# Lane Based Platoon Control of Homogeneous Platoons

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# Lane Based Platoon Control of Homogeneous Platoons

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***Abstract*—The benefits of both homogeneous and heterogeneous platooning of automated vehicles have been reported by many studies. One commonality among such studies has been that platooning does provide a positive impact on traffic dynamics through increased average speeds, flow and capacity. Also due to platooning, fuel consumption is reduced and hence positively impacts the environment through reduced emissions. This is even more so when the percentage of automated vehicles is significantly higher than non-automated vehicles. While obvious that today's and near future highways will have automated and non-automated vehicles coexisting, research points towards homogeneity in order to fully realize the benefits of platooning. Research also indicates that when platooning allows maneuvers such as merging and splitting of platoons, these maneuvers present reduced benefits in traffic dynamics and consequently its impact on the environment. ln light of these observations, this study presents a highway architecture that implements and controls lane and destination based fixed-routed platoons of automated vehicles with minimal lane changes. The study demonstrates that confining platoons to vehicles of same off-ramp destinations reduces the need for lane changes to a predetermined number, allows for more stable and longer strings of vehicle platoons of up to 24 vehicles per platoon. When compared to conventional traffic, the model presented shows between 135% and 156% increase in average speeds, 70% reduction in travel times and between 39% and 43.5% increase in highway throughput. The open-source traffic simulator, Simulation of Urban Mobility (SUMO) is used to simulate the model presented in this study.***

**Keywords—platooning, automated vehicles, homogeneous, SUMO**

## I. INTRODUCTION

Vehicular transportation has been and will continue to play a crucial role in the day-to-day lives of many. In recent years however, traffic congestion in urban areas, has become a major challenge, significantly affecting traffic flow, travel times and speeds while increasing fuel consumption and vehicular emissions. Automated Highway Systems (AHS) which employs the use of sensing technologies, communication and of control to estimate, model, management and control traffic on highways has been a promising approach to curb traffic congestion, increase traffic flow while adding safety to highway travel. AHS is further divided into four main branches, sub-microscopic, microscopic, mesoscopic and macroscopic control techniques.

Macroscopic models describe traffic dynamics such as traffic flow, density and average speeds, while microscopic models describe vehicle driver behavior considering vehicle positions, velocities and accelerations in addition to inter-vehicular communications. Mesoscopic models come between microscopic and macroscopic models. They utilize probabilistic or statistical methods to model individual vehicle dynamics and interactions in groups while sub-microscopic models describe detailed vehicle parts and driver parameters [1]. This study is mainly in the domain of microscopic modeling since the study is based on platooning, although macroscopic parameters such as average speeds, travel times and throughput are used for evaluation purposes.

The AHS control architecture consists of five hierarchical layers: Network, Link, Coordination, Regulation, and Physical. The Network layer manages the routing of vehicles through the highway network, the Link layer controls the highway density on a microscopic scale, the Coordination layer handles the inter-vehicular communications, the Regulation layer executes maneuvers by providing feedback-based control inputs to the vehicle actuators, and the Physical layer contains the vehicle dynamics. This study focuses on the coordination and regulatory layers even though network, link and physical layer parameters are utilized.

Vehicle automation has come a long way, from simple Cruise Control (CC), where vehicles are set to travel at fixed speeds, to Adaptive Cruise Control (ACC), where sensors provide information such as speed and position of neighboring vehicles to the controlled vehicle for speed adjustments, to Cooperative Adaptive Cruise Control (CACC) where control is enhanced through Inter-Vehicular Communication (IVC). Vehicular platooning with CACC is reported to significantly improve traffic flow and speeds while reducing travel times and vehicular emissions as reported in [2] and [3]. In this study, we refer to CACC platoons as platoons for simplicity.

Homogeneous traffic of automated vehicles confers far more improvement in traffic dynamics than heterogeneous traffic for obvious reasons. Effective communication between vehicles allows for timely adjustments by neighboring vehicles to allow smoother traffic flow. Obstructing vehicles behavior can be communicated ahead of time for an effective plan of action to be taken by the vehicle being obstructed. Moving in platoons also means more streamlining of vehicle speeds and reduced air-drag. These and more reasons are why a common conclusion in the literature on vehicular platooning is that in a heterogeneous traffic where automated and non-automated

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vehicles ply the same roads or highways, the positive impact of platoons is more obvious with higher percentages of platoons as reported in [4]. This can be attributed to different driving behaviors, obstruction of automated vehicles movement and preferred lanes of non-automated vehicles.

