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Evaluation of Mixed Automated/Manual Traffic

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This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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**EVALUATION OF MIXED
AUTOMATED/MANUAL TRAFFIC**

by
Petros Ioannou
Final Report MOU# 290
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This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

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ABSTRACT

The advance in research and development will make the deployment of automated vehicles a reality in the near future. The principal question is whether these technologies will lead to any benefits in terms of safety, capacity and traffic flow characteristics as they penetrate the current transportation system. Another aspect is how to exploit these technologies in order to achieve benefits without adversely affecting the efficiency of the current transportation system and the drivers who cannot afford them. The penetration of automated vehicles into the existing transportation system will lead to mixed traffic where they will coexist with manually driven vehicles.

The controversial class is where automated vehicles are allowed to mix with manually driven vehicles. The motivation behind this concept is that the current roadway will not have to undergo any major changes. Vehicles will become more and more automated independent of AHS and should have the ability to operate in lanes with manually driven vehicles. As the number of automated vehicles increases, the benefits of automation will increase until saturation, where all vehicles will be automated in the same way with cruise control, air-bags, etc.

At the initial stage, vehicles will be semi-automated with the capability to follow each other automatically in the same lane. These semi-automated vehicles will coexist with manually driven vehicles on the same roadway system.

The purpose of this report is to analyze the requirements, issues and effects on safety and efficiency that will result from allowing semi-automated and fully-automated vehicles to operate on the existing highway system together with manually driven vehicles. Two scenarios are considered : in the first scenario no changes are assumed for the current roadway system. In the second scenario it is assumed that the roadway controls the flow of traffic by issuing speed commands to both automated and manual vehicles. The roadway communicates via a roadway/vehicle communication with the automated vehicles system and through variable message signs with the manually driven vehicles.

It is found that a number of safety and human factors issues present in both scenarios need to be resolved and studied further before mixing of semi-automated/fully-automated vehicles with manual ones becomes possible. Full automation will eliminate the driver out of the driving loop which will have serious safety implications some of which are raised and analyzed. In addition the interaction of fully automated vehicles with manual ones pose several safety problems due to the unpredictable behavior of the drivers of the manual vehicles.

The effects on capacity with respect to the percentage of semi-automated vehicles penetrating the system and the derating factor due to possible lane changes are analyzed.

Theoretically as the percentage of semi-automated vehicles increases, capacity also increases in most cases due to the shorter headways of the semi-automated vehicles. In practice this may not be always the case due to the unpredictability of the manually driven vehicles and the randomness of the headway used by different drivers which may further change due to presence of the semi-automated vehicles.

Simulations reveal that significant improvement in the traffic flow can be achieved with a high degree of penetration of fully-automated vehicles in mixed traffic. Effects of lane-changing of fully-automated vehicles on mixed traffic capacity are analyzed. The lane-change derating factor is quantified as a function of market penetration of fully-automated vehicles for different percentages of automated vehicles changing lanes.

One of the significant findings of this research is that a single semi-automated/fully-automated vehicle may attenuate large disturbances caused by rapid accelerations/decelerations and prevent the slinky effect from propagating. This attenuation is shown to take place without any effect on the travel time. The stopping of the propagation of large acceleration/deceleration transients by the automated vehicle will have positive effects on fuel consumption and pollution.

KEYWORDS

Automated Highway Systems (AHS), Semi-automated Vehicle, Fully-automated/Automated Vehicle, Manual/Manually driven Vehicle, Intelligent Cruise Control (ICC), Frontal Collision Warning System (FCW), Frontal Collision Avoidance System (FCA), Variable Message Signs (VMS), Roadway/Vehicle Communication System (RVCS), Degree of Penetration, Throughput, Headway, Merge Derating Factor, Slinky-effect, Sensors, Actuators, Vehicle-to-Vehicle Communication, Zone of Relevance, Global Positioning System (GPS), Minimum Safety Spacing (MSS)

EXECUTIVE SUMMARY

This is the final report for the project entitled “*Evaluation of Mixed Automated/Manual Traffic*” in response to the contractual requirements of the Memorandum of Understanding MOU#290, between the Partners of Advanced Transit and Highways (PATH) and the University of Southern California, administered at University of California, Berkeley.

The purpose of this project was to evaluate different traffic scenarios that allow mixing of manual with semi-automated and automated vehicles. The study will examine the equipment requirements, safety issues and performance for each scenario.

The results obtained under this project are organized in two independent reports that form part I and part II of this document. Below we give a summary of the findings presented in these reports and refer to part I, II for details.

In part I we consider the following two traffic scenarios : In scenario I no changes are made to the existing infrastructure and semi-automated vehicles are allowed to mix with manual ones. The semi-automated vehicles are treated the same way as the manually driven vehicles. In scenario II the infrastructure is upgraded to provide speed, headway and other traffic recommendations to the semi-automated vehicles directly and to the manual vehicles via variable message signs. The necessary equipment on the semi-automated vehicles for two different functions; longitudinal collision warning and avoidance is specified. Several safety and human factors issues are raised. The effect of mixing on the capacity is analyzed as a function of the degree of penetration of the semi-automated vehicles. It is shown that for certain speeds the capacity will decrease with the percentage of semi-automated vehicles with longitudinal collision warning due to the relatively large reaction time for unalerted drivers that is assumed in calculating the headway used by the semi-automated vehicles. On the other hand it is shown that the capacity will increase with the percentage of semi-automated vehicles with longitudinal collision avoidance due to the smaller headways assumed for these vehicles.

Driver and semi-automated vehicle models are used to examine stability and transient behavior in vehicle following in a mixed traffic situation. It is found that the semi-automated vehicles attenuate traffic disturbances due to rapid accelerations and prevent slinky effects without affecting the travel time. This property has positive effects on fuel economy and pollution.

Part II deals with the following two scenarios : Scenario I has fully automated and manual vehicles on the current roadway system. In scenario II, the roadway has communication capability and recommend speed and headway to the fully automated vehicles. It has variable message signs for the drivers of manual vehicles. The driver of the fully

automated vehicle has no driving responsibility and is completely out of the driving loop. When the vehicle is in the automated mode, the sensor requirements and properties necessary for automated vehicles to operate in mixed traffic are enormous. Even with the availability of fast and reliable sensors that provide 360 ° view of the surroundings the problem of deciding which vehicle is “threatening” and which one is not is a difficult one due to the unpredictability of the behavior of the manual vehicles.

The presence of the uncooperative manual vehicles will limit the ability of the automated vehicles to execute lane changes, merging etc. In similar situations a human driver could take the risk of cutting-in or performing other risky maneuvers, something an automated vehicle cannot afford to do.

The effect of market penetration of fully automated vehicles on the mixed traffic throughput is analyzed. A model is developed to analyze the merge derating factor for different percentages of lane-changing automated vehicles. Results show that the throughput increases with higher percentage of fully automated vehicles because of the smaller headway assumed between them. It is seen that the merge derating factor for automated vehicles changing from high-speed to low speed lanes is marginally different than for automated vehicles changing lanes in the opposite direction.

ISSUES AND ANALYSIS OF MIXED SEMI-AUTOMATED / MANUAL TRAFFIC

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1 Introduction

2 Mixed Traffic Scenario I

3 Mixed Traffic Scenario II

4 Safety Issues in Mixed Traffic

5 Throughput Analysis

6 Transients in Vehicle Following

APPENDIX A

APPENDIX B

References

1 Introduction

The increase in road traffic and decrease in use of mass transit have resulted in congestion of the urban highways, leading to the need of additional capacity for road transportation. For example, since 1975 human population has increased by 60% while vehicle miles traveled has shot up by 135%. The problem was solved in the past by constructing new highways, but unfortunately this has turned out to be an uneconomical and a short-sighted solution. Due to these constraints, people have turned to other alternatives for increasing capacity without compromising on safety. Automated Highway Systems (AHS) have emerged as a promising solution in which we remove the human element as much as possible through automation. The appeal in AHS is that it has the potential for increasing capacity and improving safety by using advanced technologies and automation. The reduction of human involvement due to automation promises safety benefits, substantiated by the fact that driver actions caused 50.4% interstate hazards in 1994. It has been argued that the first step of AHS will be the introduction of automated vehicles in the existing transportation system forcing them to operate with manually driven vehicles.

The penetration of automated vehicles into the current transportation system will lead to mixed traffic where they will coexist with manually driven vehicles. By principle, the automated vehicles will have on-board sensor and communication technologies, and control systems that would allow them to operate without any assistance from the human driver. This however, will be the final stage of evolution of the automated vehicles. Initially vehicles will be semi-automated as it becomes evident with the development and deployment of vehicles with Intelligent Cruise Control (ICC) by almost all major automobile companies.

Different scenarios may be used for mixed traffic evaluation. In Varaiya et al[2], two different models have been suggested and analyzed. The first model has a mixed traffic lane in which automated vehicles activate their systems after entering the lane, and flow is calculated as a function of their penetration. The second model dedicates the inside lane to automated vehicles only and allows the formation of platoons. Simulations of the models have revealed an upper bound on the capacity of the freeway. Other works such as [3] investigate the improvement in total throughput as a function of the degree of penetration of the automated vehicles for different operating speeds, uniform and non-uniform spacing and merge derating factors.

In this report we look at the first stage of AHS implementation where semi-automated vehicles coexist with manually driven vehicles. The semi-automated vehicles are

vehicles equipped with intelligent cruise control that allows them to follow each other automatically in a lane[7]. The driver in the semi-automated vehicle is responsible for lane-keeping, lane-changing and in some scenarios, control of the vehicle during emergencies. Two separate scenarios have been considered : first the roadway has no role in the traffic flow. Second, the roadway plays a supporting role in the traffic flow: it has the ability to communicate to the semi-automated vehicles and issue speed and traffic recommendations based on current conditions. It posts instructions on Variable Message Signs for the drivers of the manual vehicles. Many issues that are inherent to mixed traffic environment and need investigation are raised and discussed. The required properties of vehicle sensors and on board equipment are discussed and recommendations on existing ranging sensors are made.

The highway capacity as a function of the degree of penetration of the semi-automated vehicles is studied. Semi-automated vehicles equipped with frontal collision warning (FCW) only are treated separately from those equipped with frontal collision avoidance (FCA) systems. Headway values for the semi-automated vehicles are taken from the study in [1], which considers different AHS protocols, road conditions and braking scenarios. The effect of transfer of control of the semi-automated vehicle to the human driver in an emergency is considered. It is accounted for by taking into consideration the reaction time of an unalerted driver from [9] while calculating headways. The average headway between two manually driven vehicles is taken from [6]. It is found that traffic throughput may not increase in direct proportion with the degree of penetration of the semi-automated vehicle with FCW due to the larger headway assumed for these vehicles that take into account the reaction time of an unalerted driver. For the semi-automated vehicles with FCA the headways are small and result into an increase in throughput in direct proportion with the degree of penetration of the semi-automated vehicles. However, the percentage of increase is different under different roadway conditions.

The stability and transient response of vehicles in a vehicle following mixed traffic situation are investigated. Pipes' model [13] is used to model a manually driven vehicle while the Brake and Throttle model proposed by Ioannou and Xu [11] is used to model the response of a semi-automated vehicle. Different vehicle following scenarios with sudden accelerations and decelerations are analyzed in order to study the effect of the response of a semi-automated vehicle amidst manually driven vehicles. It is observed that the presence of a single semi-automated vehicle helps dampen oscillations and reduce slinky effects, all of which have beneficial fuel and environmental implications. Semi-automated vehicles have restricted acceleration and deceleration in order to reduce passenger discomfort. A rapidly accelerating leader will not be followed by a semi-automated vehicle which helps eliminate disturbances in traffic flow. However, when the leading vehicle reaches a constant speed, the semi-automated vehicle finally catches up with it and switches to constant headway policy. In comparison with a manually driven vehicle following the same high accelerating leader, the total travel time for a distance of about say 10km remains the same. This suggests that the semi-automated vehicle

dampens out sudden accelerations/decelerations without compromising on the total travel time.

This report is organized as follows: in section 2,3 we describe the mixed traffic scenarios that are investigated. The safety issues and other considerations for mixed traffic are elaborated in section 4. Section 5 evaluates the throughput of the highway for different roadway conditions as a function of the degree of penetration of the semi-automated vehicles. Section 6 investigates the transients in vehicle following response for mixed traffic.

2 Mixed Traffic Scenario I

The simplest mixed traffic scenario is the one where semi-automated vehicles are allowed onto the current highway system used by manually-driven vehicles (see fig 2.1). Metering is done at the entrance to mitigate congestion on the highway,

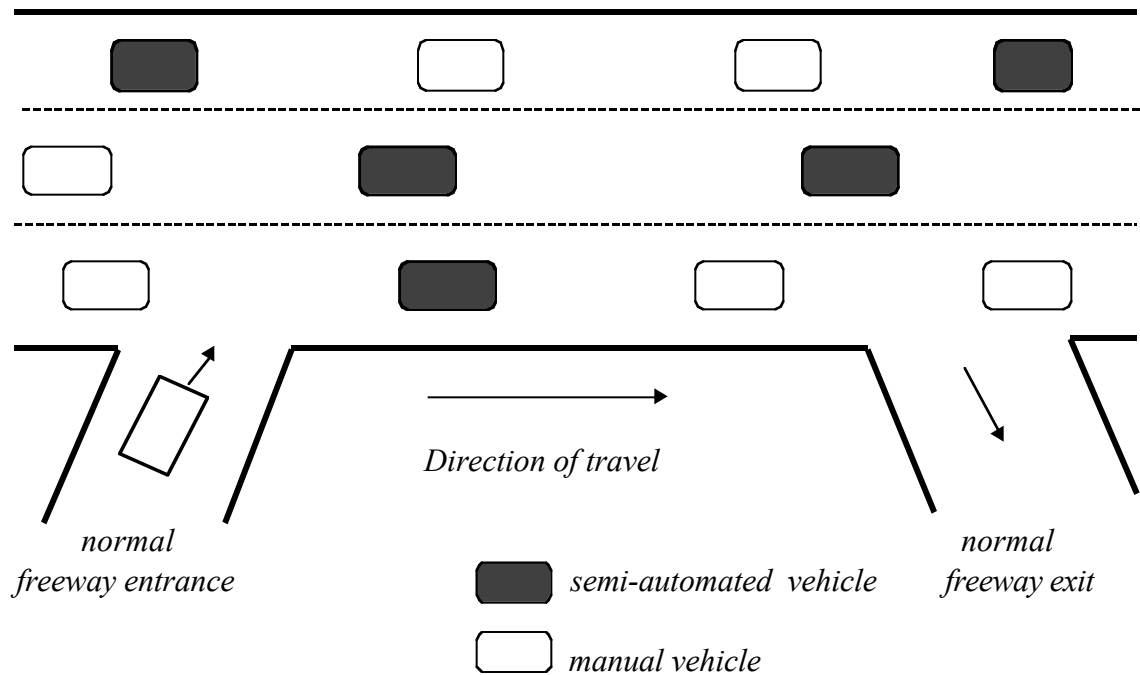


Fig 2.1 : Mixed traffic scenario I

and the semi-automated vehicle is treated just like any other vehicle waiting to enter the highway. On reaching the target lane, the driver engages the automated control system of the vehicle which takes over the longitudinal control of the vehicle. The driver is responsible for all driving functions as in a manually driven vehicle except for the longitudinal control. The vehicle has an automatic control system which controls the throttle and the brake actuators. The driver disengages the control system of the semi-automated vehicle (transition from automated to manual) to exit the lane. Then he/she takes over the control of the vehicle and performs manual lane-changing to travel in another lane or exit the highway through a normal highway exit ramp.

2.1 The Semi-automated Vehicle Equipment

The semi-automated vehicle is equipped with Intelligent Cruise Control (ICC)[7] for maintaining a constant headway and speed relative to the preceding vehicle by using a computer control system to control the throttle and the brake [11]. It is also responsible for maintaining the cruising speed selected by the driver when no vehicle is ahead. The vehicle is equipped with sensors which provide measurements of the relative speed and the relative distance to the target vehicle ahead. The vehicle receives target speed and headway commands from the driver, and responds to changes made by the driver. It also enables/disables the ICC upon request by the driver. If the ICC fails the vehicle allows the driver to take over the controls in the fall-back mode. The block diagram for the automatic control system of the semi-automated vehicle is shown in fig 2.2.

