Abstract

Autonomous Vehicles (AVs) have been the subject of extensive research in recent years and are expected to completely transform the operation of transport networks and revolutionise the automotive industry in the coming decades. Modelling detailed interactions among vehicles with varying levels of AVs penetration rates is essential for evaluating the potential impacts or benefits of AVs, and one such investigation is being performed within the InnovateUK funded ‘HumanDrive’ Project, in the U.K. This work has required the development of a behavioural model that incorporates microscopic level vehicle-to-vehicle interactions and has been based on pre-existing Adaptive Cruise Control (ACC) and lane-changing behaviour models that have been adapted in order to better replicate the limitations of AVs and allow the investigation of differing levels of intelligence or assertiveness.

The model has been implemented on two test networks, one, the M1 Motorway near Sheffield, and the second on the A19 corridor in the North East of England. This has allowed the investigation of the effects of AVs on the operation of real networks under various traffic conditions where the overall network benefits may be revealed, both in terms of advantages to AV drivers, but potentially disadvantages to non-AV traffic. Additionally, it has been possible to examine how these vary between differing road types and junctions.

Preliminary results have shown the effects on capacity, throughput, speeds, safety indicators and emissions, and have demonstrated that vehicle automation will potentially have a positive effect on network performance. This effect is made more evident as the penetration rate increases.

Keywords: autonomous vehicles, impact assessment, simulation

1. INTRODUCTION

The simulation of AVs has been investigated through the use of differing simulation software for many years and has typically been undertaken through making a range of simple approximations and changes to pre-existing behaviour, such as closer following distances, faster reaction times and ‘error free’ driving paradigms. A range of benefits have been reported such as Tientrakool et al., (2011), who reported that 100% market-penetration of vehicles equipped with automated braking capability and acceleration/deceleration decisions would be expected to increase the capacity of typical existing highways approximately by 43%, assuming 1.1 sec gaps between vehicles. Such capacity improvement could be further maximised if the technology of automated vehicles is combined with V2V (vehicle-to-vehicle) or V2I (vehicle-to-infrastructure) communication, with lane capacity reaching a maximum of 4000vph at 100% penetration rate (Shladover et al., 2012). Similarly, Bierstedt et al. (2014) found that lane capacity could be as much as doubled in a scenario with short gaps
between vehicles and aggressive accelerating/decelerating behaviour. This study also highlights the importance of fleet penetration with benefits found to be low until a high proportion (>75%) of the fleet were equipped with technology to allow enhanced following. Moreover, Studies also showed that the potential capacity gains may lead to a higher travel demand Levin and Boyles (2015). Many investigations have however been undertaken on unrealistic and/or small networks, which while enabling investigation of detailed operational trends, have not shown overall net benefit. The purpose of this paper therefore is to quantify the impact of AVs on the performance of the network using a new behavioural model that uses not only existing parameters, but also a different car following model that replicates more precisely the behaviour of AVs.

2. TESTBED DESCRIPTION

In order to capture the wide variety of effects likely to occur, the project examined two networks, the M1 Motorway near Sheffield in the U.K., and a more complex dual carriageway, the A19 near Newcastle. The M1 section examined is a 20-mile stretch of three lane Motorway, while the A19 section is a 21-mile two-lane dual carriageway along with associated parallel arterials. The two models are shown in Fig 1:

The modelled periods for the M1 were the AM peak (08:00 – 09:00) and the PM peak hour (17:00 – 18:00), with a travel demand of 37,401 trips and 42,430 trips and peak flows of 5300 vph and 5500 vph, respectively. For the A19 the modelled periods were 07:00 – 10:00 for the AM peak and 16:00 – 19:00 for the PM peak, with a travel demand of 196,812 and 224,220 trips and peak flows of 3800 and 4600 vph, respectively. The percentage of HGVs in the fleet composition was 8% for the M1 and 4% for the A19. The assumption was made that the introduction of AVs as an initial stage will only change the fleet composition of cars.