Further, as reported in [5], when maneuvers such as mergers and splits are modeled, platooning presents less positive impact on traffic dynamics due to the time needed to carry out such maneuvers. In their study, simulation results of different percentages of automated vehicles are studied with and without maneuvers. However, by allowing the formation and dissolution of platoons during transit, a measure of time is required for such actions which invariably impacts traffic. Also, although the desired lane of a platoons is considered, it is based on the maximum speed of the leader of the platoon and not the final destination of the platoon. Therefore, further lane changes may be required if the leader of the platoon leaves and a new leader which has a different maximum or desired speed assumes leadership. Platoons are also formed between vehicles who have similar routes but may have different exit ramps, this may also introduce further lane changes and splits.

By way of reiterating, mixed traffic of automated and non-automated vehicles yields less improvement than in homogeneous traffic. The implementation of maneuvers further negatively impacts traffic dynamics. And finally, numerous and uncontrolled lane changes negatively impact traffic dynamics in the platooning of vehicles and vehicular traffic in general.

It stands to reason given the above that, by dedicating special lanes on existing highways , automated vehicles can be kept separate from non-automated vehicles on dedicated lanes. This does not only allow for the attainment of the full benefits of platooning but also alleviate public concerns of the coexistence of autonomous and non-autonomous vehicles in mixed traffic while the technology is allowed to mature.

By further sorting vehicles in specific lanes according to their destinations, lane changes can be drastically reduced, and by so doing reducing the number of lane changes to a predetermined number. Random formation and dissolution of platoons can be avoided by considering the exact off-ramp destinations of vehicles during formation. Unlike the mainstream concept of cohabitation of autonomous and non-autonomous vehicles, this study considers a somewhat semidetached approach to this relationship. Viewing the network architecture in this study as an extension or modification to an existing highway structure where only autonomous vehicles ply.

The highway network is designed to suite the above requirements and constraints. It presents a subway-like representation of a highway, where much like trains, platoons depart at time intervals dependent on the current occupancy of the highway, only change lanes at designated stations, use varied lane speeds to avoid collisions and allow for the manipulation of average highway speeds. Parameters such as average speed, highway throughput and travel times are used to evaluate the validity of the model.

The remainder of this paper is organized in the following manner, section II presents a literature review on the related studies covering homogeneous and heterogeneous platooning of vehicles, the impact of lane changes, merging and splitting maneuvers on platooning and traffic dynamics in general. Section III presents the simulator used for this study Plexe-SUMO, and the peripheral platforms for simulation of platoons namely, Omnet ++ and Veins. Section IV presents the experimental setup for this study and details of the Traffic Control Interface (TraCI) script used for controlling the network, lanes and platoons of the simulation. Section V presents the results and analyses of the study. Finally, section VI presents the conclusions of the study and future studies.

## II. Literature Review

In the literature concerning automated highway platoons, two main branches emerge, homogeneous traffic where all vehicles in the study are automated and heterogeneous, where a given percentage of the population of vehicles studied are autonomous while the remainder are non-automated. Researchers in such studies often evaluate or validate their studies in terms of increased highway throughput, average speed, travel time, reduction in fuel consumption etc.

In [7] a homogeneous traffic of vehicle platoons of random sizes was studied, the study reported for an average platoon length of 20, the capacity of the highway improved by a factor of four. [8] evaluated the impact of platooning on air drag on different platoon sizes and spacing. This study reported up to 40% reduction in air drag for a four-vehicle platoons spaced at a fourth of the length of the vehicle. The reduction in air drag directly increases fuel savings and emissions. These obvious benefits are impacted negatively in a mixed traffic environment.

A micro-simulation conducted in [9] on a 15 mile urban freeway corridor to examine the impact of platooning in mixed traffic showed significant improvements in average speeds (from 53.6 km/h to 63.9 km/h) for truck platoons and (from 79.3 km/h to 84.3 km/h) for passenger cars while presenting no adverse impact on non-automated vehicles. In fact, it reports that at certain locations, traffic conditions improved as a result of the operations of the platoons.

With specific regards to CACC platooning, a common consensus among researchers is that the improvement in traffic flow dynamics and environmental benefits is directly linked to the market penetration of CACC enabled vehicles. Many studies have used varying percentages of CACC enabled vehicles to represent the degree of market penetration. Such studies report that higher penetration levels show more significant improvements in traffic flow dynamics and environmental impact. For instance, in [10], a varying combination of ACC, CACC and “Here I Am” (HIA; non-automated vehicles fitted with radios to broadcast a message including their speed and locations). Their study points out that increase in lane capacity was not significant at lower concentrations of CACC vehicles, but showed substantial increase after a point where penetration rate was substantial, following a quadratic distribution.

Further studies that support this claim can be found in [11], [12]. The impact of lane changes on traffic performance is an area that has received the attention of road traffic researchers for decades. Lane changing maneuvers can have a substantial influence on traffic flow characteristics as a result of their interfering effect on surrounding vehicles [13]. For instance in [6], they modeled lane-changing traffic dynamics in the framework of kinematic waves to investigate the impact of lane changes. The study reports a reduction in lane capacity of between 8-18% depending on the lane changing threshold.

