic conditions at the roundabout, although, unlike AVs, CAVs were also very effective in improving the traffic conditions at the signalised intersections. As before, due to the CAVs ability to receive information from the traffic signal, CAVs were able to adjust their speed to reach the intersections during a green phase, consequently reducing the need to stop and reducing queue lengths at the signalised intersections quite significantly.



(a) *(b)*

Figure 5: Performance at different traffic control systems; (a) Average queue lengths and (b) Number of stops

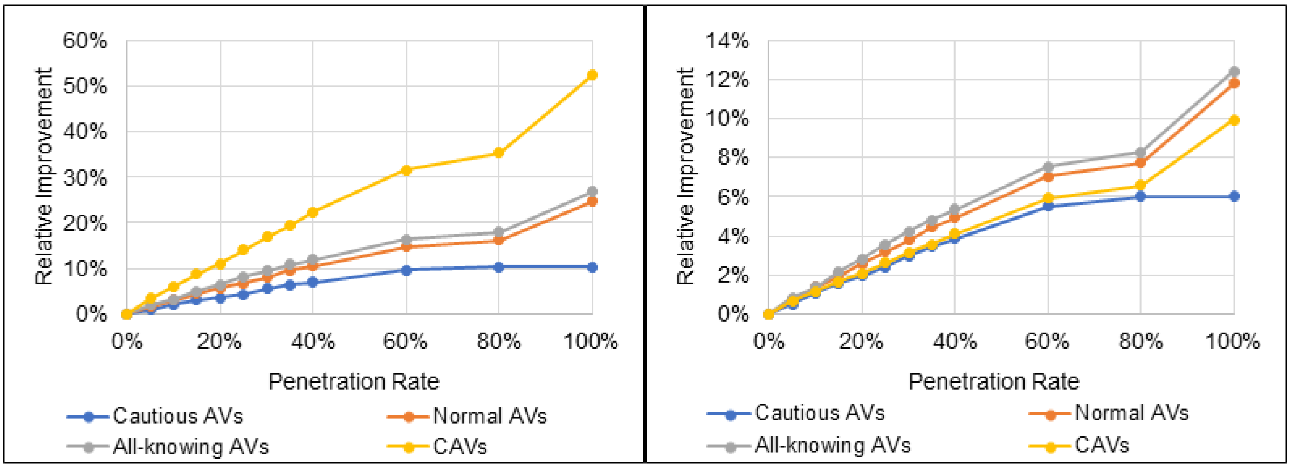
The all-way stop control appears to be the condition where AVs and CAVs had the least impact on traffic conditions. This is to be expected since both AVs and CAVs must still stop at the stop line as it cannot be avoided. However, AVs and CAVs did provide some improvement to the traffic conditions at the all-way stop, using less space than the traditional vehicle and providing a somewhat smoother traffic flow upstream of the stopping line. Olstam *et al.* (2020) supported the findings that AVs use less space but it is greatly dependent on their penetration rate.

4.3 The Effect of Penetration Rate

The potential improvements AVs are able to provide were very much dependent on their penetration rate, similar to the findings of Olstam *et al.* (2020). Figure 6(a) and Figure 6(b), respectively show the relative improvements AVs were able to provide to the average delays and travel times throughout the network at various penetration rates.

Figure 6 (a) and 6(b) show that, as the penetration rate of AVs increases i.e., as more AVs were introduced onto the road network, it generally results in increased improvements in the performance indicators. This trend was found across all the performance indicators measured in this study.

When increasing the penetration rate from 60% to 80% the effect of the relative improvement is at its lowest, as is evident in Figures 6(a) and 6(b). In other words, increasing the AV penetration rate from 60% to 80% appeared to provide little additional improvement in the average delays or travel times. Even for Cautious AVs, increasing the AV penetration rate from 60% to 100% was found to have little to no effect. This trend, where the penetration rate is increased from 60% to 80%, showed a reduced effect on the relative improvement provided and was apparent across all the other network performance indicators as well.



(a) *(b)*

Figure 6: Effect of AV penetration rate; (a) Average delays and (b) Travel time

4.4 Impact of Changing Traffic Volumes on CAVs

Figure 7 shows the average overall improvement provided by CAVs at various traffic volumes across all performance indicators. CAVs were quite robust in handling changes in traffic volumes. In some scenarios, the improvements to the performance provided by CAVs were greater when higher traffic volumes were present on the road network. This is clearly shown in Figure 7, for when 25% additional traffic was loaded onto the network, where CAVs were able to provide larger improvements in the performance indicators than for lower traffic volumes.