![Figure 1: Testbed networks of the M1 (left) and A19 (right)](image-url)
For each of the models, three test scenarios were examined reflecting different traffic conditions:

- **Base scenario**: This scenario represents the current traffic conditions in terms of travel demand.
- **Accident scenario**: This scenario represents the current traffic conditions where an accident occurs and blocks part of the road for a defined period of time (30 minutes).
  - **M1**: For the AM peak the accident occurred between 08:10 - 08:40, and for the PM peak between 17:10 – 17:40.
  - **A19**: For the AM peak the accident occurred between 08:15 - 08:45, and for the PM peak between 17:00 – 17:30.
- **Future scenario**: This scenario represents the future traffic conditions where a travel demand growth is assumed. For the M1, a demand growth of +5% was selected, and a demand growth of +2.5% for the A19.

For each of these scenarios, the two (AM and PM) time periods were examined, and for each of these five penetration rates assumed for AVs (0%, 25%, 50%, 75%, 100%) and two types of AV behavioural paradigm (Cautious and Assertive – detailed below).

### 3. METHODOLOGY

While many formulations of AV controller exist – none of these (for commercial) reasons have been endorsed by OEMS and as such all are arguably ‘R&D’ based formulations. However, it is possible to use a number which have been based on field tests, in the case of car following, this is shown below, and in the case of lane changing, we have adapted the existing behavioural paradigms within the Aimsun software to better reflect how an AV may act when selecting and making a lateral manoeuvre.

**Car-following model**

The ACC algorithm that is described in Milanes & Shladover, 2014 and was formulated based on real on-field experiments was implemented as a custom car-following model in Aimsun Next via microSDK. The main idea of the ACC controller is that it will determine the car following rule according to the clearance distance between the subject vehicle and the preceding vehicle, as follows:

The ACC controller has two range parameters: the lower detection threshold (e.g. 150m) and the upper detection threshold (e.g. 160m).

When the gap between a subject vehicle and its preceding vehicle is larger than the upper threshold, then the preceding vehicle is beyond the on-board sensors’ detection range, so the ACC controller will apply the speed regulation car following mode, aiming to reach the free flow speed and minimise the acceleration to 0.

If the gap is smaller than the lower threshold, the ACC controller will use the gap regulation mode, to help the subject vehicle follow the motions of the preceding vehicle. The gap regulation mode consists of two parts. The first part controls the gap (“gap component”) between vehicles and the second part the speed (“safety component”) between them at each time step. The k values that regulate gap and speed vary depending on the traffic conditions (see formulas below). For example, when there are high speed differences between vehicles, the k3 value that regulates
speed differences should be higher to ensure that the calculated deceleration at each time step is sufficient to prevent a potential collision.

When the gap is between the two thresholds, the controller will maintain the car following mode the vehicle used in the previous update interval. This introduces a hysteresis in the car following mode transition process. It will prevent frequent control mode change, thus creating a smooth speed profile for the subject vehicle. The two parameters are determined based on the detection capabilities of the sensors used in the testing vehicles. The implemented algorithm is presented in the flowchart below (Fig 2).

**Figure 2: Car following algorithm flowchart**

- **Speed Regulation mode:**
  \[ a_{sv} = k_1 \times (v_f - v_{sv}) \]
  - \( a_{sv} \): acceleration recommended by the ACC controller to the subject vehicle (m/s²)
  - \( k_1 \): gain in the speed difference between the free flow speed and the subject vehicle’s current speed (\( k_1 = 0.4 \) s⁻¹ in this study)
  - \( v_f \): free flow speed (m/s)
  - \( v_{sv} \): current speed of the subject vehicle (m/s).