Other research points to the fact that when lane changes are planned and controlled they present positive impact on traffic. In [14] the combined effects of variable speed limits and lane change control on traffic dynamics and the environment were studied. This study reported improvement in travel time (26-32%) as well as significant reductions in emissions (16-24%).

Another area of importance is the impact of maneuvers such as mergers and splits on the performance of platoons as in [5]. The results from this study point out that platoon maneuvers result in about 5-15% flow and speed reductions regardless of penetration rate of CACC vehicles in the simulation. This suggests that even at high penetration rates, platoon maneuvers still pose a threat to the realization of the full benefits of platooning.

In summary, vehicle platooning does present a significant amount of positive impact on traffic flow and the environment. However, these benefits are reliant on the penetration level of the technology, showing less positive impact at lower penetration levels and more at higher penetration levels. They are also subject to the impacts of maneuvers such as lane changes, mergers and splits. This study therefore presents an investigation into a control model that mitigates these impacts through dedicated highway lanes for platoons, lane change control and controlled departures of platoons and what added benefits such a model adds to an existing highway traffic of non-autonomous vehicles.

## III. Simulation Architecture

The base platform on which the simulation of this study is done on is SUMO [1], an open source road traffic simulation platform. Since the simulation in question is with regards to platoons, it is carried out on a modified version of SUMO, Plexe-Sumo. Plexe-Sumo is one of the two main components of the overall Plexe architecture. Basically, Plexe-Sumo interfaces with Plexe-Veins which is an extension of Veins [15].In turn, Veins is an extension of OMNeT++ [16] which is a modular, component-based C++ simulation library and framework for building network simulators. The two together connected via TraCI form the Plexe framework. Plexe ships with a number of pre-existing car-following models, CC and ACC and CACC models. Given this architecture, Plexe leverages the IEEE 802.11p based vehicular communication stack, channel models and mobility nodes of Veins along with the traffic simulation framework of SUMO to present researchers with a realistic and wholesome approach to simulating and studying platooned vehicles [15].

TraCI as an interface allows for the retrieval and setting of for instance simulation, vehicle, edge etc parameters such as simulation, vehicle speed, position, accelerations and routes, edge vehicle counts, IDs etc. These can then be used by the python script to control the simulation. In addition to the Plexe-Python demo provided in [15] this study takes as a precursor the work presented in [17].

## IV. Simulation Setup

In this study, the name "plane" is a concatenation of the words platoon and lane arising from the fact that platoon objects, created by the plane class below, are strictly based on their lanes and off-ramp destination. Figure 1 presents the control architecture of the plane model presented in this study. The plane class is a custom made class that allows for the creation and control of plane objects for the simulation. The simulator which takes inputs from the plane class, utility functions and cruise-control parameters controls the simulation through Traci by getting and setting network, edge, lane, vehicle etc. parameters . Traci interfaces with Sumo and Veins on the one hand and the simulator on the other. In this way, through the simulator, the above mentioned parameters can be access and manipulated. Key components of the model are discussed below.

### A. The Planes Class

The planes class is responsible for the creation of plane objects. Within the class are the following main functions:

- The topology constructor which determines platoon topology and capable of dividing plane vehicles into primary and secondary platoons for extended platoon lengths.
- The speed and spacing policy which determines speed of a plane dependent on its lane and updates the inter-platoon and intra-platoon spacing among vehicles and platoons.
- The Flag searching algorithm which determines whether a plane is at a lane change location or not and at a prefixed distance from the flag initiate lane change of the platoon.
- The move to next best lane function that allows a plane to move a lane lower towards its destination.
- The Free arrived vehicles function which switches the active controller of a plane to ACC upon reaching the lowest speed lane (lane 0) and controls the exit of the plane out of the highway.

### B. The Simulator

The Planes Simulator module handles the starting, vehicle insertion, running, vehicle and network parameters and closing of the simulation, it is also the environment in which plane objects reside. There are four main functions:

- A customized add vehicle policy which adds, spaces and names vehicles according to lane and destination.
- A lane generator function which generates the list of platoon lanes.
- A route assigning function that assigns a route to vehicles dependent on their lanes.
- A sort platoon function with sorts out the order of vehicles in a platoon.
- Communicate current plane topology, speed, locations