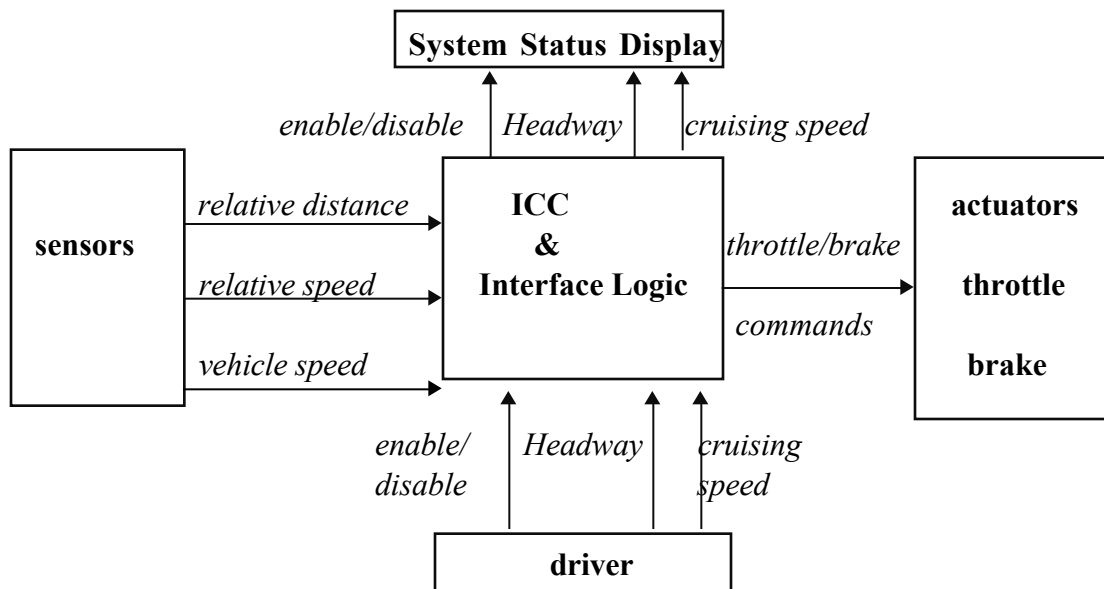


Fig 2.2 Block Diagram of automatic control system with driver interface

The semi-automated vehicle does not have lateral control, and depends on the driver for lane-keeping. However, for longitudinal control we consider two different cases : first, the semi-automated vehicle has longitudinal frontal collision warning system (FCW). In other words, it issues a warning to the driver when the constant headway policy is violated. The driver takes full responsibility for collision avoidance and initiates the

necessary procedure. Second, the semi-automated vehicle is sophisticated and equipped with a longitudinal frontal collision avoidance (FCA) system. It issues a warning to the driver when the constant headway policy is violated and at the same time performs automatic soft braking when the engine torque is not sufficient to maintain the selected headway. Automatic braking allows greater reaction time for the driver during emergencies. If the driver fails to take control of the vehicle within a predetermined time (based on a worst case analysis using [1]), then the automated control system activates hard-braking.

2.1.1 Vehicle Sensors

The semi-automated vehicle is equipped with sensors which measure relative speed and distance from the target vehicle ahead, and the closing rate between the vehicles, in addition to its own longitudinal speed, engine speed, etc. The speed sensor needs to be accurate for small speed changes of about 2-5mph[10] which humans cannot perceive. However, the longitudinal sensors are of primary importance because of their applications in mixed traffic. They must have low degradation due to weather and fast processing rates. Moreover, they must have a range of at least 3secs which is the standard safe time headway for human drivers, as per *California Driver's Handbook*. This translates into a distance coverage of approximately 90m for a speed of 65mph. The sensor must cover the entire lane so that it can track the target vehicle ahead in the constant headway mode. Furthermore, it must minimize spread to reduce (and if possible remove) interference from adjacent vehicle sensors. The ranging sensor should be able to measure the closing rate accurately. Different sensor technologies available today are evaluated for usage in mixed traffic in Table 2.2. In general no single ranging sensor can emulate human eyes and at the same time provide accurate relative speed and range measurements. This is one of the reasons that the driver has the responsibility of emergency control in the initial phase of ICC.

2.1.2 On-board Displays

Sensor display forms an important and integrated part of the semi-automated vehicle. The average glance of a typical driver is 1.28s (above 2s is unsafe)[8] so care should be taken not to overburden the driver with too much sensor information. A graded warning system is used for the longitudinal sensor, with sound and flashing red lights to indicate violation of safety headway and initiate emergency procedures by the human driver. A speech warning system may be included in the vehicle to convey short, discrete messages of the order of 150-200 words/minute [4]. The driver will have the liberty of adjusting the speaker volume (it will have a minimum point) to avoid annoyance in the case of frequent false alarms, for instance, under high traffic density conditions.

Ranging sensors			
Type	Advantages	Disadvantages	Usage
Monochrome video cameras	good spatial and angular resolution, images easy to process, low time constant, costly hardware	poor accuracy, complex range and relative velocity calculation also deteriorating performance at night and poor conditions	Not recommended
Color video camera	high accuracy for lane markers, costly hardware	images not easy to process, performance affected by night/poor conditions	Not recommended for this stage
Ultrasonic	accurate proximity sensing, low cost	degradation due to poor weather, dust/smoke, susceptible to false alarms from common noise like tire noise	Not recommended for this stage
Infrared/visible	good angle information by use of spinning mirrors and good range information, low cost	rapid degradation in poor weather false target creation by back scatter from foggy patches, also eye safety problems, may have problems from direct sunlight	Not recommended
Microwave radar	very good in dust/smoke, poor weather - no degradation in performance; good continuous tracking capabilities, low cost hardware	poor angular resolution, large physical attributes	Recommended for headway (longitudinal) sensor
Laser	good long range tracking	performance degradation in poor weather, dirt; sensor blindness	Not recommended

/false alarms from sunlight under certain conditions

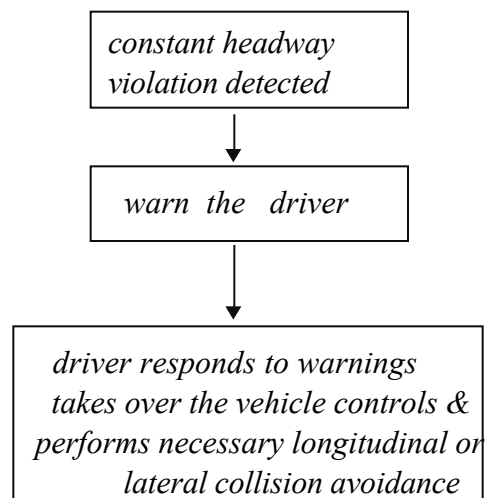
Table 2.1 Summary of different available sensor technologies and their applicability to mixed traffic

2.2 Role of the driver of the semi-automated vehicle

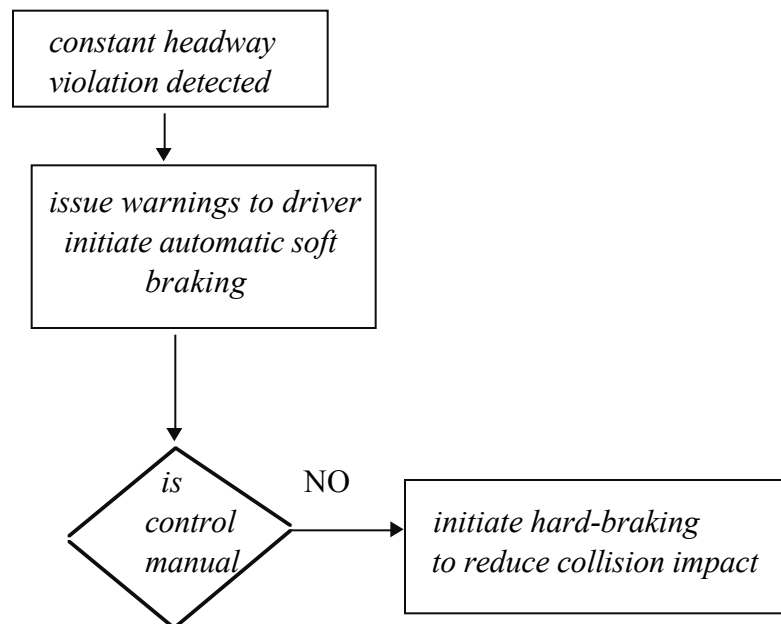
The driver of the semi-automated vehicle is responsible for all driving functions except for longitudinal control of the vehicle. The driver merges into the highway from the on-ramps and engages the automatic control system of the vehicle after reaching the target lane. There is a smooth transition from the manual to the automatic mode, and the ICC alongwith the on-board sensors allow the driver complete "feet-off" driving in the present lane. The driver is responsible for lane-keeping and keeps his/her hands on the steering wheel without performing any longitudinal control functions. When the driver wants to exit the lane, he/she disengages the ICC and takes over the complete control of the semi-automated vehicle. Then the driver performs manual lane-changing and gets into another lane or exits the highway.

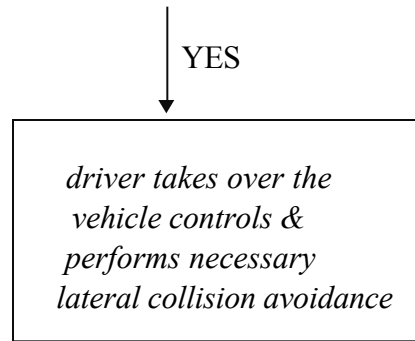
Semi-automated Vehicle in Mixed Traffic without Roadway Involvement	
Vehicle Equipment	Role of the driver
ICC, longitudinal sensors, frontal collision warning system (FCW)	<ul style="list-style-type: none"> - lane-keeping and lane-changing - responds to collision warnings - vehicle interface - longitudinal collision avoidance by braking - lateral collision avoidance
ICC, longitudinal sensors and frontal collision avoidance system (FCA)	<ul style="list-style-type: none"> - lane-keeping and lane-changing - vehicle interface - lateral collision avoidance

Table 2.2 Summary of the functions of the driver for different levels of automation of the semi-automated vehicle



(a)





(b)

Fig 2.3: The flowcharts for emergency procedures in semi-automated vehicles with FCW(a) and with FCA(b)

For emergency procedures, the role of the driver is crucial in a semi-automated vehicle with FCW. Sensors detect forthcoming danger and issue warnings for the driver to take over the controls of the vehicle. The driver is then expected to take over the longitudinal control of the vehicle and perform hard-braking or lateral collision avoidance depending on his/her judgment of the relative safety comparison of the two procedures.

The driver of the semi-automated vehicle equipped with FCA has a less demanding role. The semi-automated vehicle performs automatic soft-braking which the driver about the possible onset of an emergency which allows greater reaction time for the driver. However, if he/she does not respond, then hard-braking is initiated by the semi-automated vehicle. Table 2.2 summarizes the role of the driver of the semi-automated vehicle for the different vehicle capabilities. Fig 2.3 depicts the role of the driver during emergencies for the two different types of semi-automated vehicles.

3 Mixed Traffic Scenario II

In the previous scenario, the roadway did not require any changes. In this scenario, the roadway is assumed to be able to send messages and speed recommendations directly to the semi-automated vehicles. The same information is presented to the drivers of manual vehicles via variable message signs.

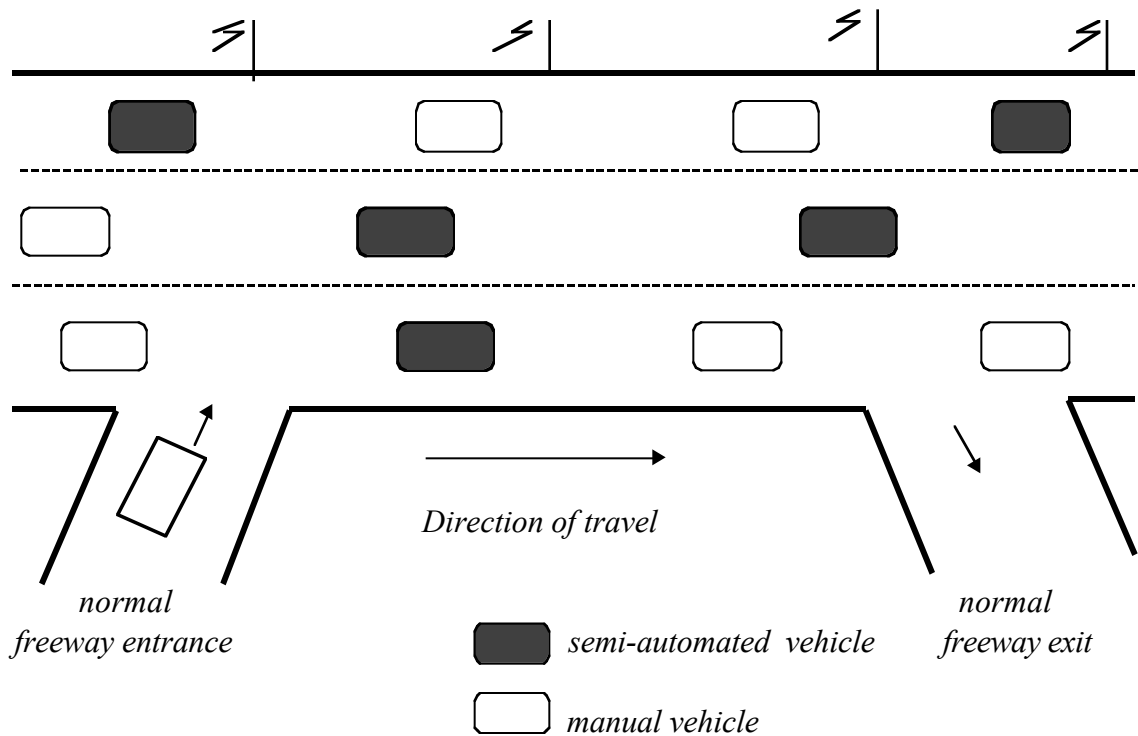


Fig 3.1 : Mixed traffic scenario II

As in the previous scenario, the semi-automated vehicles are allowed onto the highway from the ramps used by manually-driven vehicles. Metering is done at the entrance to mitigate congestion on the highway, and the semi-automated vehicle is treated just like any other vehicle waiting to enter the highway. For lane-changing or exiting from the highway, the driver first disengages the control system of the semi-automated vehicle (transition from automated to manual). The disengagement is done in a way that does not put the driver in a dangerous situation. For example, if the headway used in the automatic mode is small relative to some average assumed for manual vehicles, then the transition to manual will take place after the “safe” headway. When the driver takes over the control

of the vehicle, he/she executes manual lane-changing to travel in another lane or exit the highway through a normal highway exit ramp (as shown in fig 3.1).