- **Gap Regulation mode:**
  \[ a_{sv} = k_2 \times (d - t_{hw}v_{sv} - L) + k_3 \times (v_i - v_{sv}) \]
  - \( k_2 \): gain on position difference between the preceding vehicle and the subject vehicle (\( k_2 = 0.23 \) s⁻² in this study)
  - \( k_3 \): gain on speed difference between the preceding vehicle and the subject vehicle (\( k_3 = 0.9 \) s⁻¹ in this study)
  - \( d \): distance between the subject vehicle’s front bumper and the preceding vehicle’s front bumper (m)
  - \( t_{hw} \): desired time gap of the ACC controller (s)
  - \( L \): length of the preceding vehicle (m)
  - \( v_i \): current speed of the preceding vehicle (m/s)

The two parameters are determined based on the detection capabilities of the sensors used in the testing vehicles. The implemented algorithm is presented in the flowchart below (Fig 2).
Lane Changing model

In order to have a complete and fully operational model that describes the operation of AVs, it is necessary to examine all cases that are not only car-following. In this Section, the elements of the Aimsun Next logic that affect lateral movement and lane choice decisions, as well as adjusting to vehicles in other lanes are considered. The basis for the lane changing model is the Gipps lane-changing decision model (Gipps, 1986), with amendments that replicate the automated behaviour. Those are described in detail in the subsections below.

Gap acceptance for lane changing

The primary purpose of the Gap Acceptance model is to ensure that a vehicle that changes lane does not move into an ‘unsafe’ gap. Equally it ensures that an unsafe gap is not imposed on the new vehicle to the rear. This includes the following:

Cooperation

Vehicle cooperation consists of two parts. The vehicle that changes lane has to “target the gap” on the adjacent lane and the vehicle that is on the adjacent lane has to “cooperate” and create a safe gap for the vehicle to enter. The acceleration/deceleration of every AV is determined by the car following model that was described in the previous Section. However, it is possible that the Gipps model calculates different values of deceleration when there is a lane change. In each of the cases (target gap/cooperate) the deceleration of the vehicles will be the most restrictive value that results from the ACC model and the Gipps model.

Aggressiveness

This parameter allows vehicles to enter shorter gaps without forcing its immediate rear vehicle to brake, followed by a relaxation process to gradually recover the stability of the car following models. The aggressiveness % controls the sensitivity of a vehicle to the deceleration of the leader, determining how short can these gaps be. That is, if aggressiveness is set to 100% (which should not be used, it's the most extreme case) this means zero sensitivity, and the new allowed gap (at all speed situations) would be that needed at a stop situation (as if the vehicle was parking). For an aggressiveness of 0%, the full “normal” save gap is used, with no change in sensitivity. All intermediate values will make the gap shorter according to the aggressiveness % and also to the current speed of the leader. AVs are likely to have a 0% aggressiveness (high levels of aggressiveness might affect car following stability). However, different levels of aggressiveness can be tested, that follow a truncated normal distribution between the minimum and maximum value.

Distance Zones

In order to achieve a more accurate representation of the driver’s behaviour in the lane changing decision process, two different zones inside a section are considered, each one corresponding to a different lane changing motivation. The distance up to the end of the section characterizes these zones and which is the next turning point.

Distance Zone 1: Mainly it is the desired turning lane that affects the lane changing decision. Vehicles that are not driving on a valid lane (i.e. a lane where the desired turning movement can be done) tend to get closer to the correct side of the road where the turn is allowed. In this zone vehicles look for a gap and may try to accept it without affecting the behaviour of vehicles in the adjacent lanes.
Distance Zone 2: Vehicles are forced to reach their desired turning lanes, reducing the speed if necessary and even coming to a complete stop in order to make the lane change possible. Also, vehicles in the adjacent lane can modify their behaviour in order to allow a gap big enough for the lane-changing vehicle.

It is possible that an AV will have different distance zones than a non-AV that could be either larger to ensure turns are made or perhaps shorter with more aggressive behaviours from AVs. The distance zones are set up for each turn (Fig 3) and for each vehicle type as a factor of the turn distance zone, following a uniform distribution between the minimum and maximum value (Fig 4).

Figure 3: Distance zones set for turns
In order to promote or discourage the overtaking, there are two parameters that the user can define: ‘Overtake Speed Threshold’ and ‘Lane Recovery Speed Threshold’.

**Overtake Speed Threshold:** The percentage of the desired speed of a vehicle below which the vehicle may decide to overtake. This means that whenever the leading vehicle is driving slower than Overtake Speed Threshold % of the following vehicle’s desired speed, the following vehicle will try to overtake.