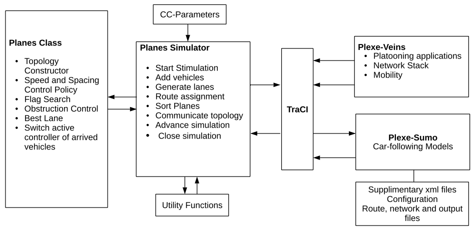


Fig. 1. Control Structure

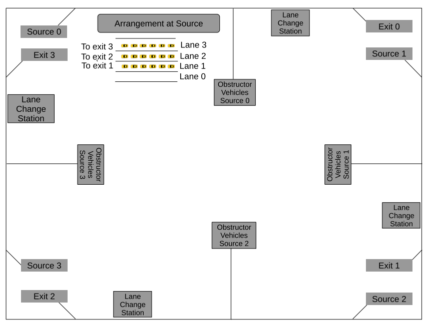


Fig. 2. Network structure

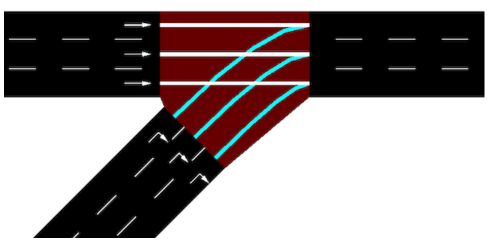

Fig. 3. On-ramp lane configuration

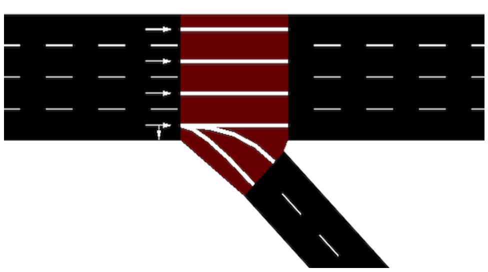

Fig. 4. Off-ramp lane configuration

through Traci to Veins and Sumo • It also starts and closes the simulation.

## C. The Network Setup

This study considered 3 different scenarios, for easy referencing we refer to these scenarios as scenarios one, two and three . Scenario one is of a 100% automated vehicle traffic, scenario two is of mixed traffic of automated and non-automated vehicles while scenario three is of 100% non-automated vehicle traffic. The same network is used in all 3 cases except for a slight modification in scenario two to be be discussed shortly. The network is a ring-road highway consisting of 4-lane edges, 4 on-ramps (8 in the case of scenario two) and 4 off-ramps. Each on-ramp is linked to a source and each off-ramp to a sink. It also has 4 lane-change stations where platoons are allowed to change lanes. They are placed at designated locations from each off-ramp to allow platoons exiting the highway ample time and space to change lanes and exit as a platoon of ACC vehicles. Only 3 out of the 4 lanes support CACC platoons, i.e lanes 1-3. Lane 0 is reserved for exiting vehicles, non-automated vehicles and can also be viewed as hard shoulders for vehicles that drop out of a platoon. The network is approximately 35km in length. Fig. 2 shows a bird's eye view of the network.

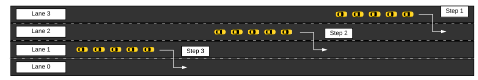


Fig. 5. Lane Change Station Protocol

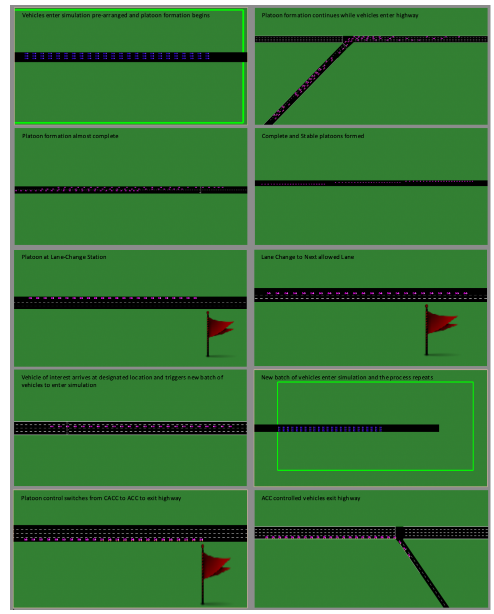

Fig. 6. Stages of Simulation

For scenarios one and two, all source lanes are directly connected to their corresponding lanes on the main highway through priority regulated junctions, vehicles have no access to any other lanes when entering the highway, as shown in Fig. 3. This ensures that platoons have direct access to their desired lanes and hence are not required to change lanes.In scenario three, vehicles are allowed two lanes through which they can access the highway. All off-ramps are designed to be accessed by only the innermost lane traffic as shown in Fig. 4.