3.1 The Semi-automated Vehicle Equipment

The semi-automated vehicle is equipped with Intelligent Cruise Control (ICC)[7] for maintaining a constant headway and speed relative to the preceding vehicle by using a computer control system to control the throttle and the brake [11]. It is also responsible for maintaining the cruising speed selected by the driver when no vehicle is ahead. The vehicle is equipped with sensors which in addition to longitudinal speed, engine speed etc., provide measurements of the relative speed and the relative distance to the target vehicle

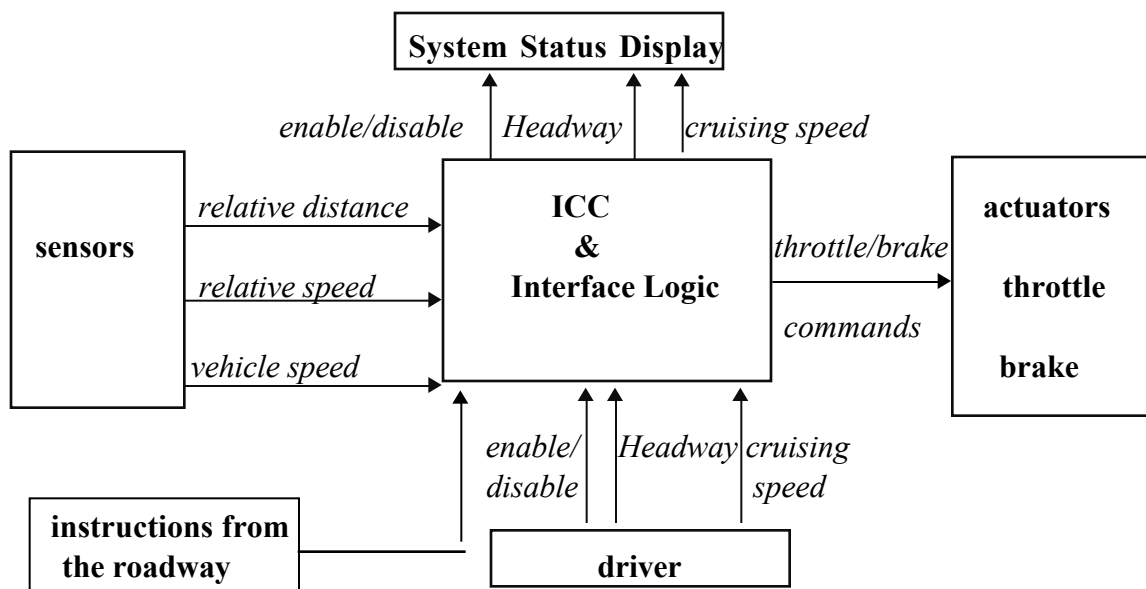


Fig 3.3 Block Diagram of automatic control system with driver interface with roadway support

ahead. The vehicle receives target speed and headway recommendations from the driver, and responds to changes made by the driver. It also enables/disables the ICC upon request by the driver. If the ICC fails the vehicle allows the driver to take over the controls in the fall-back mode. The block diagram for the automatic control system of the semi-automated vehicle is shown in fig 3.3.

The semi-automated vehicle has the capability to receive instructions from the roadway, respond to them and also display them to the driver. The on-board equipment is shown in fig 3.4. The receiver gets the message from the roadway which it transmits to the Information Processing Unit (IPU). A microstrip antenna serving as a receiver has been

field tested in [18]. The transmission speed is 512kbps and it operates in the quasi-microwave range (the frequency is 2.598 GHz). The method of conveying messages is dependent on the driver. If the voice unit option is chosen, then the IPU synthesizes syllables to combine them into words and sentences. For the Cathode Ray Tube (CRT) display, the message is displayed on the screen. Certain fixed messages could be put in IPU like ‘accident’, ‘fog ahead’ which are displayed according to need. In case of messages other than the standard, the IPU may use the word processor to display them.

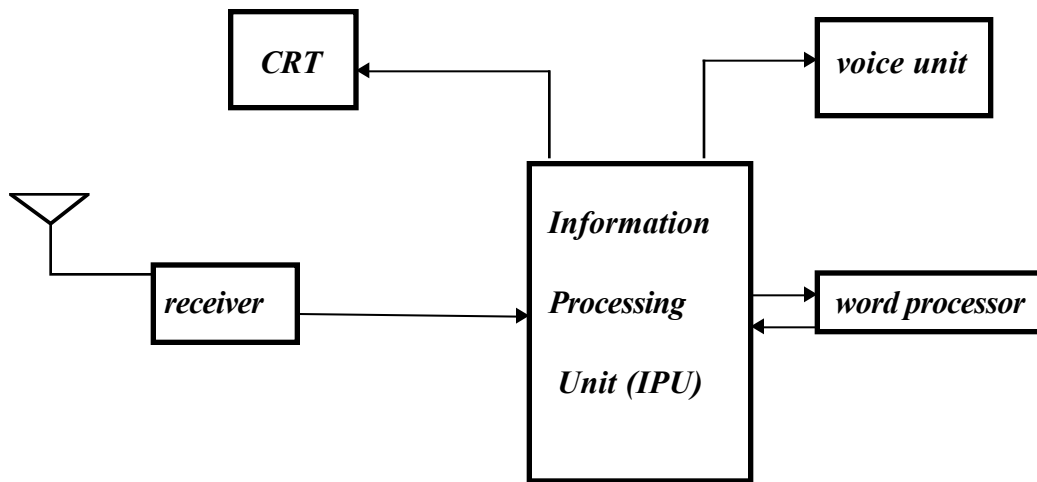


Fig 3.4 : On-board equipment of the semi-automated vehicle

The semi-automated vehicle does not have lateral control, and depends on the driver for lane-keeping. However, for longitudinal control we consider two different cases : first, the semi-automated vehicle has longitudinal frontal collision warning (FCW) system. Second, the semi-automated vehicle is equipped with longitudinal frontal collision avoidance (FCA) system. These two features are as explained in section 2.1.

3.1.1 Vehicle Sensors

The sensors on-board the semi-automated vehicle are the same as described in section 2.1.1 with the addition of a receiver described above to receive messages from the roadway

3.1.2 On-board Displays

Same as section 2.1.2 except that the vehicle has the capability to display messages from the roadway to the driver.

3.1.2.1 CRT Unit

The CRT display unit should be easily readable by the driver of the semi-automated vehicle. Studies have shown that 9 ↔ 11 dot matrix for character size ease reading[8]. The contrast ratio should be between 7:1 to 3:1, and refreshed at a rate of above 100 Hz to avoid flicker. The screen should be tilted a few degrees from the vertical for comfortable reading by the driver.

3.2 Role of the driver of the semi-automated vehicle

The driver has the same responsibilities as described in section 2.2. However, the roadway can send speed/headway instructions and traffic reports to the driver of the semi-automated vehicle. For emergency procedures, the role of the driver is similar to that described in section 2.2. Table 3.1 summarizes the role of the driver of the semi-automated vehicle for the two different vehicle capabilities.

Semi-automated Vehicle in Mixed Traffic with Roadway Involvement	
Vehicle Equipment	Role of the driver
ICC, longitudinal sensors, frontal collision warning system (FCW)	<ul style="list-style-type: none"> - lane-keeping and lane-changing - responds to collision warnings - vehicle interface - longitudinal collision avoidance by braking - lateral collision avoidance - follow speed/headway & traffic instructions from the roadway
ICC, longitudinal sensors and collision avoidance system (FCA)	<ul style="list-style-type: none"> - lane-keeping and lane-changing - vehicle interface - lateral collision avoidance - follow speed/headway & traffic instructions from the roadway

Table 3.1 Summary of the functions of the driver for different levels of automation of the semi-automated vehicle with roadway support

ISSUES AND ANALYSIS OF MIXED AUTOMATED/MANUAL TRAFFIC

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ISSUES AND ANALYSIS OF MIXED AUTOMATED/MANUAL TRAFFIC*

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Abstract

The design of Automated Highway Systems (AHS) involves the use of advanced technologies and automation to make the current transportation system more efficient in terms of capacity, safety and pollution. The principal question is whether these technologies will lead to any benefits in terms of safety, capacity and traffic flow characteristics as the degree of penetration in the current transportation system increases. There are a wide range of possible AHS configurations that vary from those with mixed automated and manual traffic, to those with fully automated traffic lanes that are physically isolated from manual lanes.

The controversial class is where automated vehicles are allowed to mix with manually driven vehicles. The motivation behind this concept is that the current roadway will not have to undergo any major changes. Vehicles will become more and more automated independent of AHS and should have the ability to operate in lanes with manually driven vehicles. As the number of automated vehicles increases, the benefits of automation will increase until saturation, where all vehicles will be automated in the same way with cruise control, air-bags, etc.

The purpose of this report is to investigate the requirements, safety issues and throughput that will result from the mixing of fully automated vehicles with manually driven vehicles on the existing roadway system. Two scenarios are considered: scenario I has the fully automated vehicles mixing with the manually driven vehicles on the existing roadway system. In scenario II the roadway controls the traffic flow by communicating with the fully automated vehicles via a roadway/vehicle communication system and with the manually driven vehicles through variable message signs.

*This work is supported by the California Department of Transportation through PATH of the University of California. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or

policies of the State of California or the Federal Highway Administration. This paper does not constitute a standard, specification or regulation.

Full automation will eliminate the driver out of the driving loop which will have serious safety implications some of which are raised and analyzed. In addition the interaction of fully automated vehicles with manual ones pose several safety problems due to the unpredictable behavior of the drivers of the manual vehicles. Simulations reveal that significant improvement in the traffic flow can be achieved with a high degree of penetration of automated vehicles in mixed traffic. Effects of lane-changing of automated vehicles on mixed traffic capacity are analyzed. The lane-change derating factor is quantified as a function of market penetration of automated vehicles for different percentages of automated vehicles changing lanes. Another finding is that a single automated vehicle in a string of manually driven vehicles will dampen oscillations and attenuate slinky effects, leading to better fuel economy and lower environmental pollution.

1 Introduction

Automated Highway Systems (AHS) has emerged as a promising solution in which we remove the human element as much as possible through automation. AHS increases capacity and improves safety by using sensors and computer processing to avoid specific collision scenarios and mitigate the effect of others.

In this report we consider two mixed traffic scenarios where fully automated vehicles coexist with manually driven ones. The automated vehicle sensors emulate the human eyes and at the same time provide accurate relative speed and ranging measurements. The driver of the fully automated vehicle has no responsibility and he/she is completely out of the driving loop while the vehicle is in the automated mode. Two scenarios have been proposed and investigated : in scenario I the fully automated vehicles coexist with the conventional manually driven vehicles on the current roadway system. Scenario II assumes an active roadway system that controls the traffic flow by issuing speed recommendations to the fully automated and manual vehicles. The roadway sends speed and headway recommendations and receives traffic information from the automated vehicles through a roadway/vehicle communication system. The infrastructure posts instructions on variable message signs for the drivers of the manually driven vehicles.

The full automation of the vehicle without any driver responsibility has serious safety issues which are raised and analyzed. Though full automation will theoretically increase the highway capacity because of the small headways assumed for the automated vehicles, it might be at the cost of compromising on safety. For example, in case of major malfunctions, the driver may not be able to take control of the automated vehicle because he/she might be involved in some other task and this will lead to potential collision threats. Moreover, the automated vehicle sensors have to emulate the human eyes and senses and distinguish between threatening and non-threatening situations which implies that failure to do so will place the vehicle at great risk. Reliable sensors with such capabilities have yet to be developed.

The highway capacity is studied as a function of the degree of penetration of the fully automated vehicles. The effect of lane-changing on traffic throughput is also analyzed. A model is used to calculate the throughput when a percentage of automated vehicles are changing lanes. It is found that the traffic throughput increases with higher percentage of fully automated vehicles. The increase in throughput is considerably larger than what we have seen in part I of this report for the semi-automated vehicles which proves that full automation leads to significant improvement in capacity. The throughput decreases with the increasing number of automated vehicles changing lanes.

Vehicle following transients in mixed traffic are studied for different vehicle following situations. The analysis is based on the longitudinal automatic vehicle following of the

automated vehicle which is the same as for semi-automated vehicles and is included in chapter 6 of part I of this report.

This report is organized as follows: in sections 2 & 3 we describe the proposed mixed traffic scenarios and examine the necessary vehicle equipment and the role of the driver of the automated vehicle. The safety issues and other considerations for mixed traffic are discussed in section 4. Section 5 presents the calculation for the throughput of the highway for mixed traffic conditions.

2 Mixed Traffic Scenario I

In this mixed traffic scenario we assume that some percentage of vehicles are fully automated and fully equipped with sensors and controllers that allow them to operate autonomously. The other vehicles are conventional vehicles, driven by human drivers. It is assumed that the roadway and the fully automated vehicles do not have any communication capability between them. Automated vehicles enter and exit the highway from the ramps which are also used by manually driven vehicles. The automated vehicles are treated just like any other vehicle when entering or exiting the highway. The driver of the fully automated vehicle could switch to the automatic control system of the vehicle at the on-ramp metering point or at any point in the lane and resume control of the vehicle at the exit ramp or at any other point in the lane after first going through a transition procedure. All the lanes on the roadway support mixed traffic and they are shared by conventional and automated vehicles, as shown in Fig. 2.1.

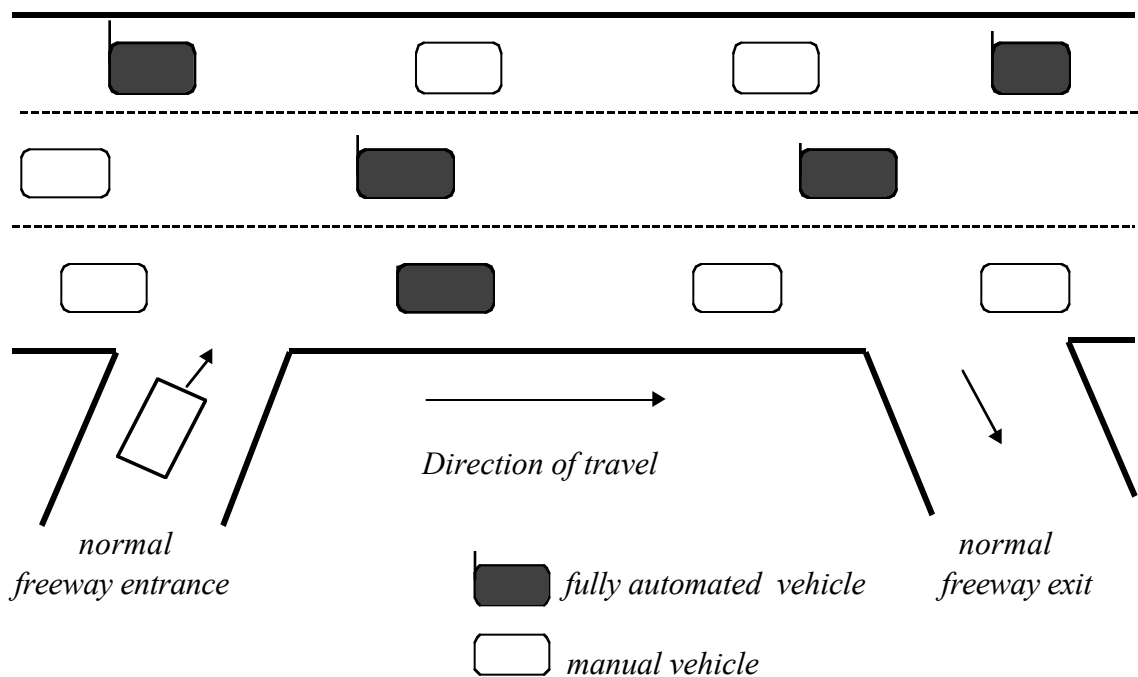


Fig 2.1 : Mixed traffic scenario I

2.1 Equipment on the Fully Automated Vehicle

The automated vehicle is equipped with throttle, brake and steering actuators. The control system has the ability to assume both longitudinal and lateral control. The functional block diagram of the control system is shown in fig. 2.2. The controller must rely on a network of sensors that provide the equivalent of 360° of vision around the vehicle. At

any time, the sensors and controllers on the automated vehicle must be aware of any obstacles and all vehicles in front, on the two sides and at the back. When an obstacle is detected, the controller on the automated vehicle will attempt to perform an obstacle avoidance maneuver, either by braking or by a lane change, in order to avoid a collision. The flowchart of the collision avoidance procedure is shown in fig 2.3.