**Lane Recovery Speed Threshold:** The percentage of the desired speed of a vehicle above which a vehicle will decide to get back into the slower lane after it has completed the overtake manoeuvre.

Therefore, if a vehicle with a desired speed of 100 mph was to follow a vehicle at a speed of 90 mph, it would try to overtake. Subsequently, when it achieved a speed of 95 mph, it would return to its original lane.

The Lane Recovery Speed Threshold value is greater than Overtake Speed Threshold, otherwise some overtaking manoeuvres may be aborted as they start. Similarly, if these values are set too small, vehicles will not initiate an overtaking manoeuvre unless the speed gap is very large and would return to the slower lane too soon.

The Overtake Speed Threshold and the Lane Recovery Speed Threshold are shown in Fig 5 below:
Give way behaviour

The gap required to make the manoeuvre is determined by the time spent waiting for a gap to appear in the opposing flows. The initial value is MaximumGap; the final value is MinimumGap. After waiting for GapReductionStartTime * MaximumGap seconds, the gap is progressively reduced, reaching the minimum gap value after GapReductionEndTime * MaximumGap seconds (Fig 6).
AVs can be either very cautious and keep waiting for a safe gap or less cautious with the gap reducing rapidly. The initial and final safety margins are set up for each turn (Fig 7) and each vehicle type provides a range of Safety Margin Factor values as multipliers for the safety margin (Fig 8), thus affecting the behaviour by vehicle type.

Figure 7: Initial and final safety gap

Figure 8: Safety margin factor
Parameters

Table 1 shows the different values that were used to replicate the behaviour of the two types of AVs that were used for the experiments, and how they compare with the values for a human vehicle (HV).

Table 1: Parameters used in the experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cautious AV</th>
<th>Human Vehicle</th>
<th>Assertive AV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Zone Factor</td>
<td>1.5</td>
<td>0.8-1.2</td>
<td>1.25</td>
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<tr>
<td>Aggressiveness Level</td>
<td>0.0</td>
<td>0.0 – 1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cooperation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Overtake Speed Threshold</td>
<td>80%</td>
<td>90%</td>
<td>80%</td>
</tr>
<tr>
<td>Safety Margin Factor</td>
<td>2.0 (x final safety gap)</td>
<td>1.0 (x initial/final safety gap)</td>
<td>1.0 (x final safety gap)</td>
</tr>
<tr>
<td>Reaction Time in car following</td>
<td>0.1 sec</td>
<td>0.8 sec</td>
<td>0.1 sec</td>
</tr>
<tr>
<td>Reaction time at stop</td>
<td>0.1 sec</td>
<td>1.2 sec</td>
<td>0.1 sec</td>
</tr>
<tr>
<td>Reaction time at traffic light</td>
<td>0.1 sec</td>
<td>1.6 sec</td>
<td>0.1 sec</td>
</tr>
<tr>
<td>Time Gap</td>
<td>1.0 sec</td>
<td>1.2 - 5 sec</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>Clearance Distance</td>
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<td>-</td>
<td>150m</td>
</tr>
<tr>
<td>Speed acceptance</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Note: For parameters that have deviation such as desired speed or clearance between vehicles at standstill, a standard deviation of 0 was set for AVs.

4. NETWORK PERFORMANCE

For the sake of brevity, we chose to present in this paper only the results from the Assertive type of AVs (which show more optimal behaviour compared to the cautious type) and for the M1 (as the A19 shows a similar pattern). The analysis that follows focuses on the AM period, as the PM peak shows similar pattern. The outputs were derived as an average of 5 simulations for each of the examined scenarios.

M1

Speed Profiles

The M1 experiences a few localised bottlenecks along the corridor for the AM and PM peak hours. AVs dilute the speed drops, even at a low penetration rate. However, in free flow conditions with low levels of congestion a slight decrease in the average speed is observed at high penetration rates (Fig 9). This occurs mainly for two reasons. Firstly, due to the fact that AVs are compliant to the speed limit of the road. (The parameter of speed acceptance for HVs was set to 1.1 meaning that they can drive at speeds 1.1 times the speed limit, as opposed to AVs that have a speed acceptance of 1.0). Second, is that they have a lower overtake speed threshold, which makes them overtake/change lane less than HVs, which results in car following at lower speeds (i.e. if the preceding vehicle is an HGV).