### D. Car-Following Models

The car-following models as presented by [18] are employed by [15] and hence are the models that are used in this study. For simulation of conventional traffic, the CC acceleration of a vehicle is as given below:

$$\ddot{x} = -k_p(\dot{x} - \dot{x_{des}} + \eta) \tag{1}$$

where:
$(\dot{x} - \dot{x_{des}})$ : error between actual and desired speeds
$k_p$: controller proportional gain
$\eta$ : random perturbation that accounts for actuator and sensing imprecision

When vehicles are controlled by ACC, the desired acceleration of the $i^{th}$ vehicle is given as:

$$\ddot{x}_{i\_des} = -\frac{1}{T}\left(\dot{\varepsilon}_i + \lambda\delta_i\right) \tag{2}$$

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}i - 1 \tag{3}$$

$$\delta_i = x_i - x_{i-1} + l_{i-1} + T\dot{x}_i \tag{4}$$

where:
$T$ : Time headway in seconds
$\dot{\varepsilon_i}$: Relative speed between the$i^{th}$ vehicle and its front vehicle
$l_{i-1}$: Length of front vehicle
$\delta_i$: Difference between desired distance $T\dot{x}_i$ and actual distance $x_i - x_{i-1} + l_{i-1}$
$\lambda$: Modeled parameter chosen to be $> 0$

For a platoon of $n$ vehicles, $n-1$ vehicles (followers) are CACC controlled while the lead vehicle is ACC controlled. The acceleration of the $i^{th}$ vehicle is dependent on both the leader and front vehicle accelerations as shown below:

$$\ddot{x}_{i\_des} = \alpha_1\ddot{x}_{i-1} + \alpha_2\ddot{x}_0 + \alpha_3\dot{\varepsilon}_i + \alpha_4(\dot{x}_i - \dot{x}_0) + \alpha_5\varepsilon_i \tag{5}$$

$$\varepsilon_i = x_i - x_{i-1} + l_{i-1} + gap_{des} \tag{6}$$

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1} \tag{7}$$

where:
$\ddot{x}_0$: Leader acceleration
$\dot{x}_0$: Leader speed.
$\ddot{x}_{i-1}$:Front vehicle acceleration.
$\dot{x}_{i-1}$: Front vehicle speed
$\varepsilon_i$: Difference in desired and actual gap
$gap_{des}$: Constant desired gap

The variables $\alpha_1$ to $\alpha_5$ are defined as follows:

$$\alpha_1 = 1 - C_1 \tag{8}$$

$$\alpha_2 = C_1 \tag{9}$$

$$\alpha_3 = -\left(2\xi - C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\right)\omega_n \tag{10}$$

$$\alpha_4 = -C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\omega_n \tag{11}$$

$$\alpha_5 = -\omega^2 \tag{12}$$

where:
$C_1$: Weighting factor between the leader and preceding vehicle accelerations with a default value of 0.5
$\xi$: Damping ratio, default value of 1
$\omega_n$: Controller bandwidth

To model the actuation lag introduced by the power-train dynamics of the physical vehicle, the actual applied control input is a modified version of the desired acceleration produced by (5) and (2), taking the lag into account as shown in (13) and (14).

$$\ddot{x}_n = \beta\ddot{x}_{des_n} + (1-\beta)\ddot{x}_{n-1} \tag{13}$$

$$\beta = \frac{\Delta_t}{\tau + \Delta_t} \tag{14}$$

where:
$n$: the $n^{th}$ step
$\Delta_t$: simulation step
$\tau$: modeled time parameter, default value 0.5s.

### E. Scenario Description

The same network is used for all three scenarios except for the 4 additional sources and on-ramps in scenario two. All three simulations have duration of 60 minutes. Also, the same vehicle models,maximum allowed speeds and accelerations are used in all simulations. Scenarios one and two employed the model in this study while scenario three is setup as conventional traffic matching the performance of scenarios one and two.

**Scenario One:**

In this scenario, vehicles enter the network as platoons of 24 vehicles per lane at time intervals (insertion time) dictated by the network occupancy. 72 vehicles per source and a total of 288 vehicles network-wide enter the simulation at each insertion time. It is assumed that a file of vehicles of common destination is formed prior to entering the simulation. Hence at insertion, the lane change mode of each vehicle is set to fixed mode. Meaning that no lane changes are allowed until the vehicles are at lane-change stations where lane changes are allowed again. With the exception of the lead vehicle which is ACC controlled and with a time headway of 2s, the rest of the vehicles are CACC controlled. Vehicles of a individual platoons are controlled by a speed and spacing policy dependent on the index of the current lane they travel on. Each platoon is given one of three possible destinations. The farthest bound plane is allocated lane 3 and the highest speed (73m/s) . The plane to the nearest destination is assigned lane 1 and the lowest speed (48m/s) while the plane to the destination between the two is allocated the middle lane with medium speed (58m/s). The difference in speed allows the planes to arrive at lane change stations at different times thereby guaranteeing collision-free lane transitions. Also it ensures that the average speed of the highway edges is directly manipulable since it is the average of the three allowed speeds.

