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# Autonomous Car Overtaking Maneuvers

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Abstract - **Presently, Safety is a key matter within the automotive industry, which promotes the development of Autonomous Vehicle (AV) functions. Research on advancing the AV to enhance highway safety and efficiency is one of the foremost studied topics in the field of Intelligent Transportation System (ITS). Driver's blunder is the key reason for the road accidents as per the statistics, which has driven an intense research in the field of AVs. Overtaking process involves acceleration, deceleration and lane-changing maneuvers and estimation of relative speed of overtaken vehicles and overtaking. Subsequently overtaking is one of the complicated maneuvers and many elements affect it, the automation of this maneuver has been the hardest challenges in the growth of AVs [1]. This maneuver needs an excellent interaction between both lateral (steering) and longitudinal (throttle and brake) actuators. The scope of this paper is to develop the test decorum and automated driving system for the accelerative/ normal and flying overtaking maneuver. V2V communication between the vehicles and fuzzy logic steering control (FLC) is developed. The developed autonomous car overtaking system is tested virtually on two possible use cases which are expected to occur in real. The disclosed result revealed a robust system having the ability to sufficiently perform an overtaking maneuver to pass the lead vehicle (LV) in absence of follower vehicle (FV) (first use case), in presence of FV (second use case) and on undivided roads. Results show that the proposed system is feasible and reliable.**

*Keywords* **—Autonomous Overtaking, Flying Overtaking, Fuzzy Logic, Test Protocol, Vehicle-to-Vehicle Communication.**

## I. INTRODUCTION

Overtaking on two-lane roads or on the highway is a major traffic safety problem. Making a slip-up while doing this manoeuvre can lead to awful accidents. That's why all the efforts to develop driving aids for this operation are one of the main issues of ITS. This has given rise to the necessity for the development of overtaking assistance system [2]. Overtaking is a convoluted and important manoeuvre in undivided roads in which the vehicles use the other lane to overtake the slower vehicles in presence of approaching vehicles from the opposite direction. The ability to pass is influenced by varied factors including the volumes of traffic from through and opposite direction, differential speed between the overtaken and overtaking vehicles, geometry of highway. Therefore, the knowledge of lane-changing and overtaking behaviour of vehicles is significant in understanding of traffic behaviour on undivided road and on highway. Autonomous Car overtaking could be a notion where an autonomous host vehicle is controlled effectively to perform comfortable and safe overtaking of a slower moving lead vehicle using developed automated driving system.

### A. *Types of Autonomous Car Overtaking*

The types of autonomous car overtaking are based on:

1. Categories of overtaking
2. Systems Concepts
3. Overtaking control strategies

#### *A.1. Categories of overtaking*

According to Hegeman et al. [2] and Wilson et al. [3], an overtaking manoeuvre can be categorised as follows:

i. Accelerative: The host vehicle follows a vehicle and waits for an ample distance to perform an overtaking manoeuvre.

ii. Flying: The host vehicle does not adjust its speed to the speed of the vehicle which is to be overtaken but continues at its current speed during the overtaking maneuver.

iii. Piggy Backing: The host vehicle follows another vehicle that overtakes a slower vehicle.

iv. 2+: The host vehicle performs the overtaking manoeuvre of two or more vehicles.

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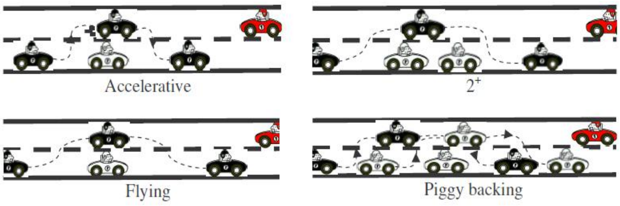


**Fig 1.1.1 Overtaking Strategies**

*A.2. System Concepts*

The Various system concepts for vehicle platooning are given in Automated Highway System (AHS) [4]. The methods to design the platooning can also be altered for autonomous car overtaking as follows:

i. Autonomous – based on onboard sensors.
ii. Cooperative – based on V2V communication.
iii. Infrastructure supported – based on support from smart infrastructure i.e., dedicated roadways.

*A.3. Overtaking Control Strategies*

The most commonly used control strategies are:

i. Constant spacing control – The desired inter-vehicle spacing is independent of the velocity of host vehicle. The tracking requirement is tough as every controlled vehicle has got to match its position, acceleration and velocity with the ahead vehicle (platooning).

ii. Constant time gap – The desired inter-vehicle spacing varies with the velocity of host vehicle. Hence, the tracking requirement isn't tough compared to the above case. Schmidt et al. focused on the constant-time-gap policy, where d = (r + h v) as the desired gap with the headway time h and the desired spacing at standstill r (for v = 0) while developing CACC for vehicle following during lane changes [5]. The considered constant headway time was 0.5 s.