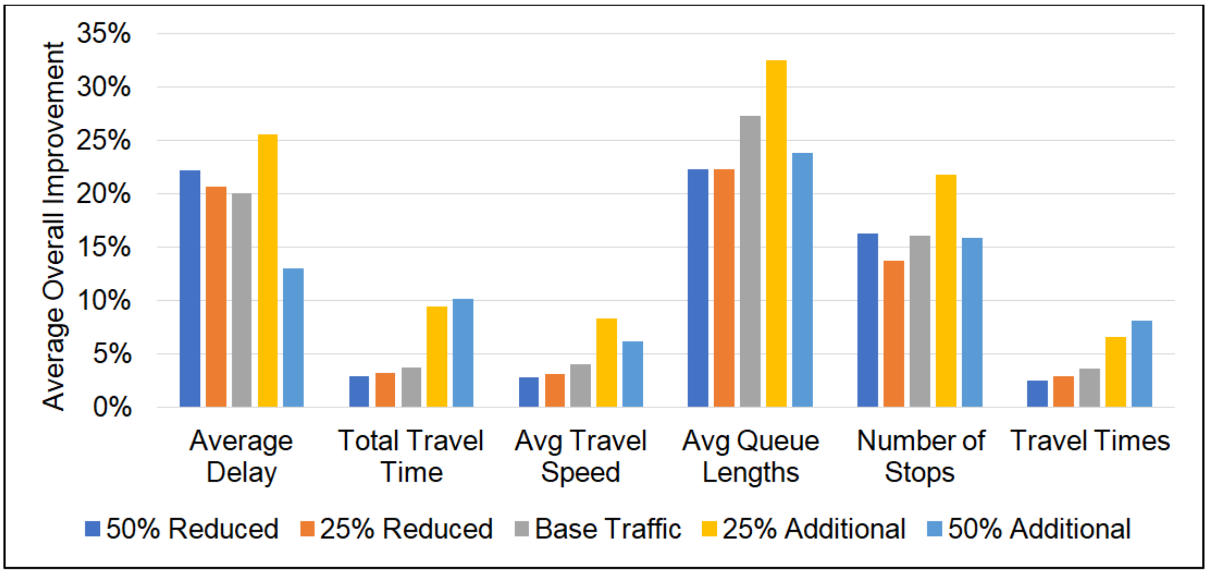


Figure 7: Impact of changing traffic volumes

However, a level is reached where the improvement provided by CAVs when traffic volumes are increased incrementally, start to diminish. This is evident when considering Figure 7, for when 50% additional traffic was loaded onto the network, the improvements provided by CAVs did decrease. However, CAVs were still able to provide significant improvements to the performance indicators compared to traditional vehicles.

The findings are consistent with the study of Asadi *et al.* (2019), where they found that CAVs were able to improve the capability of the road network to cope with increases in traffic and CAVs provided significant improvements in reducing congestion and delays.

5. CONCLUSION

The main aim of this study was to investigate how AVs and CAVs would operate in an urban environment. As the introduction of AVs on road networks is moving towards reality, it becomes essential to gain at least some insight into what such a future might look like. The findings showed that AVs were quite capable in improving various performance aspects through the network. The added connectivity of CAVs was particularly effective in reducing delays, queue lengths and the number of stops. However, the performance of AVs and CAVs are very dependent on their penetration rate.

The study also found that AVs were the most effective at improving traffic conditions at a roundabout control system. At signalised intersections and all-way stops AVs were not able to provide any major improvements. However, CAVs were especially effective at the signalised intersections, using much less space than traditional vehicles and the other AV levels, providing much smoother traffic flow conditions. These findings were anticipated since the capability of CAVs to receive information from traffic signals truly comes into play and provides significant improvements in the traffic flows.

The findings also showed that AVs were not that effective in improving the average speed and the travel time through the network. Also, the added connectivity of CAVs was found to have little effect in improving the travel times and travel speeds.

The study went further by investigating the robustness of the CAVs and how the performance of CAVs would change with variations in the traffic volume. The findings showed that CAVs were quite capable in handling changes in the traffic volume. In some cases, the improvements provided by CAVs were more significant during higher traffic volumes compared to lower traffic volumes. However, the improvements provided by the CAVs reduce at higher traffic volumes.

5.1 Recommendations for Future Research

A notable advantage of developing models like the one developed in this study is that these models can be updated and altered as needed. The models could be extended to also consider other performance indicators and modifications, such as the environmental impact of AVs and CAVs, the impact of other modes of transport as well as the effect of increasing the size of the network being modelled. Future research could also include investigating the sensitivity of the different driving behaviour parameters for defining the following behaviour, lane-changing behaviour, etc., for optimising the calibration and programming of AVs.

5.2 Final Remarks

This study shows that AVs and CAVs have significant potential in addressing and improving congestion parameters. However, for the implementation of AVs to be successful, sufficient planning and preparation is essential. This research provides a useful albeit significant first step in understanding the incremental introduction of CAVs and AVs in South Africa from a traffic engineering perspective.

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