When a plane is at a distance to a lane change station the look-for-flag method is invoked, and at a preset distance from the flag lane change is commenced. Planes traveling on the highest speed lane move one lane down to medium speed lanes, the medium speed plane moves to the lowest while a plane on the lowest moves a lane down to the exiting lane in succession as shown in Fig. 5 This process is repeated as the planes move forward towards their destinations. Hence a plane which started off on lane 3 travels on all three platoon controlled lanes, its travel speed is the average of all three lanes. One starting on the second averages two lane speeds while the lowest speed lane plane travels only at that speed. This ensures that farther traveling vehicles are given a head-start over vehicles traveling to closer destinations.

At each insertion time when a new batch of vehicles enters the simulation, a Vehicle of Interest (VI) is identified. The VI is chosen to be one of the four leaders of the planes that travel the farthest. Because of the symmetry of the network design and plane trips any of the four leaders can be chosen as VI. A location is then chosen along the path of the VI such that when the VI is at the said location a new batch of vehicles are inserted and a new VI is assigned. In choosing the location, the different travel velocities and lane changes of all old and new planes are considered such that it is guaranteed that new planes will not catch up with the old or vice-versa. This process is repeated for the duration of the simulation. The main stages of the simulation are shown in Fig. 6.

**Scenario Two:**

The set up in scenario two is the same as in scenario one except that the normal flow of traffic of the planes is obstructed by additional non-automated vehicle inserted at sources located downstream of each plane between each plane's on-ramp and off-ramp, depicted in 2 as obstructor vehicle sources. This is done such that the desired lanes and routes of automated and non-automated vehicles coincide with each other upstream. At insertion,the non-automated vehicles are also assigned fixed lane change modes, they maintain this state until they are found to be obstructing the movement of a plane at which point the non-automated assigned new lane change modes that allow them to cooperatively change lanes to allow for the planes to overtake them.

**Scenario Three:**

For this scenario, random trips of vehicles are generated and offset with a binomial distribution where the maximum number of simultaneous arrivals is set to 0.962 to ensure that vehicles have the same arrival rate as those in scenario one and two. The total number of inserted vehicles in scenarios one and two are also matched to ensure that the network is handling similar traffic conditions. Fringe factor options are also used to ensure all trips start from source and end at sinks as in scenarios one and two. At insertion time, vehicles are, through their set lane change modes allowed to perform strategic, cooperative, speed gain and right drive lane changes. The on-ramp junctions are regulated by priority as in scenario one and two.

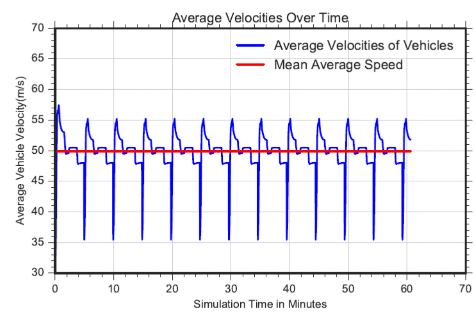


Fig. 7. Mean Travel Speed under Fully Automated Plane Control

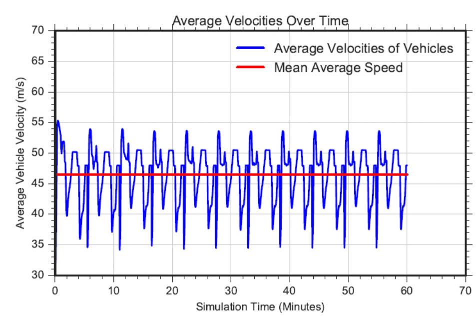


Fig. 8. Mean Travel Speed of Highway under Mixed Traffic Plane Control

## V. Results and Analyses

The main purpose of this study is to present the lane-based platoon control model. Simulations were carried out in three different scenarios to evaluate the performance of the model using the same road network and setup parameters. Scenarios one and two employed the model in this study.Scenario one shows the simulation of the model with 100% automated vehicles, while scenario two represented mixed traffic of 96% automated vehicles and 4% non-automated using the same model. The 4% non-automated traffic is seen here as a mild perturbation to investigate the performance of the model.