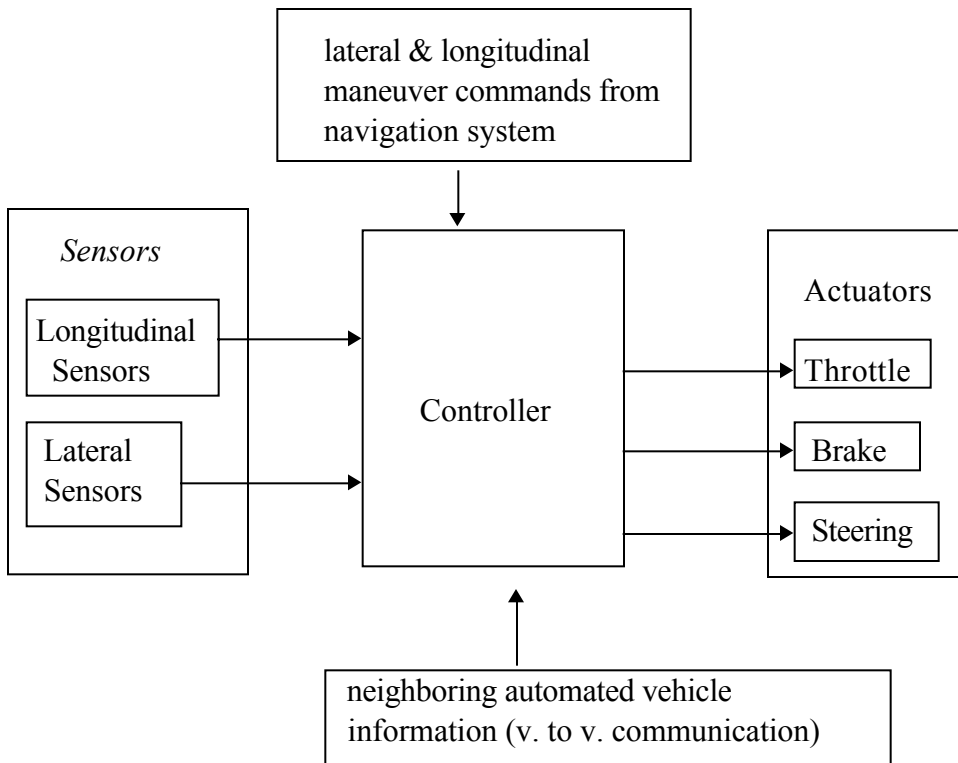


Fig 2.2 The functional block diagram of the automatic lateral and longitudinal control system

Unlike the vehicles we call “semi-automated” which depend on the human driver for collision avoidance, the fully automated vehicles can perform both lateral and longitudinal collision avoidance maneuvers without any human intervention. These systems afford the potential for drastically reduced inter-vehicle spacing and improvements in traffic throughput as we will show in section 5. The driver can, however, override the automatic control system and take over the control of the automated vehicle after a smooth transition procedure that guarantees the driver is not put in a situation that he/she cannot handle.

The navigation system plans the route from origin to destination as selected by the human driver and directs the lateral and longitudinal controller of the vehicle. Vehicle-to-vehicle communication can help the controller coordinate certain actions with other vehicles.

However, since mixing of manual vehicles is allowed, this communication and coordination may not always be available.

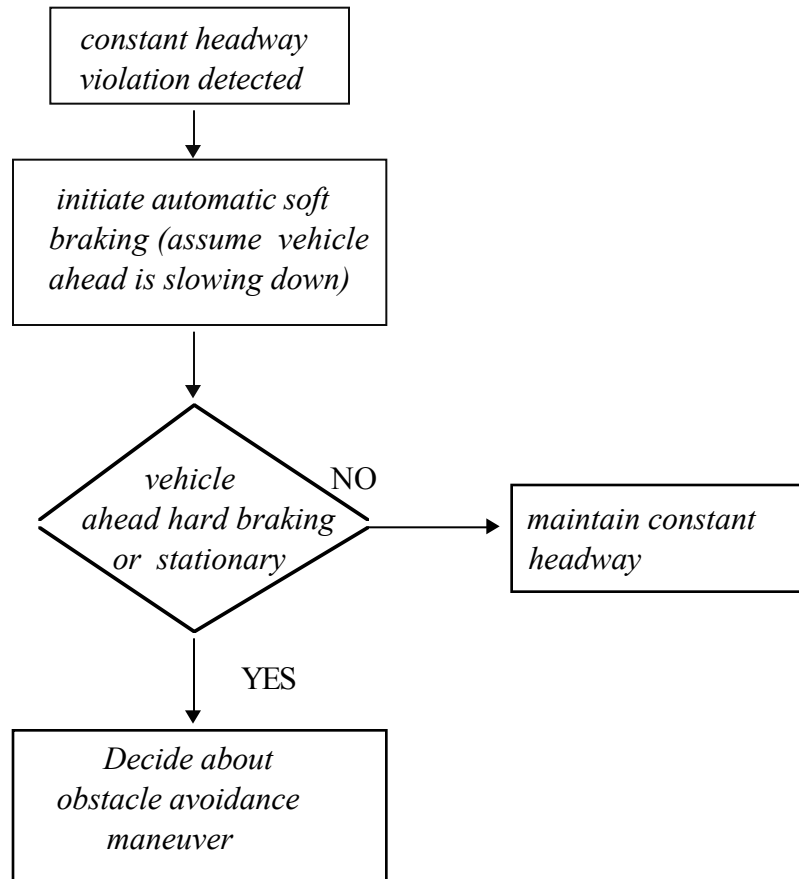


Fig 2.3 :The flowchart for collision avoidance in fully automated vehicles

The fully automated vehicle has automated lane-changing capability. The vehicle recognizes the need to change lane either for exiting or to travel in another lane. Before beginning the maneuver, the vehicle must use its lateral sensors to see if the necessary spacing in the target lane is available. The lateral sensors can check for the presence and position of other vehicles in the target lane. They can detect if there are vehicles changing lanes simultaneously from other lanes and if any vehicle in the target lane is approaching at a threatening speed. If any of the above conditions exist, the lane-change is aborted. The flowchart in fig 2.4 describes the automated lane-changing procedure.

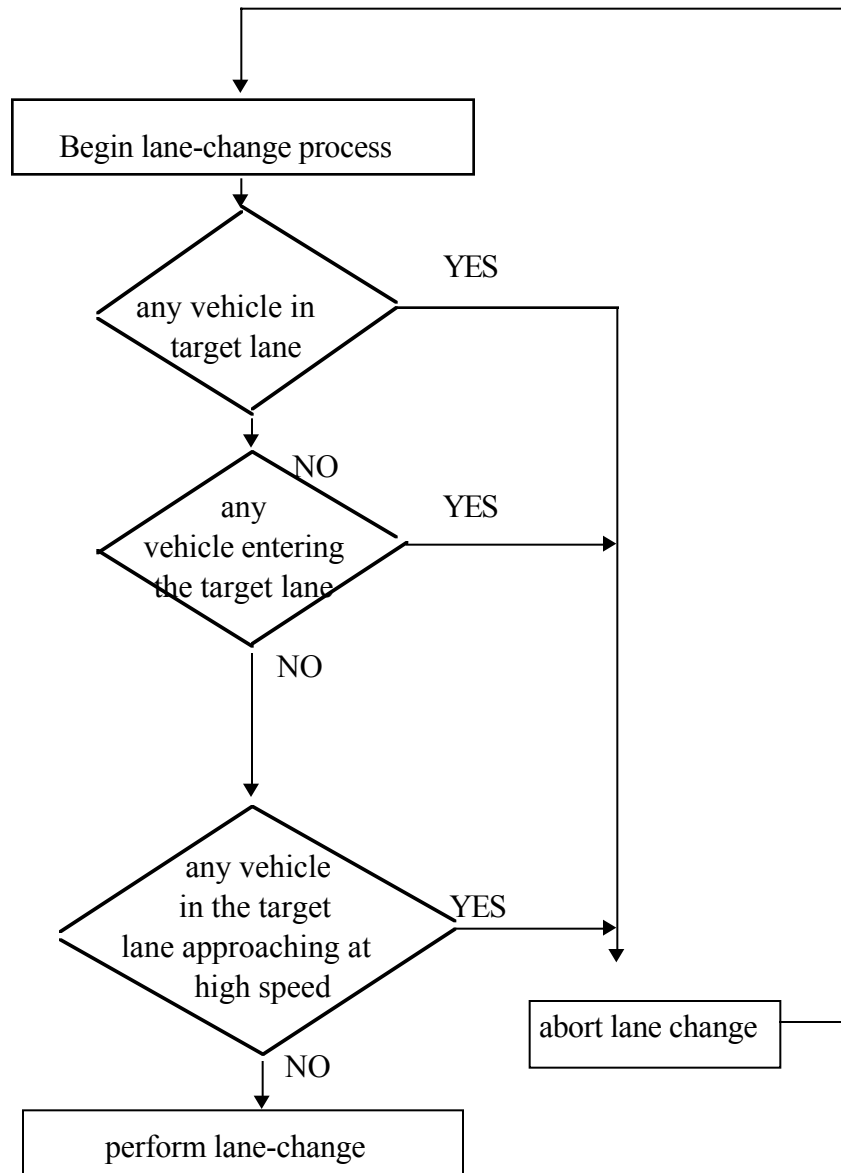


Fig 2.4 : Flowchart for automated lane changing

2.1.1 Vehicle-to-Vehicle Communication

All automated vehicles are equipped with communication systems. The vehicles communicate with each other and exchange information about vehicle status and traffic flow conditions. For example, when an automated vehicle detects a stopped vehicle it will communicate to other vehicles about the obstacle. After receiving this information, other vehicles will start slowing down, changing lanes and propagate the message to other automated vehicles behind. The automated vehicles will apply soft braking which will slow down the whole traffic stream including any manually driven vehicles between the

automated vehicles. Thus, the disturbance caused by stopped vehicles is attenuated and the traffic flow is smoother. However, there is always some risk that a manually driven vehicle is unable to slow down or stop and may collide with another (manual or automated) vehicle ahead.

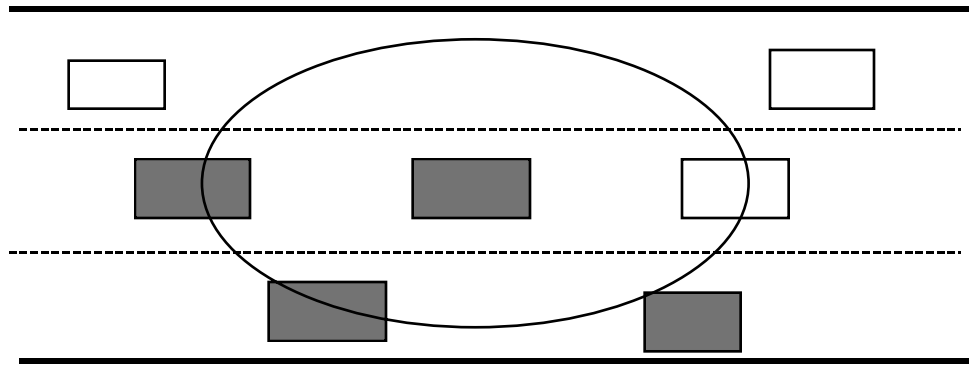


Fig 2.5 : ‘Zone of Relevance’ of an automated vehicle

The vehicle-to-vehicle communication system is two-way communication, with each vehicle simultaneously transmitting and receiving information. The transmitted signal will be acknowledged by each receiving vehicle, thus allowing the automated vehicles to detect the surrounding vehicles. The frequency of operation is an open issue. Frequencies as high as 64GHz have been proposed [3]. Each automated vehicle will have a ‘zone of relevance’ around it [3] to which communication and data exchange will be restricted (fig 2.5). It is obvious that this zone may include fully automated vehicles with communication capability as well as manually driven vehicles without communication capability. An appropriate strategy for dealing with this is the following: When a vehicle in the ‘zone of relevance’ does not acknowledge the transmission, it will be automatically classified as a manually driven vehicle. This will improve traffic coordination as the automated vehicles will know where other automated vehicles are in the immediate surrounding. Furthermore, it will circumvent the potential danger due to failures of the communication system on an automated vehicle. An automated vehicle with a non functional communication system should be treated as a manually driven vehicle.

For each pair of automated vehicles, both the leader and the follower must exchange information like the ‘Double Boomerang Transmission System’ [4]. Exchange of vehicle information like braking capability and tire pressure in addition to traffic conditions will reduce the minimum safe inter-vehicle spacing. The required information data transfer rate is over 1Mbps, and the processing rate is between 1000MIPS and 9000MIPS [5]. Contingencies will exist for emergency measures (like hard braking) which will override any ongoing message and will be given top priority.

2.1.2 Vehicle Navigation System

The on-board navigation system helps to guide the vehicle from the originating point to the final destination selected by the driver. The navigation system plans the route depending on the driver's chosen priority such as minimum travel time, minimum distance, most scenic etc. The navigation system continuously monitors the vehicle's current position using the Global Positioning System (GPS)[6]. It displays the current vehicle position on a map. The driver will have the option to override the navigation system at any point of the journey. He may issue a "Disable" command or override the lateral and longitudinal control of the vehicle by first going through a transition procedure during which the headway and speed are adjusted to levels the driver can handle. The driver can also specify a desirable route to the navigation system for the vehicle to follow.

2.1.3 Vehicle Sensors

The fully automated vehicle is equipped with sensors which measure the relative distance and relative speed to all vehicles in the immediate neighborhood of the automated vehicle. Naturally, vehicles ahead must be detected with the highest accuracy and precision. Relative speed readings need to be accurate and sensitive to small speed changes of less than 2mph.

The forward looking longitudinal sensors must have a range sufficient to allow the vehicle to come to a stop even under the assumption of a "brick wall scenario". A simple calculation shows that a vehicle traveling at 80 mph which has a maximum deceleration ability of 0.65g needs 100 meters to come to a complete stop. Therefore this range should be the basis for specifying the range coverage of the front vehicle sensors. Furthermore the front sensors must cover the adjacent lanes as well and they must be able to distinguish and resolve the position of all the target vehicles in two dimensions, i.e. relative distance and relative angle. The sensors must be able to track the target vehicle regardless of the presence of other vehicles in the adjacent lanes, in straight roadway segments and also along curves. It is quite a task and it may require the combined powers of sophisticated radar systems and real-time image processing.

The backward looking sensors have to measure the relative position and relative speed of the following vehicle and must be able to detect potential rear-end collision threats. It is also needed to evaluate the available spacing during lane changing and merging.

The lateral sensors are needed mostly to assist the automated vehicle during lane-changing. They detect if there is any vehicle in the destination lane, if any other vehicle is merging from the other side or if a vehicle is approaching at a threatening speed in the target lane. They should be able to detect reliably all kinds of vehicles, even motorcycles.

The demands on the backward looking and lateral sensor systems for a fully automated vehicle are quite complex. Candidate technologies include ultrasound, radar and video systems. Ultrasound sensors detect target position and range by bouncing acoustic energy pulses off a target and estimating time-of-flight. Radar sensors measure range and relative speed using the echo from radio frequency pulses and measuring time-of-flight as well as the Doppler effect. Video based sensors rely on efficient real-time image processing for target recognition. They all have individual advantages and disadvantages and combinations of sensor types may offer the only reliable way of meeting all the complex requirements on them. Different sensor technologies available today are presented and evaluated for their applicability in mixed traffic in Table 2.1.