## II. Literature Review

There are limited studies that emphasize on overtaking behavior of vehicles on undivided roads. Matson and Forbes [6] used photographic techniques to calculate the space between the lead and host vehicle at the start and therefore the end of the maneuver. Polus et al. [7] developed prototypes to enumerate the most components of the parsing process and compared the outcomes with existing highway design prototypes. A model showing the connection between the speed of the blocking vehicle and therefore the passing distance was rectified. Hegeman et al. [8] had introduced the instrumented vehicle method presented a core analysis on observations of overtaking maneuvers on two-lane rural roads to understand the behavior of drivers before, during, and after an overtaking maneuver. The difference in duration of overtaking maneuvers between different speeds of vehicles and varied overtaking strategies were observed. Roozenburg [9] suggested that there are several input variables to develop a mathematical prototype of overtaking behavior. The variables are often the oncoming vehicle speed, lead vehicle speed, headway between host and lead at the start, the margin of safety between oncoming vehicle and host vehicle at the completion, and vehicle acceleration. Gray and Regan [10] studied the control strategies and processes of drivers who were overtaking maneuvers. In most cases, the drivers instigated an overtaking maneuver when the oncoming car's distance was above a critical value, while there wasn't enough time for completing a secure maneuver. Mocsari [11] inspected the overtaking pattern of vehicles on two-lane roads in Hungary. After 230 overtaking case studies, it was found that 55% were accelerative overtaking, 20% were continuous (flying) overtaking, and some were multiple vehicles overtaking cases. Just within the case of continuous overtaking, there was a far better difference within the average speed of vehicles compared to accelerative overtaking. However, overtaking time didn't differ significantly because overtaking distance was longer for continuous overtaking. the standard time of overtaking for accelerative overtaking was 8.5 s and for continuous overtaking, it was 7.9 s. The length of the spacing did not depend on the overtaking vehicle's category and also, spacing wasn't influenced by the speed of the vehicle to be overtaken, either. Gordon and Mart [12] stated that drivers are unable to estimate the overtaking distances and safety margins accurately as these calculations rely on the speed of the involved vehicles especially the overtaken vehicle. Gong et al. [13] deployed various sensors like camera, radar, lidar for environmental perception, GPS receiver for self-location, and V2X communication for interaction information. (e.g. distance, velocity) Vicente et al. [14] used a camera for vehicle detection and IMU, GPS for positioning while developing the intelligent automatic overtaking system for 2 Citroen Berlingo cars. Schmidt et al. [15] developed CACC using radar, lidar, and V2V communication for vehicle following during lane changes. Ray et al. [16] considered the information obtained from the sensors as frontal lidar and cameras to detect obstacles on the road, and communication with other vehicles in an exceedingly cooperative way for the automated overtaking maneuver. Gindele et al. [17] designed a decision-making state machine for his or her vehicle "AnnieWAY" through urban scenarios that successfully entered the finals of the DARPA urban challenge in 2007. They also developed decision-making logic for the lane changing. TU Braunschweig's research vehicle "Leonie" is one among the vehicles having the facility of fully automated driving in real urban traffic scenarios and this university has previously participated in the DARPA grand challenge [18]. While driving this fully automated vehicle in an urban environment, they also developed a decision-making approach for performing lane changes. Basjaruddin et al. [19] developed a decision-making system that supported fuzzy logic for the overtaking assistant system. Nicklas [19] developed an automatic drive system using decision-making for overtaking, roundabout, and intersection scenarios using PreScan and CarMaker simulation environments. Ruiz et al. [20] developed the decision-making algorithm for different overtaking scenarios. In large scale production of Automated

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vehicle, it majorly uses fuzzy logic techniques to solve common challenges as well as to embody human procedural knowledge. Car driving may be a special control problem because mathematical models are highly complex and can't be accurately linearized. Naranjo et al. used fuzzy logic because it's a well-tested method for handling this type of system, provides good results and may incorporate human procedural knowledge into control algorithms [21]. The automated and instrumented two Citroen Berlingo vans for overtaking maneuver using ACC. Vicente et al. used fuzzy controllers (steering, throttle, and brake) for developing an intelligent automatic overtaking system for two Citroen Berlingo vans and tested it during a private driving circuit with good results [22]. Autonomous driving is a stimulating field to use fuzzy logic using human driver experience as expert knowledge [41]. Intelligent techniques like fuzzy controllers have shown powerful capabilities handling nonlinear overtaking behaviors [1].

## III. Architecture

Autonomous Car Overtaking maneuvers can be understood as a mixture of Lane Change Assist (LCA), Blind Spot Monitoring (BCM), Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), and Lane Departure Warning (LDW) systems tied with Fuzzy Logic Controller (FLC) and decision-making algorithm. It is plausible that a lot of driving tasks are shifting to autonomous systems and so the control systems will get the most interacting part of a vehicle. The basic architecture of the automated driving system is shown in figure3.1.