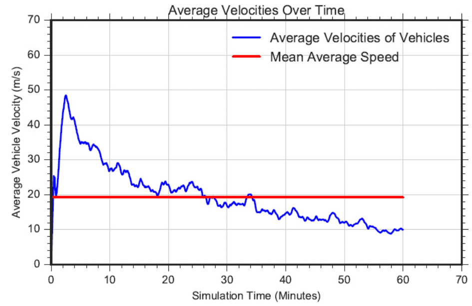


Fig. 9. Mean Travel Speed of Highway under Conventional Traffic

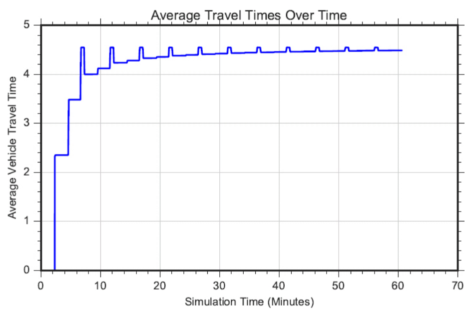


Fig. 10. Mean Travel Time under Fully Automated Plane Control

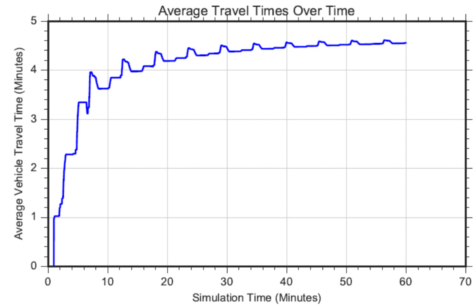


Fig. 11. Mean Travel Time under Mixed Traffic Plane Control

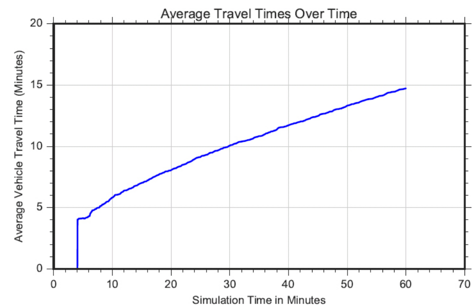


Fig. 12. Mean Travel Time under Conventional Traffic

Lastly, scenario three is a simulation of conventional traffic of 100% non-automated vehicles.

The results show that the model does present positive impact on traffic dynamics in the areas mentioned above. Fig. 7, Figure 8 and Fig. 9 show a comparison between the average mean speeds of the three scenarios.Cumulative average velocities over the 60 minute simulation for scenarios one, two and three, depicted by the red lines, are 50 m/s, 46 m/s and 19.5 m/s respectively. Similar patterns can be observed in both Fig. 7 and 8 . The Difference in cumulative average speeds in scenarios one and two is attributed to the obstruction caused by non-automated vehicles in the mixed traffic scenario. The nature of the two graphs also suggests repeatability , meaning, these speeds can always be replicated given the same constraints. In Fig. 9, the average speed peaks at about 48 m/s between 2 and 3 minutes of the simulation but thereafter dips to below the cumulative average due to congestion at on-ramps. This represents 156% and 135% improvement in average speeds in scenarios one and two respectively over scenario three.

Figures 10 - 12 show mean travel times in the three scenarios respectively. Average travel times in scenarios one and two are very similar.The nature of the graphs suggest stabilization at about the 4.5 and 4.6 minute marks for the two scenarios respectively. In the case of scenario three, average travel times continuously increased over the simulation period, reaching just above 15 minutes by the end of the simulation. The nature of the graph suggests further increments with time. The results show a 70% reduction in travel times in scenarios one and two over scenario three.

Throughput is another area where the model presents obvious improvements as shown in Fig. 13 - 15 in the order of scenario numbers. The graphs show number of running and arrived vehicles over simulation time. In Fig. 13 and 14, it can be seen that the number of running vehicles over time remained between 100 and 400 vehicles in a repeated pattern, while the cumulative number of arrived vehicles increased repetitively and constantly reaching about 3360 and 3200 vehicles mark respectively by the end of the simulation. In the case of scenario three in Fig. 15, it can be seen that both the number of running and arrived vehicles increased with time. The rise in number of running vehicles created congestion mainly at on-ramps which explains the drop in average speeds and increase in travel times as observed earlier in Fig. 9 and 12. Further, the total number of arrived vehicles in scenario 3 can be seen to be around the 2300 vehicles mark. Indicating about 43.5% and 39% increment in throughput of scenarios one and two respectively over scenario three.

Finally, the number of lane changes over time of the three scenarios is compared. Fig. 16 - 18 represent the number of lane changes performed by vehicles over time in the order of scenario numbers. It can be seen that the number of lane changes are grouped in Fig. 16 and 17, indicating groups of 24 instantaneous lane changes network-wide at lane change stations and immediately followed by periods of no lane changes while planes travel to their next lane change stations. In Fig. 17 the shorter spikes indicate lane changes of non-automated vehicles yielding their preferred lanes to planes. It