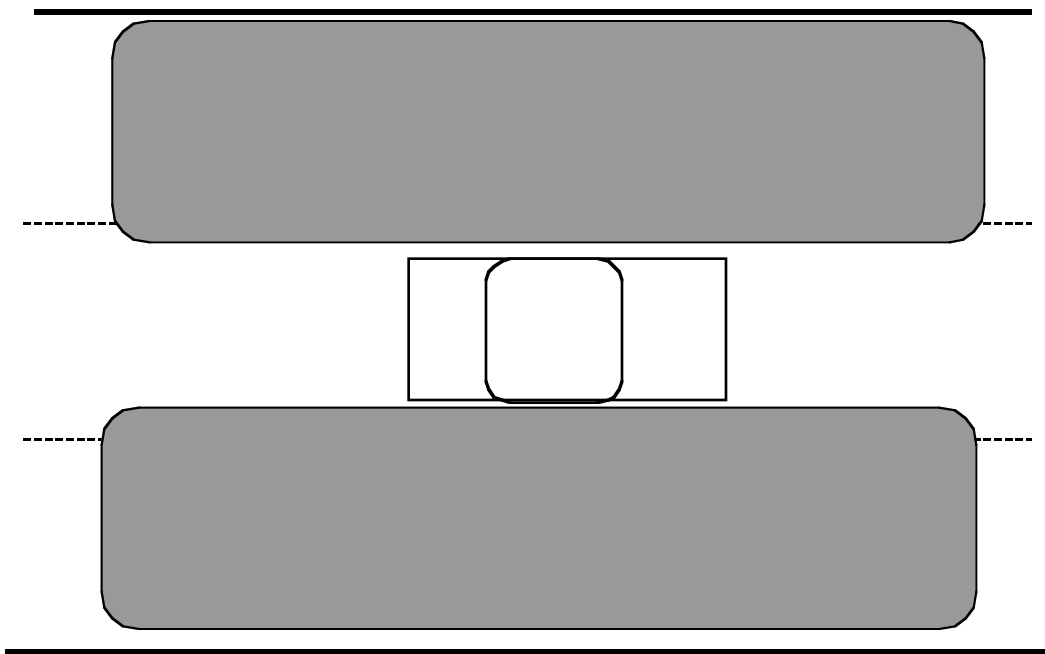


Fig 2.6 : Coverage of lateral sensors on both sides of a fully automated vehicle

Ranging Sensors for Fully Automated Vehicles			
Type	Advantages	Disadvantages	Usage
Monochrome video cameras	good spatial and angular resolution	Limited accuracy, difficult to estimate range and relative velocity, complicated process, performance deterioration in poor light conditions	Forward sensor Backward sensor Side sensor
Color video camera	Good accuracy recognizing lane markers	Same as monochrome camera	Forward sensor
Ultrasonic	Accurate at short ranges, low cost	Performance degradation in poor weather, limited range	Side sensor
Infrared range sensors	Good accuracy, accurate at short ranges, low cost	Performance degradation in poor weather, false target detection.	Side sensor
Microwave Radar	Good accuracy in widest range of conditions, no degradation in performance, medium cost	Limited angular resolution, size of antenna, high cost for high performance	Forward sensor Backward sensor Side sensor
Laser (Ladar)	Good accuracy	Performance degradation in low visibility conditions, affected by dirt and mud high cost for high performance	Forward sensor Backward sensor

Table 2.1 Summary of different available sensor technologies for automated vehicles and their applicability to mixed traffic

2.1.4 Sensors for Lane Keeping and Lane Changing

The lane keeping sensors provide the lateral measurements to the automated vehicles equipped with automatic lateral guidance. They measure the vehicle's lateral displacement from the center of the lane. The lane reference sensor continuously measures lateral deviation, lateral speed, lateral acceleration and yaw rate. The lateral controller generates the steering corrections in order to keep the vehicle on the desired path. Several types of

sensors are being considered for this applications. They can be vision or laser systems detecting visual stripes on the surface of the roadway, radar systems detecting radar reflecting stripes on the surface of the roadway, or magnetometers detecting magnetic stripes or discrete magnets embedded in the surface of the roadway.

Vision Systems can be used to provide real time images of the road, the lane markers as well as any obstacles ahead or on the side. A problem with this sensor technology is that solid-state cameras (CCD) have a dynamic range of about 20dB while the sun lit roadway may present light level variations up to 50dB[7]. More than one camera are often needed, with different focal length lenses for each, as the number of pixels is insufficient to simultaneously provide high resolution and a wide field of view. Cameras have circular symmetry which produces only radial distortions of the image.

The need for camera calibration is an important consideration of this system. Values can be found in [8]. However, there are systems which do not require any calibration like ASSET[9]. It is fed by a stream of digitized video pictures taken by a video camera and processed to give two-dimensional pictures.

Laser systems, have been employed like the Lateral-Effect Photodiode (LEP) scanning sensor[10]. A 0.9mW laser diode is used with a 10kHz modulation which maximizes signal-to-noise ratio and eliminates dc offsets. LEP has greater accuracy than CCD for close ranges. However, these two technologies can be integrated like in *Prolab* where the laser is fused with a camera to give three-dimensional sensor image[11].

Radar Systems for lateral position detection are given serious consideration because of their all-weather capabilities. A special tape containing microwave wavelength reflectors, essentially small pieces of wire, needs to be striped on the surface or just below the surface of the roadway. A radar system can be designed to track this target, under the car as well as up to a short distance ahead of the car.

Magnetic sensor based systems for lateral position detection is another very strong candidate, again because of their robustness in changing conditions and their all-weather performance. Either a magnetic tape or discrete magnetic rods are embedded on the surface of the roadway, while flux magnetometers under the car can detect them and thus generate a relative position signal in relation to them [18]. An additional benefit is that magnetic polarity reversals can be used to encode binary information which can be read out as the vehicle travels over them and provide additional information such as preview of any upcoming curvature changes [19].

2.1.5 On-board Warnings and Displays

Information displays become an essential and extremely important part of the automated vehicle. A variety of warnings may need to be used to alert the driver about the

possibility that he/she may have to assume the longitudinal or the lateral control of the vehicle when a sensor, communication or controller failure renders the automated system incapable of performing its task. Warnings with sounds and flashing yellow and red lights must indicate to the driver a violation of the minimum safe headway or lateral position deviation as well as the severity of the condition. It is also necessary to warn the driver and passengers whenever emergency maneuvers are executed by the automated vehicle to avoid frightening them each time the vehicle does something “unusual”. A speech warning system may need to be included in the vehicle which conveys short, discrete messages of the order of 150-200 words/minute [12]. It seems preferable to other type of audible alerts that emit electronic “beeps” since the necessity to have a large multitude of warnings makes it very hard for the humans to remember what each sound pattern might be telling them. The driver will have the option to adjust the speaker volume but only down to a preset minimum. This may be needed to avoid annoyance in the case of frequent false alarms, for instance, under high traffic density conditions.

The vehicle can also have a traffic situation display as shown in fig 2.7. At the center is the driver’s vehicle and the surrounding vehicles within the sensor range are shown. The display will indicate automated vehicles in communication with the driver’s vehicle by a connecting arrow which will help the driver know the spatial distribution of automated and manual vehicles in his/her immediate surrounding. In general what and how much information should be provided to the passengers of the automated vehicle is a human factors issue that needs extensive analysis and field testing.

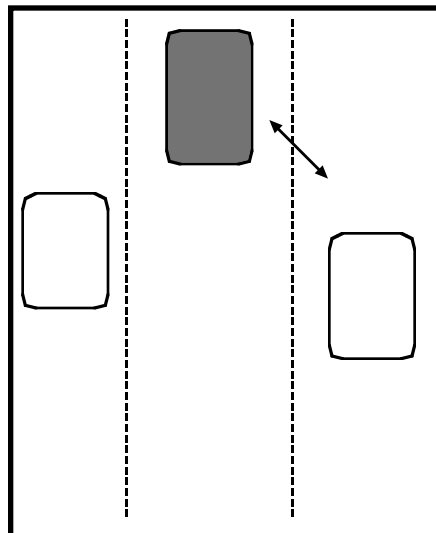


Fig 2.7 : On-board display of peripheral sensor reading with special indicator for communicating (automated) vehicle

2.1.6 Vehicle Displays

The vehicle could communicate information and system status to the driver with the help of a cathode ray tube (CRT) display or liquid crystal display (LCD) unit. The display unit should be easily readable by the driver of the automated vehicle even when he/she has assumed the driving of the vehicle. Studies have shown that character fonts consisting of a 9 × 11 dot matrix improve readability[13]. The contrast ratio should be between 7:1 to 3:1, and refreshed at the rate of above 100Hz to avoid flicker.

2.2 Role of the driver of the Automated Vehicle

The human driver of the automated vehicle will have very few responsibilities when the vehicle is operating in the automated cruising mode. The vehicle will be fully equipped to interact with the surrounding traffic. The driver will activate the automatic control system before entering the highway at the metering point on the on-ramp or while in the lane. After that point the control system will guide the automated vehicle in the longitudinal and lateral direction. The driver then has only a supervisory role and does not perform any direct actions.

The displays and the indicators will keep the driver informed at all times about the performance of the control system equipment like the throttle, brake and steering actuators, their corresponding controllers, the longitudinal and lateral sensors and the communication system. Messages will be displayed for the driver to notify him of any malfunction as soon as it is detected. For minor malfunctions the driver may only need to be reminded about the need for a system check up after the end of the trip. However, for major malfunctions like lateral control failure, the driver will be asked to take over the control of the vehicle. If the driver is incapacitated or for some reason fails to resume control of the vehicle, an emergency backup system will be activated which will make sure that the vehicle will gradually slow down and stop as soon as possible without endangering the safety of the driver and passengers. Depending on the nature of the malfunction, it may be safer to stop the vehicle in its current or if it is possible the vehicle will be guided to the side of the roadway or to an exit, so that it does not interfere with traffic flow.

What will happen after a malfunction is detected and the vehicle stops is an open issue, with one obvious possibility being that the vehicle will just wait for the driver to resume control or for the tow truck to take it away. In fact, if the communication system is still functional, the notification of the tow truck can take place automatically after a short time-out period lapses.

2.3 Role of the Roadway

In this scenario the role and the roadway is the same as with the current manual traffic. The automated vehicles are allowed onto the highway from the ramps which are also used by manually driven vehicles. Metering is done at the entrance to mitigate congestion on the highway, and the automated vehicle is treated just like any other vehicle waiting to enter the highway. The driver of the fully automated vehicle switches to the automatic control system of the vehicle at the on-ramp metering point or later on in the lane. The automated vehicle exits the highway through a normal highway exit ramp after making the transition to manual mode.

3 Mixed Traffic Scenario II

In this mixed traffic scenario we assume that some percentage of vehicles are fully automated and fully equipped with sensors and controllers that allow them to operate autonomously. The other vehicles are conventional vehicles, driven by human drivers. In contrast to the scenario analyzed in the previous section, it is assumed here that the roadway and the fully automated vehicles have extensive communication capabilities and they can communicate with each other. All the lanes on the roadway support mixed traffic and they are shared by conventional and automated vehicles.

3.1 Equipment on the Fully Automated Vehicle

The automated vehicle has the same equipment as described in section 2.1. One major difference is that the vehicle can communicate with the roadway.

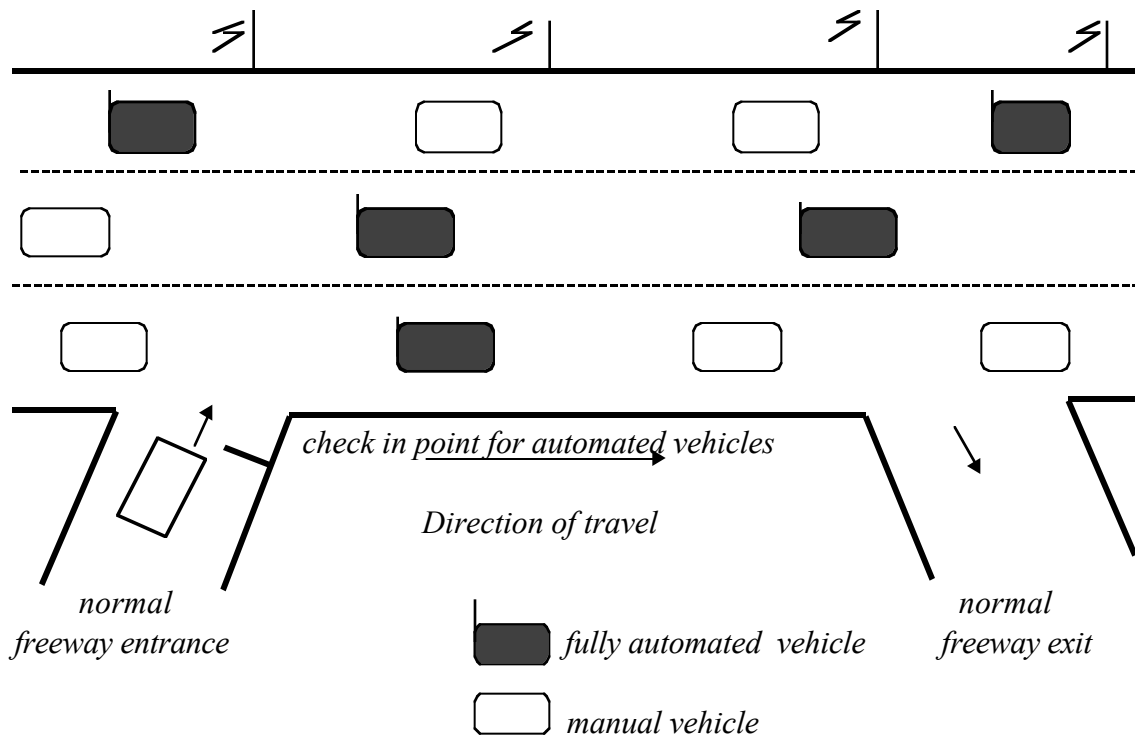


Fig 3.1 : Mixed traffic scenario II

3.1.1 Vehicle-to-Vehicle Communication

The communication system on-board the automated vehicle is elaborated in section 2.1.1., with the additional capability to transmit requests and information to the infrastructure and to receive commands and information from the infrastructure. Therefore, in a scenario

with roadway communication, the vehicle exchanges information both with the roadway and with other automated vehicles. The exchange of information with the roadway is done when the vehicle passes near a roadside beacon as explained in section 3.3.2. The vehicle communicates with other automated vehicles within the ‘zone of relevance’, as described in section 2.1.1.

3.1.2 Vehicle Navigation System

The navigation system has the same equipment described in section 2.1.2. However, it is assisted by additional information provided by the infrastructure, such as present location information and current travel times and flow conditions.

3.1.3 Vehicle Sensors

The automated vehicle has the same on-board sensors as given in section 2.1.3.

3.1.4 On-board Displays

Same equipment as before except that the vehicle will be displaying current traffic reports and instructions received from the roadway. The recommendations will be displayed as a notification to the driver of the automated vehicle that the vehicle should be traveling at a particular speed and headway.

3.2 Role of the driver of the Fully Automated Vehicle

The driver of the automated vehicle have the same responsibilities detailed in section 2.2. In case of major malfunction when the driver takes over the control of the automated vehicle, he/she will be guided by the infrastructure to the nearest exit from the highway.

3.3 Role of the Roadway

In the previous scenario, the roadway did not require any changes and so it was developed on the existing infrastructure. In this case, however, the roadway has communication capabilities and therefore requires some investment in the infrastructure. The additions suggested are such that they can be implemented on the existing infrastructure. The benefit from such addition is a more efficient control of traffic flow especially during congestion by influencing the speed and the density distribution along the lanes[23].

3.3.1 The Roadway/Vehicle Communication System

The roadway communicates with the automated vehicles. The communication system is ‘two-way’. The roadway recommends speed and headway distributions to the vehicles. It

also instructs maneuvers such as to change lanes to avoid stopped vehicle ahead, and to take a detour because of traffic congestion ahead. The vehicle transmits traffic conditions information to the roadway. The most recent information received from the vehicles is used to dynamically update traffic reports at the roadway traffic control center. The vehicles inform the infrastructure about possible congestion build-up and accidents which have just taken place. The autonomous navigation system can recognize each beacon it passes. Using this information, it calculates the travel time (dependent on current traffic conditions for the link) and transmits it to the roadway[15]. This helps the roadway to know better about different sections of the highway. It also aids other navigation systems planning their route when they receive the latest travel time for the different sections of the highway.