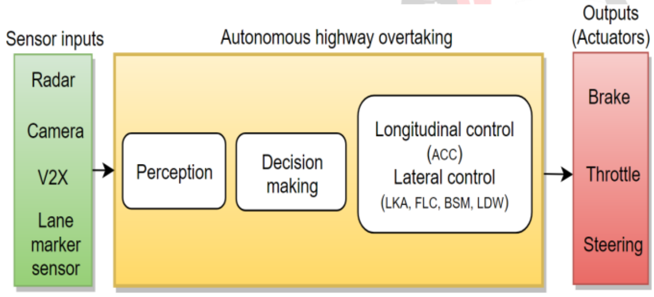


**Fig. 3.1: Architecture of automated driving system**

With the assistance of the sensors, the perception of the environment is carried out. After that different overtaking decisions are taken in the decision-making algorithm using sensor inputs. These decisions are passed on the various ADAS systems which finally controls the HV using steering, brake and throttle actuators.

### A. Sensor Inputs

For getting the complete perception, only V2V communication and onboard sensors are used. All the sensors are divided into subgroups: there are external sensors which will detect the obstacles at the surrounding of the vehicle, internal sensors which measure the states of vehicle and then there are sensors which are used to communicate with other vehicles (V2V) and with the infrastructure (V2X). Radar, cameras and ultrasonic sensors are classic external sensors whereas Gyroscopes, accelerometers, etc. are internal sensors.

1. Radar Sensor

Radar Sensors transmit radio waves and based on the signal received; target angle, target relative velocity and target range of the dynamic obstacles are deliberated in real-time. It improves driving efficiency and safety. For relative high speeds, long-range radars (77-Ghz) are employed to deliver sufficient accuracy and resolution. Blind-Spot detection and collision mitigation system are detected using mid-range or short -range radar systems (24-Ghz). Radar sensors provides excellent speed and range accuracy. It is independent of weather conditions. It can detect 25+ objects at a time.

2. Camera Sensor

Camera is a device which can record the information of the reality which can be observed as an image. Camera can be used both in digital and analog electronic imaging devices. Here, camera is used to detect colors and contrast for reading street signs, road markings and traffic signals. It is also used to identify objects. But it has some limitations like poor range accuracy and the accuracy get affected due to light and weather conditions.

3. Vehicle to Everything (V2X) Sensor

V2X communication permits map usage by improving positioning data when GPS is not available. V2X assists the vehicle to effectively understand the purposes of surrounding vehicles so that the HV receiver guidance from infrastructure and cloud connectivity. Area with tall buildings can block GPS signals completely. Therefore, V2X sensor is used to augment GPS which provide always-available positioning. V2X compose of both receiver and transmitter which can share and receiver data about the position and velocity of the vehicle. This sensor provides high accuracy.

4. Lane Marker Sensor

It provides data about the lane lines on the roads. It provides data as intersections between the scan lines and lane lines relative to the sensor. The intersection is determined for up to four look-ahead scan planes. The look-ahead scans are depleted perpendicular to the sensor's boresight [24] The lane marker sensor is used for the LKA and LDW system.

### B. Perception Layer

In this phase, the possession of the surrounding environment information is carried out with the help of sensors. The major sensorial inputs consist of a camera, a lane marker sensor, radar and V2V communication. To obtain the target vehicle data, the sensor data is used which will be pass to the next phase i.e. decision-making algorithm.

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### C. Decision-Making Layer of Overtaking

In the process of overtaking, decision-making is vital because incorrect decision might result in a crash when passing or lane changing. Crash during lane changing cause due to lack of attention to distance and velocity of the lead and follower vehicle. Distance and Speed are the two variables which must be consider in developing decision-making for overtaking. Stateflow is a powerful graphics designing and development tool for simulating and modelling and decision-making systems [25]. The data flow is shown by signal lines. Stateflow diagram can be executed by dragging junction, states and functions from the graphical pallet into the design workspace. Transitions show the connection between different states which may consist of conditions.

The decision-making algorithm imitates the tactical layer of human driving which is shown using flowchart in figure 3.2. The flowchart clearly shows when to decrease and increase the speed of host vehicle. Also, it illustrates when it is possible to overtake and is it necessary to overtake. Normally, this algorithm keeps the HV in the left lane. It alters the reference route to left lane and keeps it till the HV passed the LV when the overtaking act starts. After that the algorithm pick the reference route to the right lane and the HV gets shift to the right lane. The algorithm picks the right driving mode to assure a smooth changeover and to continue the automatic path.

The decision-making algorithm take 3 inputs, the first two inputs are the headway-time between the host-follower and host-lead vehicle which are occupied from V2V communication. The third input is the scope between the lead and the host vehicle which can be occupied from radars or V2V communication. There are 5 outputs of the algorithm, the last three outputs give the steering angle values from the LKA and FLC systems. The First output determines the anticipated driving lane of the HV. ACC determines the active status of the HV.