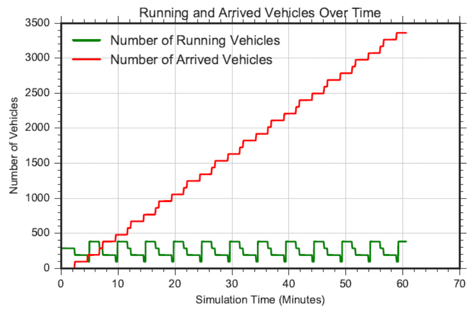


Fig. 13. Running and Arrived Vehicles under Fully Automated Plane Control

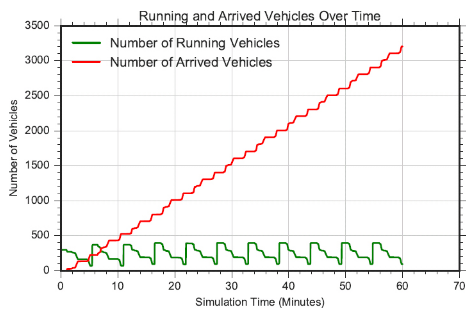


Fig. 14. Running and Arrived Vehicles under Mixed Traffic Plane Control

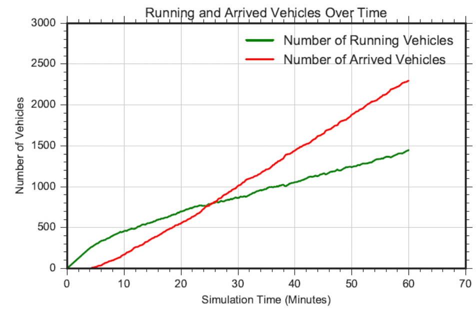


Fig. 15. Running and Arrived Vehicles under Conventional Traffic

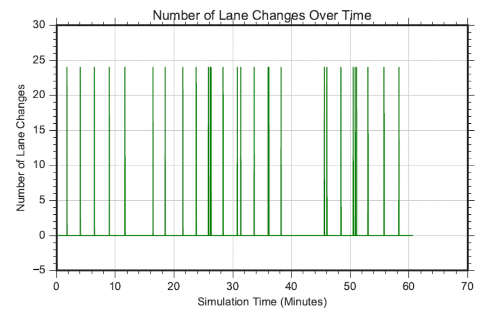


Fig. 16. Lane Changes Over Time under Fully Automated Plane Control

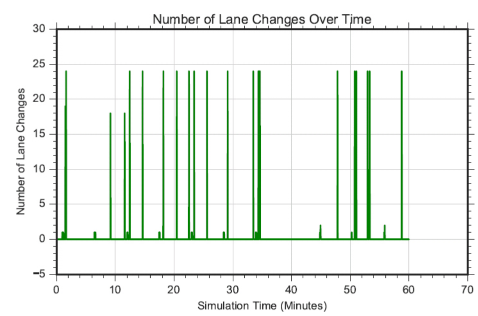


Fig. 17. Lane Changes Over Time under Mixed Traffic Plane Control

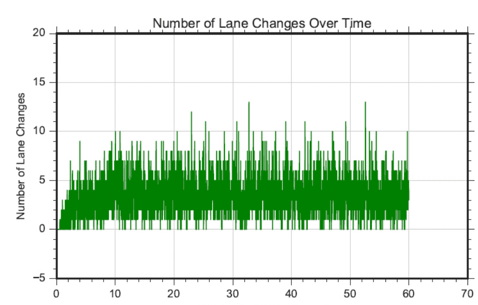


Fig. 18. Lane Changes Over Time under Conventional Traffic

can also be noted in Fig. 17 that some spikes around the 1, 10 and 12 minute marks are around 18 lane changes instead of 24. This is as a result of collisions that occurred due to the presence of obstructing non-automated vehicles. In Fig. 18 however, it can be observed that numerous lane changes occurred at each step of the simulation. These lane changes may obscure, slow down or even trigger further lane changes in the network. Thereby contributing to the longer travel times, low average speeds and throughput observed in this scenario as discussed earlier.

As shown in the analyses above, the model presented in this study has shown significant improvements in average speed, travel times and throughput. The model presented in this study showed between 135% and 156% improvement in average speed over conventional traffic. It also showed around 70% improvement in travel time and between 43.5% and 39% increment in throughput. We also demonstrated the impact of structured lane changes on average speeds, travel times and throughput. Finally, the results show stability of the system and equally important, repeatability.

## VI. Conclusion

From the results obtained above, this study has not only further backed the claim that platooning of vehicles on highways do present significant benefit to highways but has also shown that dedicating specific lanes for autonomous vehicles on highways presents even more significant benefits in traffic flow and capacity. A highway system such as described in the study could easily be retrofitted to existing infrastructure while the technology for autonomous vehicles matures. As far as future studies goes, further research needs to be done to compare the model to other platooning models to further validation. We plan to investigate the impact of system wide maneuvers such as mergers and splits on the model at locations depicted in Fig. 16 and 17 where no lane changes were observed, given that there is ample time and spacial difference between platoons, the effects of such maneuvers should pose little challenge to the model. Further optimization of insertion time can be investigated in order to boost the throughput of the model.

## VII. Acknowledgment

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