Fig 9 and Fig 10 show the speed profile for the base scenario for each of the penetration rates of AVs for the southbound and northbound direction of the M1, respectively.
Figure 9: Speed profile for each penetration rate for the southbound direction (Horizontal scale 20 miles)
Roundabouts

The introduction of AVs not only has an impact on the motorway, where the speeds are higher and there are low levels of congestion, but also at areas where speeds are lower and congestion levels higher (i.e. roundabouts). Results show that AVs can cause a significant reduction in delays for the congested arms of the roundabouts at the M1 Junctions. The lower reaction times combined with the shorter headways between vehicles at car following and standstill situations has a great impact on reduction of delays and the overall operation.

The following figures show how delays decrease for each of the penetration rates, for two highly congested roundabouts of the network.
Meadowhall Roundabout

Figure 11: Meadowhall roundabout

Figure 12: Delay decrease on congested arms of Meadowhall roundabout
Accidents

Next, the case of an accident in the southbound and northbound direction of the M1 was examined. The accident occurs on each of the directions and has a duration of 30 minutes. Results show that the performance of the network is improved when there is an accident. The ability of AVs to create gaps for lane changing combined with the lower reaction times is likely to improve the behaviour of vehicles at locations where an accident has occurred and result in faster clearance of queues.
Fig 15 and Fig 16 show the speed profiles for the southbound and northbound direction respectively.

Figure 15: Speed profile for the accident scenario for the southbound direction of the M1 (Horizontal scale 20 miles)
Both for the southbound and northbound direction of the M1 there is significant
decrease in delays, with benefits maximising at 100% penetration rate, where delays
are expected to decrease more than 35%. The benefits of the efficient behaviour of
AVs at locations where accidents occur in terms of delays decrease is shown in Fig
17:

**Figure 16: Speed profile for the accident scenario for the northbound direction**
(Horizontal scale 20 miles)

**Figure 17: Delay decrease at locations with accidents**
**Emissions**

It is difficult to estimate the potential of AVs in the reduction of greenhouse gas emissions (GHG) due to a series of variable factors that condition the functioning of the future transport system, such as travel demand and land use. However, results suggest that GHG are likely to reduce for the examined pollutants (CO\(_2\), NO\(_x\)). The chart below (Fig 18) shows how those pollutants are likely to decrease for each penetration rate as compared to 0%.

![Graph showing emissions reductions compared to base](image)

*Figure 3: Emissions reductions compared to base*

5. **CONCLUSIONS**

In this paper we have shown how micro-simulation modelling is being used in the HumanDrive project being undertaken in the UK. As part of this we have demonstrated the variety of techniques and evaluation methodologies that are required in order to assess the potential impact that the introduction of AVs. Results show that overall the introduction of AVs is likely to have a positive impact on the network performance. The main conclusions that were derived from this approach are:

- AVs appear to provide more benefits in congested situations such as complex merges and accidents. These benefits result in higher throughputs and average speeds in the motorway mainline and are mainly due to lower reaction times at traffic lights and better behaviour in stop-and-go situations. In free flow situations, a slight decrease in average speeds is observed, due to less lane changing and lower speed acceptance.

- Delays caused by an accident can be significantly reduced with high penetration rates; up to ~45% reduction.
• There is a reduction in emissions that maximises at 100% penetration rate; up to ~8% reduction of CO$_2$ and NO$_x$ emissions

• More homogeneous distribution of congestion across the M1 even at low penetration rates of assertive AVs

Further work

The next step for assessing the impact vehicle automation will be to examine how autonomous vehicles (AVs) would behave using V2X technologies (CAVs). For this purpose, a new car-following algorithm has been developed based on cooperative adaptive cruise control (CACC) and a new V2X application in Aimsun Next. A series of tests are being currently undertaken to quantify the impact of CAVs on network performance.

ACKNOWLEDGEMENTS

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