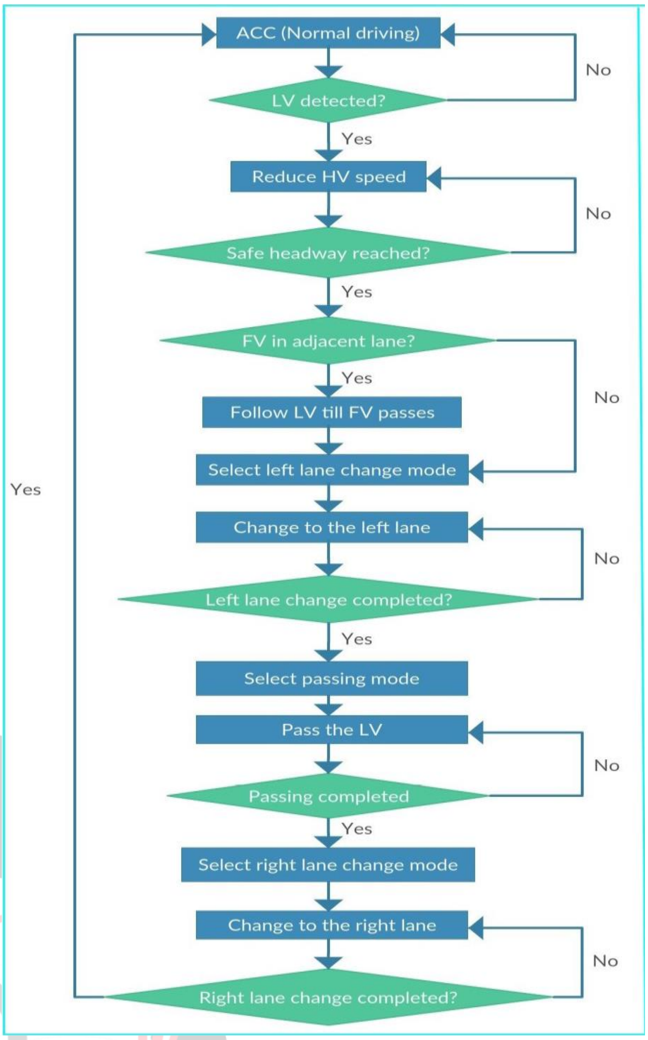


**Fig. 3.2 Overtaking flowchart and decision-making**

### D. Lateral and Longitudinal Control (FLC)

Fuzzy logic is used to handle the vehicle in the preferred trajectory. The design of the fuzzy inference system (FIS) is as shown in figure 3.3.

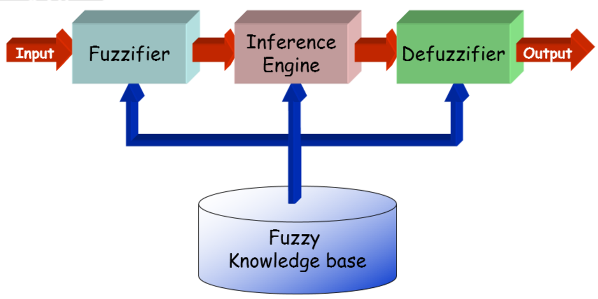


**Figure 3.3: Fuzzy Inference System design**

The three cognitive stages of FLC are:

i. **Fuzzifier:** The responsibility of the fuzzifier is to convert the crisp input values into a set of fuzzy values. It uses the membership functions in the fuzzy knowledge base. It computes the degree of truth for each one input value. Lateral_Error and Angular Error from reference lane are considered for lateral control.

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ii. **Inference Edge:** Inference engine translates the fuzzy input to the fuzzy output using if-else fuzzy rules. It produces the matching of the conditions to the conclusions, generating the contribution of each rule to the control action. For this, Sugeno inference method is used.

iii. **Defuzzifier:** It is the transformation of the output fuzzy values that are produced by applying the inference method into crisp values that can be used to output control intentions. Weighted average method is used.

**Fuzzy Knowledge Base:** Fuzzy knowledge base is composed of rule base and variable base. The rule base consist number of fuzzy If-Then rules whereas a variable base consist the different semantic values that they ponder.

**Rule base:** The main objective of rule base is to keep the vehicle to the preferred lane.

**Variable base:** There are two inputs, Lateral_Error and Angular_Error. It has three values named left, right and center, each with their respective membership function. The fuzzy output variable SteeringWheel has two semantic labels i.e. left, right. The shape of the membership functions depends on how much we want these variables to affect the control.

Two FLC are designed, one for Lane Change and another for straight path. During the overtaking maneuver the pedals and the steering of the HV needs to be controlled. The angle of steering is controlled by FLC which cause the HV to change lane. The brake and throttle control are attained by ACC. Lateral_Error determines the distance between the HV position and preferred lane centerline. Whereas the Angular_Error gives angle between the HV longitudinal axis and reference lane centerline.

A. **Straight Path FLC:** The objective of this definition is to succeed how centered the vehicle's path is in the lane.

B. **Lane Change FLC:** The objective is to regulate the HV when its preferred path changes from a preferred lane.

## IV. Implementation Protocol

The protocol escorts the engineer by predefining, how to develop the HV and track for the implementation and which test cases to perform. The protocol in this paper is developed for the 'Highway and Undivided overtaking' scenario. Different points such as requirement, terms and definitions, test conditions, test procedure, and finally empirical findings for the highway overtaking maneuver are discussed in the further sections. The developed protocol is proven and validated analytically. The developed procedure is for the accelerative overtaking while the simulations for the flying overtaking category are also carried out. By blending the ACC, LCA, LKA, LDW, BSM, and FLC systems, the HV carry out the overtaking maneuver automatically. These regimes have the potential generate the speed and the required steering angle during the test.