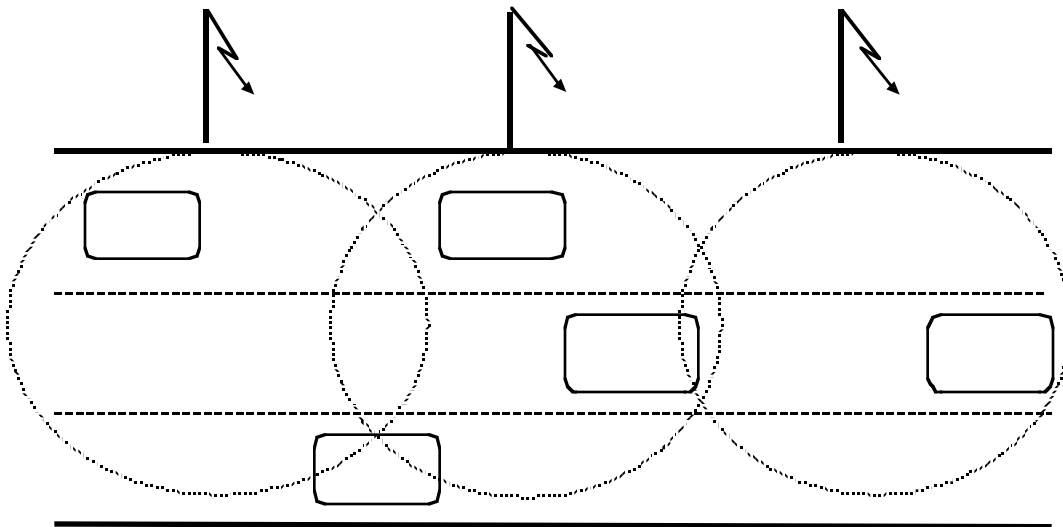


Fig 3.2 : Ellipses depicting communication zones

The information beacons set up on the roadway pass traffic information to the automated vehicles. The communication zones around the beacon cover a limited area (fig 3.2), so they have to be uniformly distributed in order to cover the whole area and to reduce interference. Vehicles exchange information when they pass through the zones.

The method of operation of the system is described in [16] and is as follows :

- (i) the beacon transmitter connects to the receiver of the semi-automated vehicle mostly on ‘line-of-sight’ within each communication zones
- (ii) quasi-microwave frequency of 2.3-2.6GHz is used
- (iii) data split into several frames are transmitted to the semi-automated vehicle

3.3.3 Variable Message Signs (VMS)

The roadway will communicate to the manually driven vehicles via Variable Message Signs (VMS) boards. The VMS boards convey traffic information to the manual vehicle drivers and is updated at the same rate as the communication beacon system. The VMS will post information on current traffic conditions, road works and road and lane restrictions. To notify vehicles about a detour, it will cross-out the original sign, display the reason and flash the detour route. A study has shown [17] that this method has the lowest non-compliance rate (about 0.9%) among human drivers. This is probably due to the fact that drivers “trust” the system more when the directions are justified and do not seem arbitrary. Moreover, this method has the advantage that vehicles take less time to exit for their destinations and they increase their speed once they have exited. All these factors contribute to a smoother traffic flow.

4 Safety Issues

The essence of mixed traffic is that automated vehicles coexist with manually driven vehicles. The primary concern for AHS has always been safety, and this becomes more important and crucial when we consider mixed traffic. Other AHS configurations like [1] considers only automated vehicle traffic while calculating safety headways. However, in mixed traffic, the driver of the manual vehicle plays an important role. The unpredictable and sometimes erratic behavior of the manual vehicle driver needs a thorough investigation for safety analysis in mixed traffic. Furthermore, complete automation of the fully automated vehicles pose several constraints on safety considerations. We have identified several important safety issues that are summarized in Table 4.1 and discussed below.

Safety issues in mixed traffic	
Sensors	Sensors may be unable to provide accurate information about the position, velocity and path of the manually driven vehicles.
Collision Avoidance	An accurate threat analysis by the automated vehicle may not be feasible because of the uncertainty regarding the intentions and actions of human drivers.
Over-reliance in automated system	The driver may be unable to take control of the vehicle in case of a major malfunction.
Navigation problems	Automated vehicles cannot merge or exit at a predetermined point because of a manually driven vehicle.
Tailgating	Driver of manual vehicle might misinterpret constant headway following policy of fully automated vehicles as tailgating.

Table 4.1 Summary of the safety issues in mixed traffic environment

4.1 Sensors of the Fully Automated Vehicle

In a fully automated vehicle we have a serious issue about the coverage of the front and the rear longitudinal sensors. The shaded area shows the desired coverage of the longitudinal sensors while the crossed area indicates the actual area covered by a single beam sensor. With a single sensor we are very likely to have problems, such as failing to detect sudden vehicle cut-ins, and failing to detect small vehicles like motorcycles. This is a concern both at the front and the back of the fully automated vehicle.

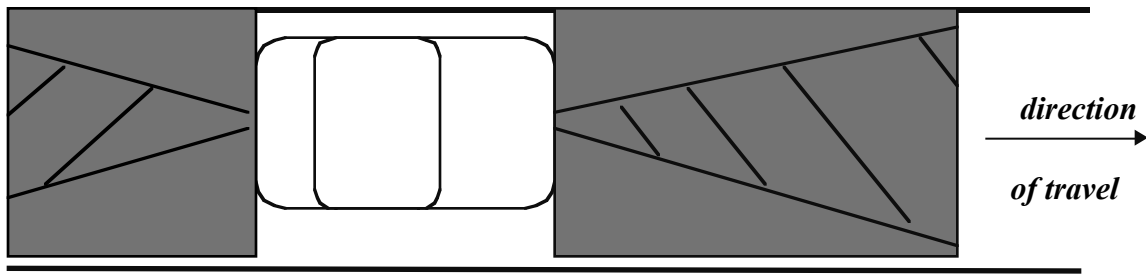


Fig 4.1: The shaded area denotes ideal sensor coverage, while crossed area denotes actual coverage for single beam sensor

A possible solution is to have dual longitudinal sensors, front and rear, so that we can have one on each side of the vehicle. The concern that this approach brings forth is that with increases in the market penetration of fully automated vehicles, many vehicles will have multiple radar sensors, all operating at similar frequencies. This will result in greater interference and shorter effective radar ranges. In this case a combination of a narrow beam radar with a video camera may provide the desired properties of a ranging and obstacle detection sensor.

Another issue is the coverage and accuracy of the side sensors. The area of coverage must be sufficient, perhaps extending more than the width of the adjacent lane, yet they must be insensitive to stationary objects and clutter on the side of the roadway.

A potential serious problem is the “blinding” of the forward looking sensor by the transmissions of the backward looking sensor of the vehicle ahead and vice versa. The same problem may exist between the side sensors of vehicles traveling on parallel lanes. This problem can be avoided by allocating different frequency bands for the operation of the forward and backward looking sensors, and different frequency bands for the operation of the left-looking and right-looking side sensors.

4.2 Collision Avoidance

There are two elements in collision avoidance, longitudinal collision avoidance and lateral collision avoidance. For longitudinal collision avoidance in mixed traffic, we have a potential problem when an automated vehicle has to stop behind a manually driven vehicle that applies emergency braking. It is preferable to have an additional margin of spacing when an automated vehicle follows a manual vehicle as presented in the throughput analysis in section 5. This margin makes a collision with a manual vehicle in front rather unlikely, yet there are issues to be resolved. For example, the automated vehicle may be able to avoid a collision with the vehicle in front by applying emergency braking. Yet, a manual vehicle behind may fail to stop and it may collide with the

automated vehicle from the rear. The automated vehicle may sense the oncoming collision threat from the rear and may try to avoid a collision by reducing its deceleration in order to give more space for the manually driven vehicle to stop. This option may not always be available, depending on the situation in front of the automated vehicle. A rear-end collision by a manually driven vehicle may be completely unavoidable. The issue now becomes if the automated vehicle should attempt any other kind of evasive maneuver in trying to avoid such a collision. One such option may be to perform a lane change, provided a space is available in an adjacent lane. But performing a lane change as a response to an emergency has the risk of leading to an offset collision, a potentially destructive move. All vehicles are designed in a way that they are able to absorb a collision along the axis much more than an offset collision. Since passenger safety is a priority, we have to accept the risk of an on-axis collision and discourage lane changes as a response to emergency.

Lateral collision avoidance becomes necessary when the automated vehicle performs a lane change or when a vehicle in an adjacent lane performs a lane change. A vehicle changing into the adjacent lane from the other side may continue its lateral motion and collide with the automated vehicle or it may stay in the adjacent lane. There is no way for the on-board controller to determine when the lateral collision threat is real until the vehicle has come too close. At that point there may not be enough time for any collision avoidance maneuver to be taken.

For example, consider an automated vehicle traveling in the left lane as shown in fig 4.2. A manually driven vehicle changes lane from the right lane to the center lane. It might be that the merging vehicle comes very close and within the sensor warning range of the fully automated vehicle. This will trigger off the warning system of the vehicle. However, there might be instances when the manually driven merging vehicle is just completing an innocuous lane-change and is under the control of the driver. On the other hand, it could be a potential threat when the human driver is incapacitated and may collide into the adjacent vehicle.

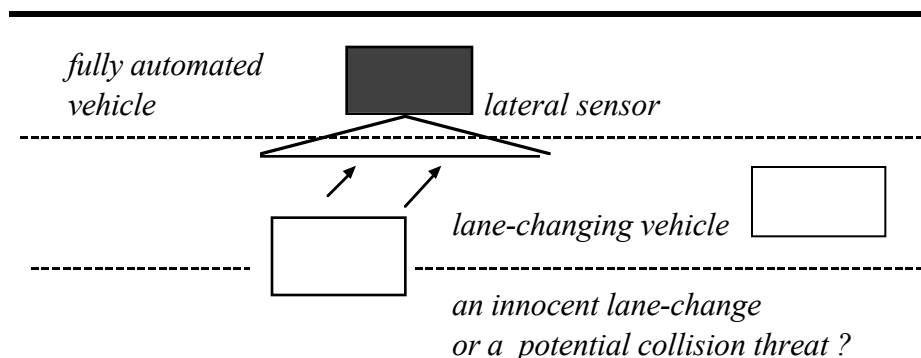


Fig 4.2 : Lateral sensor cannot distinguish a lane-change from a potential collision threat

The issue remains how to distinguish between the two cases. Both have similar characteristics and while the control system might assume that it is just a lane-change, it might be too late when the manually driven vehicle cuts-in or collides in the side. On the other hand, if the controller attempts to react, then the traffic flow conditions will be affected by these disturbances due to the cautious actions of the system.

4.3 Over-reliance on Automated Control System

The automated vehicle can continue to operate in case of minor failures in a channel of the avoidance system or communication system. But if a major malfunction such as lateral control or the throttle actuator system failure occurs, then the vehicle informs the driver to take control and switch to manual mode. If the driver has overconfidence on the system then he/she will not be aware of the current situation and may be engaged in other tasks. This is a high possibility in vehicles with lateral control where the driver has ‘hands off and feet-off’ driving and is completely out of the driving loop. Then the driver is incapacitated and unable to take immediate control of the vehicle. Such a situation in mixed traffic where manual vehicle drivers are not aware of the loss of control will pose serious safety threats.

4.4 Navigation Problems

Automated vehicle use on-board vehicle navigation to reach a destination. The navigation system directs the automatic control system and specifies exit and merging points for the vehicle. However, a situation may arise that the vehicle cannot merge into a lane or exit from a lane due to the presence of a manually driven vehicle. This will upset the route planned by the navigation system. However, the automatic control system of the vehicle should not execute any maneuver that can become a collision threat just to get back on the earlier route. This will affect the safety considerations of the automated vehicle. The navigation system should attempt to get back to the pre-planned route through a detour or choose an alternative route.

4.5 Tailgating

The driver of the manual vehicle might be uncomfortable and consider it to be tailgating when an automated vehicle might keep a safe inter-vehicle distance from a manual vehicle. Furthermore, the fact that the automated vehicle equipped with cruise control will (try to) maintain a constant headway might worsen the situation. It has been argued that the

opposite is true because of an additional one-half second time gap [20]. Nevertheless this issue cannot be completely ignored because the perception of tailgating depends solely on the attitude of the driver being followed. He/she might think his/her is a victim of tailgating while this is actually not the case. The response of the driver of the manual vehicle is a human factors issue that needs further investigation.

5 Throughput Analysis

In this section, we analyze the theoretical traffic throughput for the mixed traffic scenarios considered.

5.1 Mixed Traffic Throughput Model

Random sequencing of automated and manual vehicles in mixed traffic operations produce different combinations of pair of vehicles adjacent to each other. The analysis carried out in [20] proposes a model to incorporate this scenario based on the probabilistic likelihood of each event occurring. The study assumes that the entire vehicle population is large relative to the number of vehicles we consider in the analysis. The expression for throughput is a function of market penetration of automated vehicles. We adopt a headway model for each one of the four possible vehicle combinations, i.e., manual-manual, manual-automated, automated-manual and automated-automated.

An automated vehicle will know if the leader is automated or manual by attempting to communicate to the vehicle ahead. If the leader does not acknowledge, then it is a manually driven vehicle. The following vehicle will select and maintain the appropriate inter-vehicle spacing (headway) accordingly. On the other hand, a manually driven vehicle will always use the same inter-vehicle spacing regardless of the type of vehicle ahead.

Let the market penetration of the automated vehicles be a . The probability that a vehicle is automated or manual is given by,

$$\begin{aligned} P(\text{automated vehicle}) &= a \\ P(\text{manual vehicle}) &= 1-a \end{aligned}$$

For example, when $a=0.1$, 10% of the vehicles in mixed traffic are automated, i.e. for a population of 1000 vehicles, $1000a = 100$ vehicles are automated.

We also define the following probabilities

$$\begin{aligned} P(A,M) &= \text{probability that an automated vehicle is followed by a manual vehicle} \\ P(A,A) &= \text{probability that an automated vehicle is followed by an automated vehicle} \\ P(M,A) &= \text{probability that a manual vehicle is followed by an automated vehicle} \\ P(M,M) &= \text{probability that a manual vehicle is followed by a manual vehicle} \end{aligned}$$

So we have

$$\begin{aligned} P(A,M) &= a \leftrightarrow (1-a) \\ P(A,A) &= a \leftrightarrow a \\ P(M,A) &= (1-a) \leftrightarrow a \end{aligned}$$

$$P(M,M) = (1-a) \leftrightarrow (1-a)$$

The final throughput expression in [20] is formulated based on inter-vehicle data for the four possible outcomes. We carry out the analysis based on headway data and follow the notation given below for headways

H(A,M) : Headway of a manual vehicle following an automated vehicle

H(A,A) : Headway of an automated vehicle following an automated vehicle

H(M,A) : Headway of an automated vehicle following a manual vehicle

H(M,M) : Headway of a manual vehicle following a manual vehicle

The average headway of the mixed traffic is given by

$$av_head = [P(A,A) H(A,A) + P(A,M) H(A,M) + P(M,A) H(M,A) + P(M,M) H(M,M)] \quad (1)$$

and the throughput can be calculated as

$$throughput = 3600 / av_head$$

5.1.1 Manual vehicle headways H(A,M) & H(M,M)

A manually driven vehicle in mixed traffic will always maintain the same inter-vehicle spacing irrespective of the type of vehicle ahead, i.e. H(A,M)=H(M,M). The headway of a manual vehicle depends on the driver and it has been found to follow a shifted log-normal distribution as seen in fig 5.1 [2]. It has a mean value of 1.8s which results in a throughput of 2000 vehicles per hour per lane. In fact the capacity of 2000 veh/hr/lane has been termed as the ‘national average’ in the 1985 Highway Capacity Manual [21].

5.1.2 Automated vehicle headways H(A,A) & H(M,A)

The headway values for the automated vehicle H(A,A) are taken from the study carried out by Ioannou et al[1]. The study considers spacing (and headway) for vehicles in different AHS configurations. We used the data for free agent automated vehicles which depend on communication with other automated vehicles to make headway decisions. When an automated vehicle follows another automated vehicle, they are assumed to communicate to each other their braking capabilities and the follower selects a headway based on that.

An automated vehicle following a manually driven vehicle will not have any information about the braking capabilities of the leader. However, since the automated vehicle is equipped with reliable sensors, it will react the same way as it would when following another automated vehicle without any vehicle-to-vehicle communication. We use the

intervehicle spacing tool to calculate the headway for autonomous automated vehicles[22].

There is an issue when an automated vehicle follows a manual vehicle. The unpredictable behavior of the manual vehicle may force the automated vehicle to perform sudden maneuvers. This erratic behavior can be attenuated by allowing extra spacing between the leading manual vehicle and the automated vehicle. This will act as a cushion that will allow the automated vehicle to smooth out the leader's sudden maneuvers by performing soft braking. To account for that, we add 0.5s to the data obtained from the spacing tool when we calculate $H(M,A)$.

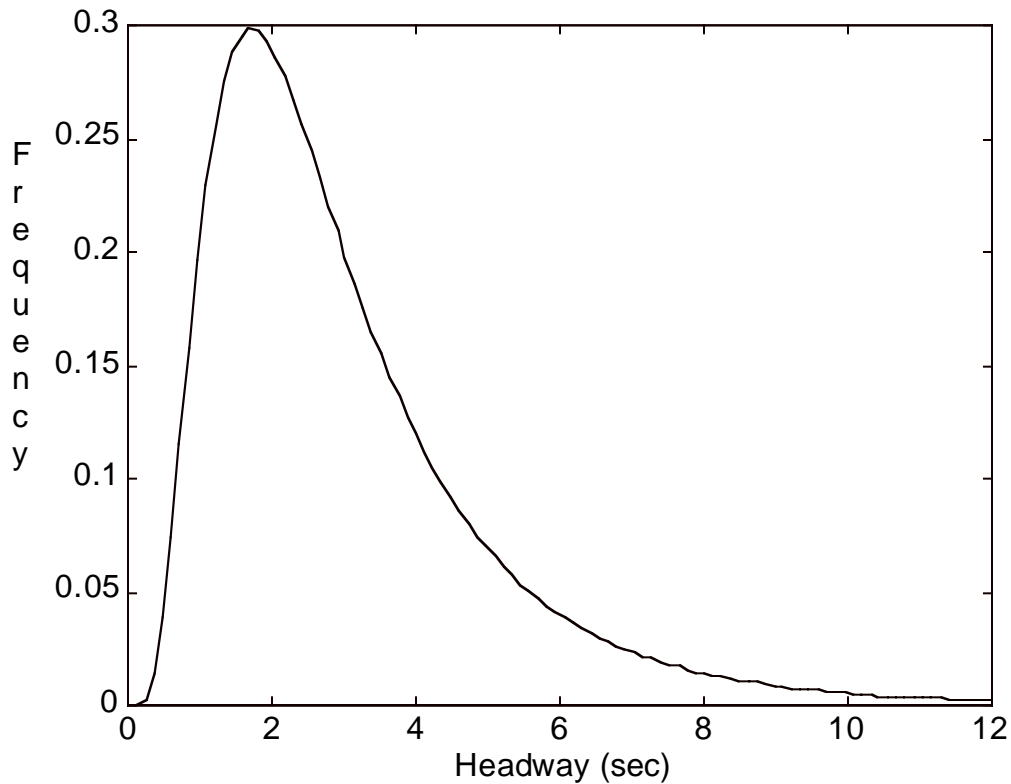


Fig 5.1 : Empirical time headway distribution for manual traffic

5.2 Mixed Traffic Throughput Model with Automated Vehicle Lane Changing

The effect of lane-changing on the total traffic throughput is dependent on multiple factors such as density and speed of the originating lane, density and speed differential between the originating and the target lanes, time required to complete the lane-change and the angle of departure of the lane-changing vehicle from the originating lane[22].

The decrease in throughput due to lane-changing is because of the additional headway needed by the merging vehicle both in the originating and the destination lanes. This increased spacing requirement and the transients associated with the merging vehicle adjusting its speed reduce the traffic throughput for a particular time interval, after which the system recovers (assuming it is stable) and traffic flow comes back to the original throughput.

The lane-changing scenario depends on whether the merging vehicle is automated or manual. An automated vehicle performing an automated lane-change will have a smooth deceleration gradient to minimize the disturbance. On the other hand, the behavior of a manually driven vehicle performing a lane change is driver dependent, and the lane-change can be abrupt or very smooth. To model a manual vehicle lane-changing, a lot of uncertainties are involved because the lane-changing behavior of the human driver is too complicated to duplicate and analyze. There are numerous instances of drivers abruptly cutting-in from other lanes, and drivers taking unnecessary long time to change lanes. However the lane changing behavior of automated vehicles can be simulated because they follow a predetermined algorithm [22]. Hence, we identify a model to analyze throughput with lane-changing by automated vehicles only.

For a better understanding, let us consider the following example. Ten vehicles (manual and automated) are traveling in a single lane at a constant speed of 60mph as shown in fig 5.3. The second vehicle 'v2', assumed to be automated, wants to change to a slower lane and starts adjusting its speed accordingly. The disturbance caused by the vehicle slowing down is propagated upstream and vehicles 'v3' through 'v10' must slow down. The merging vehicle 'v2' needs extra safety spacing from its leader and its follower during the lane change. The amount of additional spacing is dependent on factors like the velocity differential between the originating lane and the destination lane and the time to complete the lane-change.

So 'v2' starts adjusting its speed and creating the necessary spacing at the beginning of the lane changing maneuver at time t . The vehicles 'v3' through 'v10' have to slow down because of 'v2' and at this time the throughput falls. But after 'v2' merges into another lane, 'v3' to 'v9' are able to speed up to 60mph again and the system recovers to its earlier throughput. This is shown in fig 5.3.

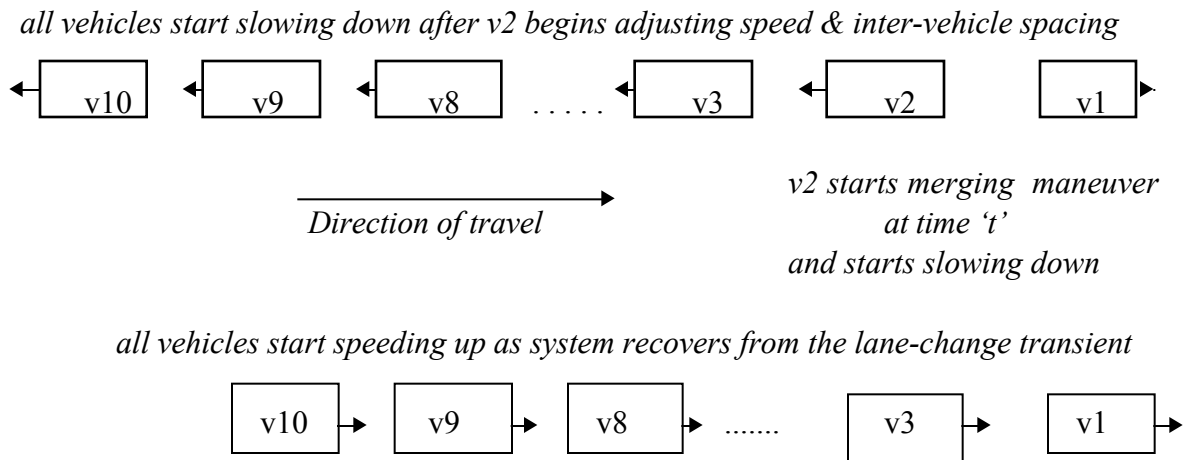


Fig 5.3 : Effect of lane-changing and transients

The previous case considers a single vehicle lane-change. If we have another automated vehicle ‘v9’ changing lanes at $t+\Delta t$, the spacing requirement for ‘v9’ will be dependent on Δt . If ‘v9’ begins to change lanes before the transients have died down when the vehicles are traveling at a speed lower than 60mph, then the required spacing will be smaller than the spacing required by ‘v2’, because of the lower speed. But if Δt is large enough so that ‘v9’ starts after the system has recovered, the spacing requirement will be identical to ‘v2’.

Taking a conservative approach, we consider that the spacing required when two or more automated vehicles are changing lanes simultaneously is identical and equal to the case when a single automated vehicle is changing lane in an undisturbed system. This means that the spacing requirement in the originating lane for all vehicles changing lanes is identical which is stated below as assumption A(III). The calculation from this analysis gives the lower bound of the throughput.

A similar effect is seen in the destination lane where the following vehicles must adjust their speed and create spacing for the merging vehicle. Considering the worst case scenario stated above and assuming equal lane-changing time for all merging vehicles, we see that the spacing requirement in the destination lane is identical for all lane-changing vehicles.

The assumptions for the model are:

A(I) : the traffic density in the originating and the destination lanes is high.

A(II) : the speed of the traffic in the originating and the destination lanes is high.

A(III) : the spacing requirements for all lane-changes are identical.

A(I) and A(II) are necessary to ensure that lane-changing will always affect the traffic flow throughput. In real life, however, this might not be the case. A vehicle changing lanes smoothly in low density traffic will hardly influence the total throughput. Based on the previous assumptions, we propose the following model.

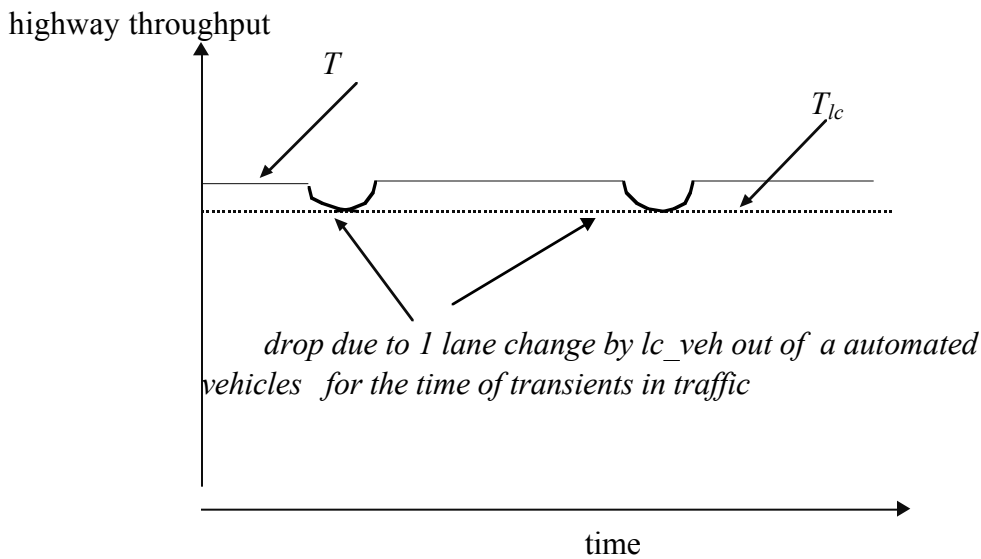


Fig 5.4 : Effect of lane-changing transients on highway throughput

Throughput is a constant for a given headway and speed (T in fig 5.4) when there is no lane-changing or merging and, at best, is equal to the pipeline capacity determined by the existing conditions. However, for a single vehicle lane-change there is a drop in the throughput because of the disturbance caused by the transients during lane-changing. Multiple vehicle lane-changes will cause multiple consecutive drops in the throughput since each lane-change is identical, according to A(III). The throughput drops from T to $T - \Delta T$ during the disturbance. We calculate the lower bound T_{lc} of the resulting throughput when 3%, 7% and 10% of the automated vehicle population change lanes simultaneously. The reduced throughput due to the lane-changing (by the automated vehicles) gives an estimate of the lane change derating factor.

If av_head denotes the average headway for mixed traffic without lane changes, lca_head denotes the average headway with lane-changes and lc_veh is the percentage of automated vehicles changing lanes, then the cumulative headway of a single highway lane for a given penetration 'a' is

$$cum_head = lc_veh \leftrightarrow a \leftrightarrow lca_head + (1 - lc_veh \leftrightarrow a) \leftrightarrow av_head \quad (2)$$

where lca_head is calculated using (1) by replacing the automated vehicle headway by the lane-changing headway.

The reduced throughput is given by

$$T_{lc} = 3600 / cum_head \quad (veh/hr/lane)$$

This is the lower bound for the throughput when lc_veh out of a automated vehicles change lanes. The lane-changing headway lc_head is evaluated in the next section.

5.2.1 Lane Change: Minimum Safety Spacing and Headway

When a vehicle performs a lane-change, the intervehicle spacing required must be such that if either one of the leading vehicles in the originating or the destination lane or the merging vehicle performs emergency braking, there should be no collision. This is referred to as the *Minimum Safety Spacing* (MSS) and is calculated taking into account the reduced braking ability of the merging vehicle due to simultaneous lateral and longitudinal acceleration. Simulations for lane-changing by automated vehicles give the headway values for the leader and the follower in the originating and the destination lanes. The MSS is dependent on the type (manual or automated) of the following vehicles ‘f1’ and ‘f2’ and the type of the leading vehicles ‘l1’ and ‘l2’ (fig 5.5). If any of the vehicles is automated, it can communicate with the merging vehicle about their braking abilities and this can reduce the lane changing headway requirement between the pair. The worst case is when all four vehicles surrounding the merging vehicle are manual vehicles.

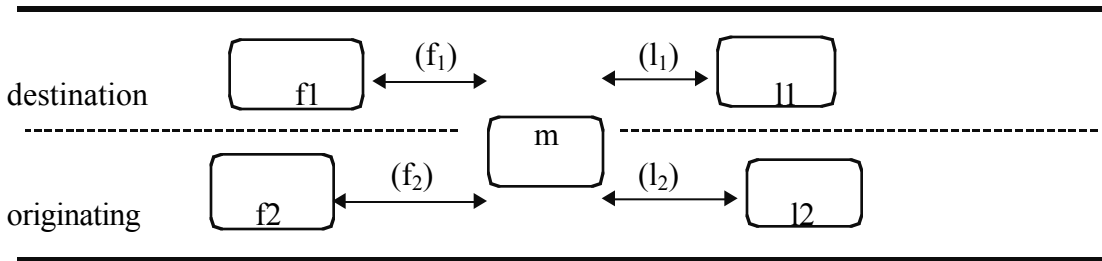


Fig 5.5 : Vehicle changing lanes and the necessary MSS

We assume a constant time of 5sec for merging into the target lane for all lane-changes. We also assume that when the merging vehicle begins to adjust its speed and the following vehicles begin to slow down, the other following vehicles maintain the same average

headway. This means that during disturbances, when vehicles begin to slow down/speed up due to a lane-change/merge, they maintain the same time-headway.

We compute the lane changing headway by first obtaining the headways (l_1) , (l_2) , (f_1) and (f_2) . Then we compare (f_1) and (f_2) with the average headway for manual traffic $H(M,M)$ and if it is larger then the difference is added to the lane changing headway together with (l_1) and (l_2) . Then we take the average of the computed headway in the originating lane and the destination lane and use it in Eq.(1) to get the average mixed traffic headway with lane changing. We use the average mixed traffic headway with lane-changing and the average mixed traffic headway without lane-changing to obtain a weighted average depending on the percentage of vehicles that are changing lane.

5.2.2 The Lane-changing Headway computation

The headways (l_1) , (l_2) , (f_1) and (f_2) are calculated for the worst case scenario with manual vehicles. The manually driven vehicles have larger response time than automated vehicles, therefore a larger spacing is necessary to merge between them. The spacing software calculates the MSS for both cases when either one of the leaders performs emergency braking. We take the worst case scenario between the two. In the originating lane, we compare the headway between the merging vehicle and the following vehicle with the average manual vehicle headway. If (f_2) is greater than the average manual vehicle headway then it means that the merging vehicle will need this extra spacing therefore we add this to lc_head .

In the destination lane the length of the merging vehicle is added to the spacing calculated by the software to get the total spacing required for the lane-change maneuver. This is the spacing that vehicle 'f1' must allow for the merging vehicle. We compare this with the manual vehicle headway and we add the difference to the lane-changing headway. This applies to both (f_1) and (l_1) .

Case 1 : Speed of originating lane < Speed of destination lane

As an example let us assume that the speed in the originating lane is 26 m/s and the destination lane is 30 m/s. The spacing values are:

$$\begin{aligned}(l_1) &= 0.01s (0.39m) \\(f_1) &= 2.61s (78.18m) \\(l_2) &= 1.06s (27.45m) \\(f_2) &= 1.45s (37.81m)\end{aligned}$$

In the originating lane, (f_2) is less than the average manual headway, while $(l_2) = 1.06s$ is added to lc_head .