### *A. Requirements*

The requirements for the overtaking maneuver are supported ISO 15622 (Adaptive control System), ISO 17387 (Lane Change Decision Aid Systems), ISO 17361 (Lane Departure Warning Systems), and ISO 11270 (Lane Keeping Assistance Systems) [26] [27] [28] [29] [30].

- ACC: It helps the HV to maintain safe distance while following the LV by managing the engine, brake and powertrain [27].
- BSM: It perceives the presence of target vehicle in more than one of the adjacent zones and warns the HV [28].
- Close Vehicle warning function: It perceive closing vehicle from the rear zones and warns the HV [28].
- LCA: It includes the BSM and closing vehicle warning function [28]. They are radars combined together in a single system.
- LDW: It warns the HV in the absence of suppression requests [29].

LKW: It perform actions to alter the lateral movement of the HV to keep the vehicle steady in the lane. It uses camera combined with LDW in a single system.

### *B. Terms and Definitions*

In accordance with the ISO standards following terms and definitions are applied:

- **Initial set speed:** It can be set either by control system or by the driver. It is the maximum desired speed of the vehicle under ACC control [27].
- **ACC following sub-state:** It is the state in which the system manages the clearance to the LV in accordance to selected time gap [27].
- **ACC speed control:** State in which system controls the speed in accordance to the set speed [27].
- **Adjacent zones:** Left and right sides of the HV are knowns as adjacent zones. They are independent of any lane markings and are defined w.r.t HV [28].

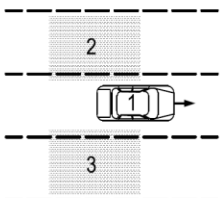


**Fig. 4.2.1 Adjacent zones**

- **Rear zones:** Area behind and to the sides of the HV are declared as rear zones.

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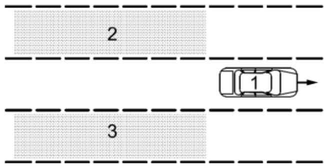

Fig. 4.2.2 Rear zones

- **Lateral clearance:** It is the distance between the near side of the target vehicle and the side of the HV. The host vehicle is shown by marking '1' on the top.

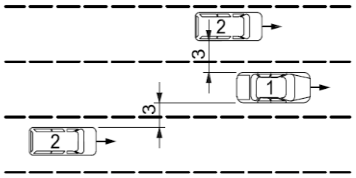

Fig. 4.2.3 Lateral clearance

- **Relative speed (RS):** Relative speed gives the difference between the host and the lead vehicle's speed [28].
- **Time to collision (TTC):** It is the time required to collide if the two vehicles continue to the same path at their current speed [32]. It is not accurate if HV accelerates or deaccelerates to prevent a lead vehicle.

$$TTC = \frac{Relative\ Distance}{Relative\ Velocity}$$

- **Overtaking speed (OS):** The difference of speed between the HV and LV during the overtaking maneuver [28].
- **Rate of departure (ROD):** Approach speed of the HV at a right angle to the lane outlines [29].
- **Distance to Lane Edge (DTLE):** The lateral distance between the outermost edge of wheels and lane edge, before the HV crossed the lane edge [31].
- **Time to line crossing (TTLC):** TTLC is calculated by dividing the lateral distance, between the verified part of the vehicle and the lane outline by the ROD of the vehicle relative to lane [29].
- **Lane:** Region of roadway that vehicle would be expected to ride along in absence of any hindrance. 3.5m would be the default width of lane [29].

## C. Overtaking Conditions

To ensure a safe overtaking maneuver, a certain set of conditions need to be satisfied by the host vehicle. It is made sure that before overtaking the follower vehicle should not begin to overtake the host vehicle i.e., overtaking vehicle, there must be adequate distance in front of the lead vehicle [37].

**Conditions for safe overtaking:**

- The LV must be in the same lane as HV [35].
- The velocity of the HV must be higher than the LV in order to overtake [33].
- The LV should be riding along the straight path with constant velocity [33].
- The overtaking lane should be free to complete the overtaking [38].
- The LV cannot increase its speed once the overtaking maneuver has been initiated by the HV and the overtaking must be completed in less than 15s [34].
- The HV should avoid tailgating with the LV [37].
- The blind spots must be verified or checked before the maneuver [37].
- The road must have a lane marking and road edge [36].
- There must be proper V2V communication so that the overtaking maneuver takes place smoothly.
- Normal weather conditions are expected.
- No drift or uncertainty of sensors.