In the destination lane, the total spacing necessary is $0.39\text{m}+78.18\text{m}+5\text{m}$ (vehicle length) = 83.57m , translating into a headway of 2.79s . So the manually driven vehicle 'f1' will have to generate $2.79-1.8=0.99\text{s}$ extra headway for the merging vehicle.

So the average lane-changing headway necessary is

$$lc_head = (1.06+0.99)/2=1.03\text{s}$$

Case 2 : Speed of originating lane > Speed of destination lane

In this case, the speed in the (faster) originating lane is 30 m/s and in the (slower) destination lane is 26 m/s . The spacing values are

$$\begin{aligned} l_1 &= 1.38\text{s} (35.8\text{m}) \\ f_1 &= 1.27\text{s} (33\text{m}) \\ l_2 &= 0.37\text{s} (11.17\text{m}) \\ f_2 &= 2.03\text{s} (60.8\text{m}) \end{aligned}$$

In the originating lane, (f_2) is larger by $2.03-1.8 = 0.23\text{s}$ than the average AHS manual headway which is added to lc_head . The lane-changing vehicle headway (l_2) = 0.37s is smaller than the average automated vehicle headway (= 1.05s), so the latter is used for simulation. So the total headway needed in the originating lane is 1.28s .

In the destination lane, the total spacing necessary is $35.8\text{m}+33\text{m}+5\text{m}$ (vehicle length) = 73.8m , translating into a headway of 2.84s . So the manually driven vehicle will have to generate $2.84-1.8=1.04\text{s}$ of extra headway for the merging vehicle.

The average lane-changing headway for automated vehicles is

$$lc_head = (1.28+1.04)/2=1.16\text{s}$$

Thus, we note that the additional headway for the lane-change of an automated vehicle from a high speed lane to a low speed lane and vice-versa is almost the same, which is intuitively acceptable.

5.2.3 Throughput calculation with lane-changing

We investigate the total throughput for a section of the highway which includes losses in throughput due to lane-changing averaged over a particular time period. For a given percentage of automated vehicles, we have

$$T_{lc} = 3600 / cum_head$$

$$= 3600 / (lc_veh \leftrightarrow a \leftrightarrow lca_head + (1 - lc_veh \leftrightarrow a) \leftrightarrow av_head) \quad (3)$$

where T_{lc} denotes throughput in veh/lane/hr

For example, if no automated vehicles are changing lanes (i.e. $lc_veh = 0$), we have

$$T_{lc} = 3600 / av_head = T$$

or in other words, the throughput is at its maximum. (as seen in fig 5.4)

5.3 Throughput for mixed traffic of automated vehicles

The manual vehicle headways, $H(M,M)=H(A,M)=1.8s$ are taken from [2]. The automated vehicle headway $H(A,A)$ is 0.31s which is calculated using the spacing tool [1]. The details can be found in the study [1] which we briefly elaborate for the benefit of the reader. The leading automated vehicle communicates its braking capabilities to the follower which uses the information to select the headway. We assume a worst case scenario where the following automated vehicle is assumed to be in an acceleration mode of 0.1g and has a 10% inferior braking capability from the leader (fig 5.6). The follower has a detection delay of 0.1s and the leading automated vehicle is assumed to have a maximum deceleration of 0.8g. We calculate the headway assuming an average highway speed of 28 m/s (the average of the two lanes considered in the lane-changing scenario).

When the leading vehicle performs emergency braking, it communicates its braking intentions to the vehicle behind. When the automated vehicle detects that the leader is braking and at the same time receives the information that this is emergency braking, it immediately begins emergency braking.

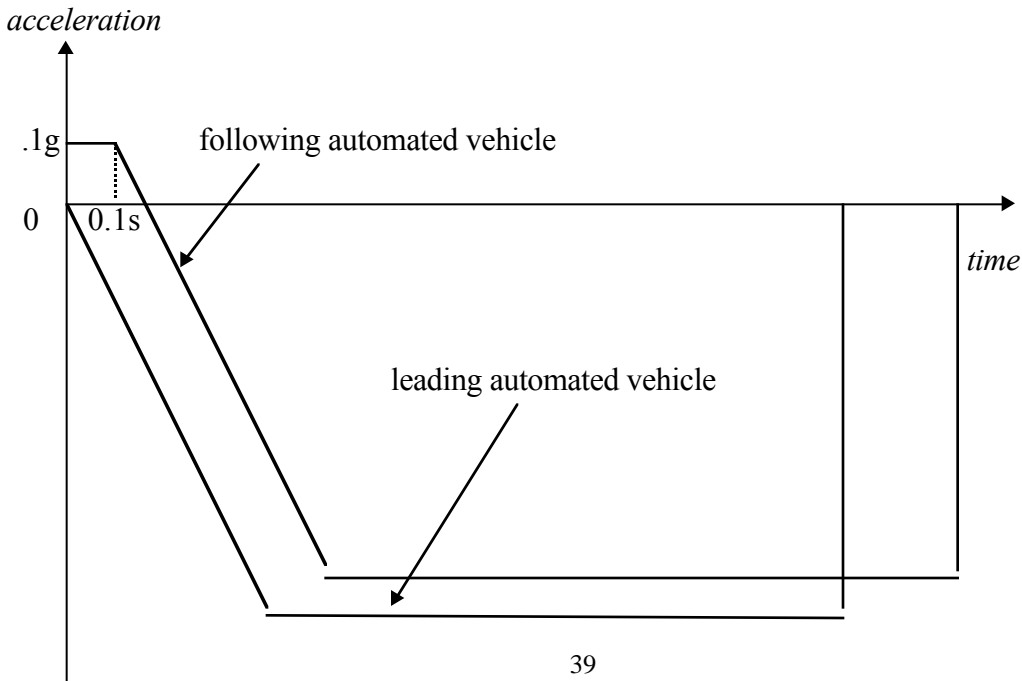


Fig 5.6 Acceleration profiles of an automated vehicle following another automated vehicle equipped with vehicle-to-vehicle communication performing emergency braking

The headway for the automated vehicle following a manual vehicle $H(M,A)$ is 0.55s and is calculated using the spacing tool[1]. We assume a worst case scenario similar to above at a speed of 28 m/s. The leader performs emergency braking which is detected by the follower after a delay of time t_l (fig 5.7). Since the follower does not know if the leader is performing emergency braking, it applies limited jerk and executes soft-braking. At time t_e it detects and initiates emergency braking.

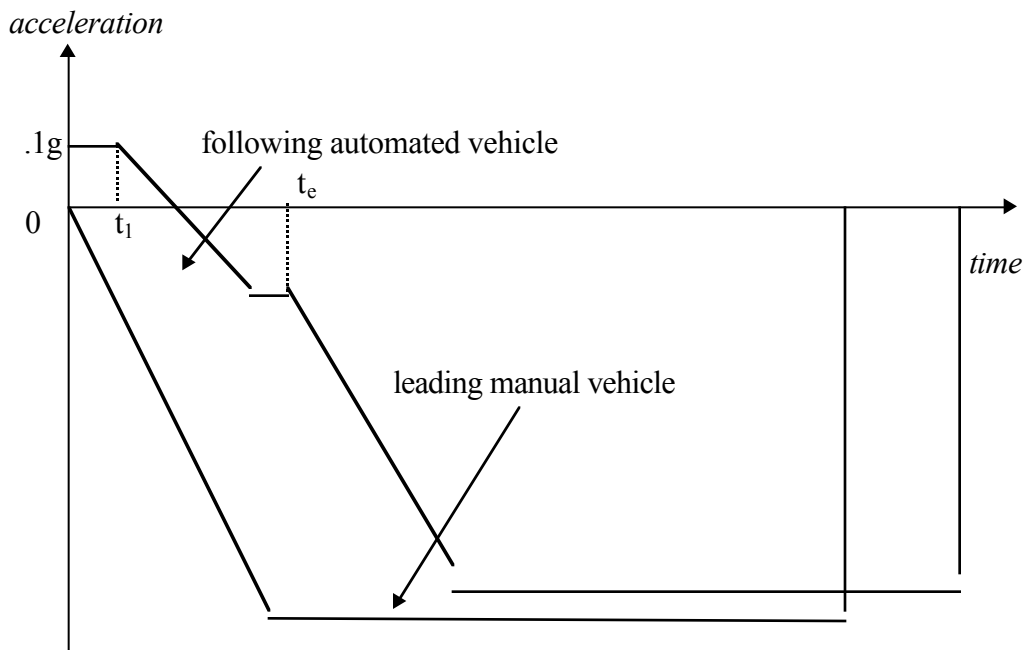


Fig 5.7 Acceleration profiles of an automated vehicle following a manual vehicle performing emergency braking

The throughput result as a function of the percentage of market penetration of automated vehicles when the vehicles are changing from a low speed lane to a high speed lane is shown in fig 5.8. The throughput peaks at 11600 veh/hr/lane for full automated traffic, an increase of about 5.5 times over the all-manual vehicles case. The rate of increase rises

monotonically with increasing number of automated vehicles. Lane-changing reduces the throughput significantly when we consider a high penetration rate of automated vehicles. The reduction has a very minor dependence on the direction of lane-change.

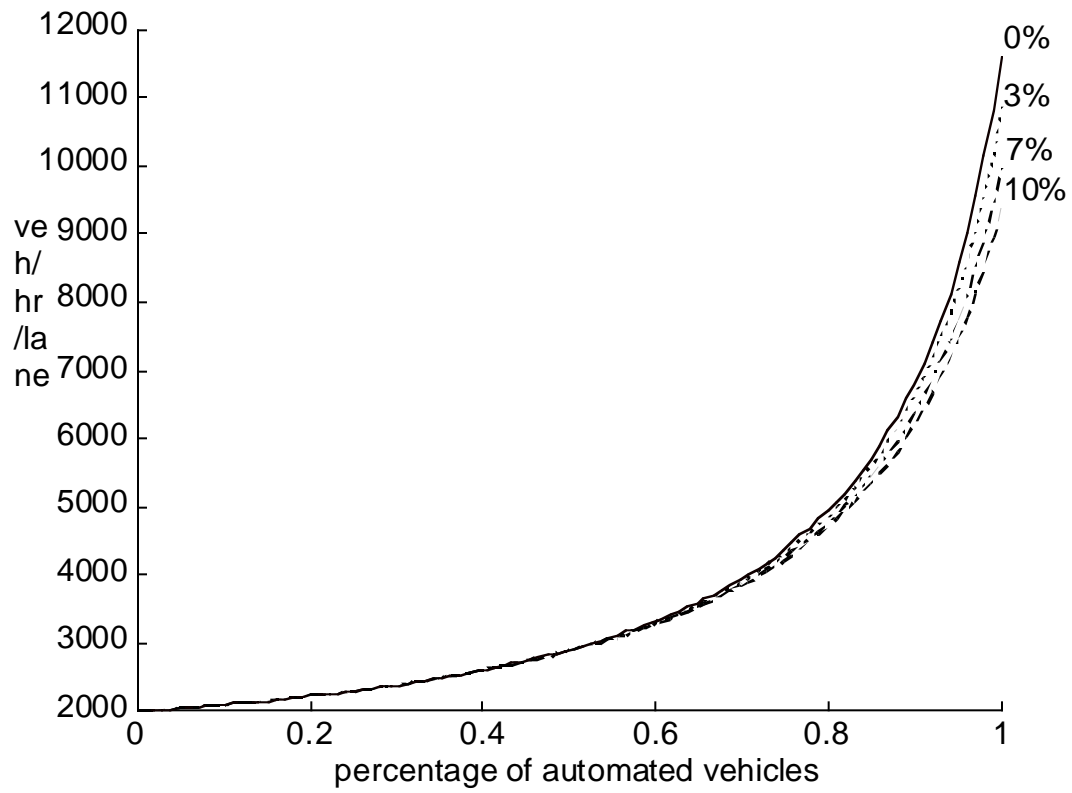


Fig 5.8: Throughput as a function of market penetration of automated vehicles for different percentages of automated vehicles changing from low speed to high speed lanes where the speed differential is 4m/s

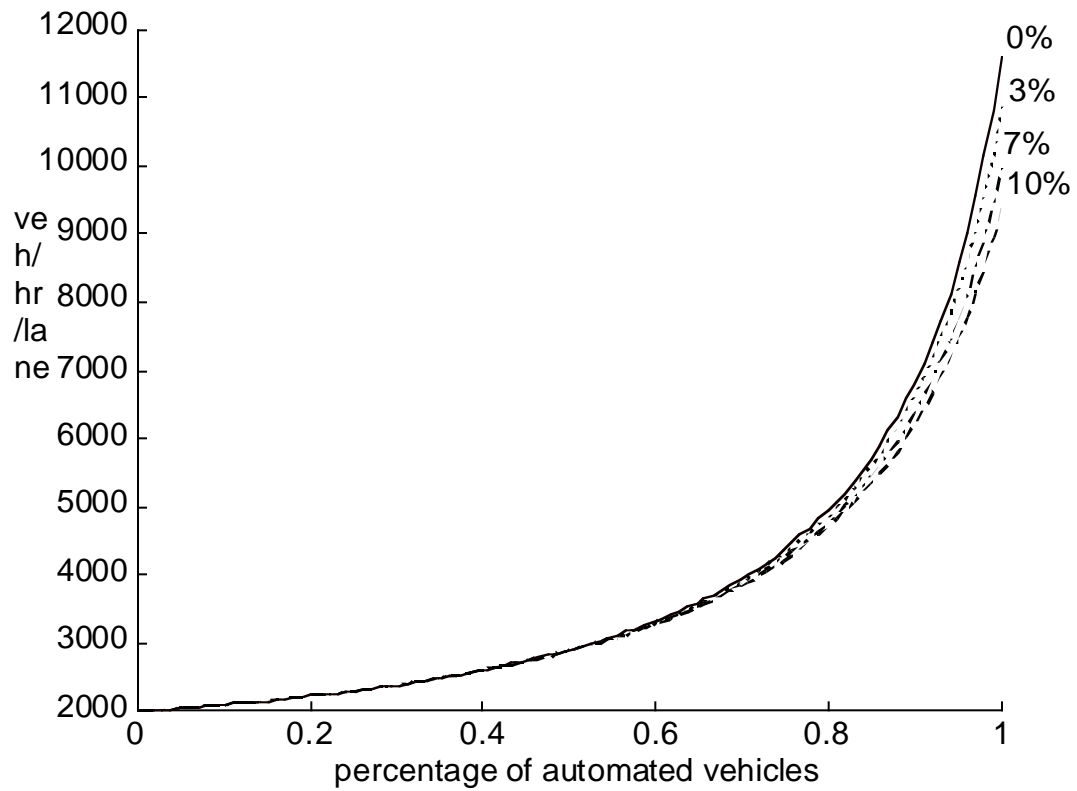


Fig 5.9: Throughput as a function of market penetration of automated vehicles for different percentages of automated vehicles changing from high speed to low speed lanes where the speed differential is 4m/s

The merge derating factor representing the reduction in throughput due to 3% vehicles and 10% vehicles changing lanes from a low speed lane to a high speed lane is 6.3% and 18.7%, respectively. For vehicles changing from a high speed lane to a low speed lane, the derating factor is 6.4% and 18.8% respectively. These are theoretical estimates when the lane-change is in one direction only. For a more realistic estimate, the upper bound of the derating factor for a percentage of lane changing vehicles can be assumed to be the maximum of the two values.

5.4 Conclusions

- Highway throughput improves at an increasing rate with increasing penetration of automated vehicles. The highest throughput of approximately 11600veh/hr/lane is observed for fully automated vehicle traffic, approximately a 5.5 times increase over conventional manual vehicle traffic throughput. The high throughput computed for fully automated vehicle traffic in comparison to the value obtained in part I of this report for semi-automated traffic indicates that full automation is prerequisite for a significant throughput increase.
- The lane-change derating factor is about 18.8% when 10% of the automated vehicles change lanes from a high speed lane to a low speed lane in fully automated traffic. This factor drops to about 6.3% when 3% of automated vehicles change from low speed to high speed lanes.

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