## D. Overtaking Procedure

The overtaking procedure verifies the safety performance during the maneuver. The overtaking procedure should satisfy all safety categories and it should be driver independent. The overtaking maneuver includes HV overtaking the LV at different scenarios and at varied speeds. The HV must be driven such that it come across the LV which is moving slowly. Once the HV overtakes the LV the maneuver or overtaking procedure is finished. The HV will be driven back again to the initial lane i.e. lane before overtaking, once the overtaking is completed. Host (HV), Lead (LV) and follower vehicle (FV) are shown in the figure 4.4.1. The safe time gap (0.8s) is indicated by red box which is the region of interest in which the maneuver is safe to perform.

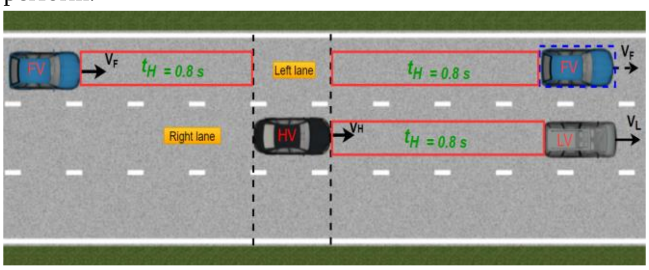

Fig. 4.4.1 Safe gap

Different phases of overtaking maneuver shown in the form of timing sequence figure 4.4.2. The headway time are indicated by $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, $t_5$ and $t_6$ between the vehicles. When the HV is behind the LV then it is considered as positive headway time and when the HV is ahead of LV then it is considered as negative headway time. The overtaking time i.e., $t_5 - t_2$ must be less than 15s.

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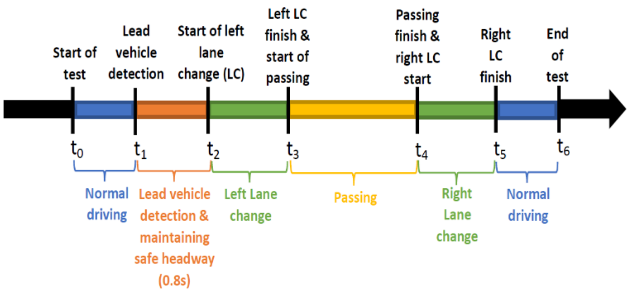


*D.1. Start of the procedure (normal driving)*

The first phase in which the HV is moving at a constant velocity $V_H$. During this phase systems such as BSM, LKA and ACC are activated. With the help of LKA the HV remains in its lane and maintain constant speed. The headway distance $d_{HL0}$ between HV and LV must be greater than 150m.

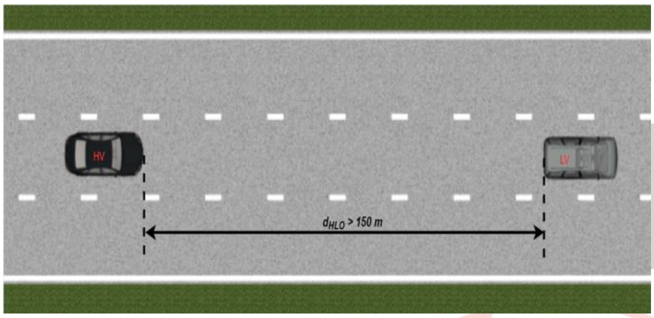


**Fig. 4.4.3 Initial position (Normal driving)**

**Analytical Verification:**

Consider,

- Host vehicle initial speed ($V_H$) = 27.78m/s (100km/h).
- Lead vehicle initial speed ($V_L$) = 22.22m/s (80km/h).
- Initial range between the HV and LV, $d_{HL0}$ = 170m.

The headway time ($t_H$) at initial stage is calculated as:

$$HWT\ (t_{H_0}) = \frac{Headway\ Distance}{V_H} = \frac{170}{27.78}$$

$$t_{H_0} = 6.1s$$

*D.2. Lead Vehicle Detection*

In second phase the LV which is moving slowly with velocity $V_L$ than the HV. The LV will be detected by ACC when the headway distance or range between them is equal to 150m. This detection range is depending upon the type of radar used. The headway time ($t_{H1}$) can be calculated as:

$$t_{detection} = \frac{Headway\ Distance\ (150m)}{V_L}$$

Time taken by HV to cover the range between the start $t_0$ and LV detection $t_1$ is given as:

$$\Delta d_{L_{0-1}} = V_L \times \Delta t_{0-1}$$

$$\Delta d_{H_{0-1}} = V_H \times \Delta t_{0-1}$$

$$\Delta d_{H_{0-1}} - \Delta d_{L_{0-1}} = d_{HL_0} - d_{detection}$$

$$(V_H - V_L)\Delta t_{0-1} = d_{HL_0} - d_{detection}$$

$$\Delta t_{0-1} = \frac{d_{HL_0} - d_{detection}}{V_H - V_L}$$

Total Time at $t_1$,

$$t_1 = t_0 + \Delta t_{0-1}$$

**Analytical Verification:**

The headway time at 150m is calculated as:

$$t_{detection} = \frac{Headway\ Distance\ (150m)}{V_H} = \frac{150}{27.78}$$

$$t_{H_1} = 5.4s$$

Time taken by HV to cover the range between the start $t_0$ and LV detection $t_1$ is given as:

$$\Delta t_{0-1} = \frac{d_{HL_0} - d_{detection}}{V_H - V_L} = \frac{170 - 150}{27.78 - 22.22}$$

$$\Delta t_{0-1} = 3.6s$$

Total Time at $t_1$,

$$t_1 = t_0 + \Delta t_{0-1} = 0 + 3.6$$

$$t_1 = 3.6s$$

*D.3. Start of Left Lane Change*

Once the LV is detected, it is suggested that the HV should gradually decrease the speed with the safe overtaking headway time i.e. 0.8s.

Distance travelled by the LV is given by:

$$\Delta d_{L_{1-2}} = V_L \times \Delta t_{1-2}$$

where, $\Delta t_{1-2} = t_2 - t_1$;

Distance travelled by the HV is given by:

$$\Delta d_{H_{1-2}} = V_L + \frac{a\Delta t_{1-2}^{\ 2}}{2}$$

Also, $V_L = V'_H = V_H - a\Delta t_{1-2}$

Deacceleration is given by:

$$a = \frac{V_H - V_L}{\Delta t_{1-2}}$$

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**Analytical Verification:**

Consider,

$t_H = 0.8s$

$V_L = V_H$

Distance travelled by the HV is given by:

$$\Delta d_{H_{1-2}} = V_L + \frac{a\Delta t_{1-2}^{\ 2}}{2}$$

Also, $V_L = V'_H = V_H - a\Delta t_{1-2}$

$$a\Delta t_{1-2} = V_H - V_L = 27.78 - 22.22 = 5.56$$

Headway time at $t_2$ is given as:

$$t_{H_2} = \frac{\Delta d_{L_{1-2}} + 150 - \Delta d_{H_{1-2}}}{V'_H} = 0.8$$

$$0.8 = \frac{(22.22 \times \Delta t_{1-2}) + 150 - \left[27.78 \times \Delta t_{1-2} - \frac{a\Delta t_{1-2}^{\ 2}}{2}\right]}{22.22}$$

After solving the above equation,

$$\Delta t_{1-2} = 45.56 \text{ s}$$

Deacceleration is given by:

$$a = \frac{V_H - V_L}{\Delta t_{1-2}} = \frac{5.56}{45.56}$$

$$a = -0.12 m/s^2$$

Total time at $t_2$ is given by:

$$t_2 = t_1 + \Delta t_{1-2} = 3.6 + 45.56$$

$$t_2 = 49.16 \ s$$

*D.4. Left Lane Change*

During this phase, systems like FLC, BSM, LCA and LDW are activated. Once the overtaking headway threshold becomes 0.8s the HV ensure that there are no rear vehicles approaching, if a vehicle is approaching then the HV waits for follower vehicle to pass or it will establish V2V communication to perform the overtaking maneuver. After all this, the HV initiate the lane change approach. Headway time at the end of Left lane change is $t_3$.

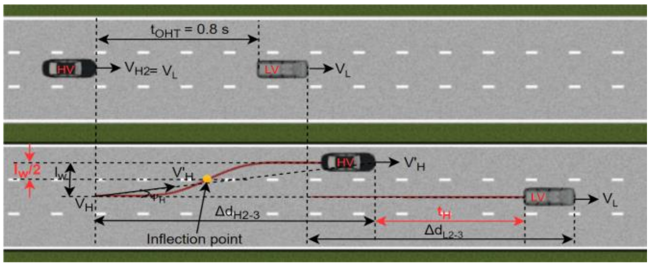


**Fig. 4.4.4 Left lane change**

Consider,

Yaw angle ($\Psi_H = 0^o$)

$l_w$ = lane width = 3.5m

$V_H = V'_H$ = host vehicle velocity at the end of this phase

Time period for this phase is given by:

$$t_{LLC} = t_3 - t_2$$

For changing the lane to left lane, HV has to orient the steering angle. Yaw rate of the HV during the lane change is given by,

$$\Psi_H = \frac{V_H}{L_H} \times \tan\delta_H = \frac{V_H}{L_H} \times \delta_H$$

$$\Psi_H = \frac{V'_H}{L_H} \times \delta_H \times t$$

Applying small-angle estimation for $\Psi$ and $\delta_H$:

$\sin(\Psi_H) \approx \Psi_H$

$\cos(\Psi_H) \approx 1 - \frac{\Psi^2_H}{2} \approx 1$

$\tan(\delta_H) \approx \delta_H$

$\tan(\Psi_H) \approx \Psi_H$

Where, LH = HV wheelbase = 2.94m

$\delta_H$ = 10 deg/s

HV velocity ($V'_H$) at the end of the LLC (Left lane change) phase can be calculated as,

$$V'_H = V_{H_0} + [a \times t]$$

Where, $V_{H0}\,(t=t_2) = V_L$ *and* $a = 3.5\ m/s^2$

By integrating the Yaw rate, we get Yaw angle,

$$\Psi_H = \int_0^t \Psi_H \, dt$$

$$\Psi_H = \int_0^t \left[\frac{V_{H_0} + [a \times t]}{L_H} \times \delta_H \times t\right] dt$$

$$= \frac{\delta_H}{L_H}\left[V_{H_0}\frac{t^2}{2} + a\frac{t^3}{3}\right]_0^t = \frac{0.175}{2.94}\left[V_{H_0}\frac{t^2}{2} + a\frac{t^3}{3}\right]_0^t$$

$$\Psi_H = 0.06\left[V_{H_0}\frac{t^2}{2} + a\frac{t^3}{3}\right]_0^t$$

Speed and distance of HV until the point of inflection,

$$\Delta d_{H_y} = \frac{l_w}{2} = 1.75m$$

$$V_{H_y} = V'_H \times \sin(\Psi_H)$$

$$V_{H_y} = (V_{H_0} + at)\Psi_H$$

$t_{LLC}$ can be calculated by,

$$\Delta d_{Hy} = \int_0^{t\frac{LLC}{2}} [V_{Hy}]\ dt = \int_0^{t\frac{LLC}{2}} [(V_H + at)\Psi_H]\, dt$$

$$1.75 = \int_0^{t\frac{LLC}{2}} [(V_H + at)\Psi_H]\, dt$$

Total time at the end of left lane $t_3$ can be calculated as,

$$t_3 = t_2 + t_{LLC}$$

During this phase, longitudinal distance travelled by HV,

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$$\Delta d_{L_{2-3}} = V_L \times t_{LLC}$$

Longitudinal HV speed component,

$$V_{H_X} = V'_H \times \cos(\Psi_H) = V'_H$$

$$V_{H_X} = V_{H_0} + at$$

Straight path (longitudinal) distance travelled by HV,

$$\Delta d_{H_{2-3}} = \int_0^{t\frac{LLC}{2}} [V_H + at]\, dt = V_{H_0} t_{LLC} + \left[\frac{at^2{}_{LLC}}{2}\right]$$

At the end of LLC, the speed of HV is given by,

$$V'_H = V_{H_0} + at_{LLC}$$

Headway time at the end is given by,

$$t_H = t_{H_3} = \frac{\Delta d_{L_{2-3}} + (0.8 V_{H_0}) - \Delta d_{H_{2-3}}}{V'_H}$$

**Analytical Verification:**

Yaw rate of HV while lane change is given by,

$$\Psi_H = \frac{V'_H}{L_H} \times \delta_H \times t$$

HV velocity ($V'_H$) at the end of the LLC (Left lane change) phase can be calculated as,

$$V'_H = V_{H_0} + [a \times t]$$

Where, $V_{H0}\,(t=t_2) = V_L$ and $a = 3.5\ m/s^2$

By integrating the Yaw rate, we get Yaw angle,

$$\Psi_H = 0.06\left[V_{H_0}\frac{t^2}{2} + a\frac{t^3}{3}\right]_0^t = 0.06\left[22.22\frac{t^2}{2} + 3.5\frac{t^3}{3}\right]_0^t$$

$$\Psi_H = 0.66t^2 + 0.07t^3$$

$t_{LLC}$ can be calculated by,

$$\Delta d_{Hy} = \int_0^{t\frac{LLC}{2}} [V_{Hy}]\, dt = \int_0^{t\frac{LLC}{2}} [(V_H + at)\Psi_H]\, dt$$

$$1.75 = \int_0^{t\frac{LLC}{2}} [(22.22 + 3.5t) \times (0.66t^2 + 0.07t^3)]\, dt$$

$$1.75 = [0.61t_{LLC}^3 + 0.06t_{LLC}^4 + 0.001t_{LLC}^5]$$

After solving above equation,

$$t_{LLC} = 1.254s$$

Total time at the end of left lane $t_3$ can be calculated as,

$$t_3 = t_2 + t_{LLC} = 49.16 + 1.254$$

$$t_3 = 50.41s$$

During this phase, longitudinal distance travelled by HV,

$$\Delta d_{L_{2-3}} = V_L \times t_{LLC} = 22.22 \times 1.254 = 27.8m$$

Longitudinal HV speed component,

$$V_{H_X} = V'_H \times \cos(\Psi_H) = V'_H$$

$$V_{H_X} = V_{H_0} + at$$

Straight path (longitudinal) distance travelled by HV,

$$\Delta d_{H_{2-3}} = \int_0^{t\frac{LLC}{2}} [V_H + at]\, dt = V_{H_0} t_{LLC} + \left[\frac{at^2{}_{LLC}}{2}\right]$$

$$\Delta d_{H_{2-3}} = (22.22 \times 1.254) + \left[\frac{3.5 \times 1.254^2}{2}\right]$$

$$\Delta d_{H_{2-3}} = 30.61m$$

At the end of LLC, the speed of HV is given by,

$$V'_H = V_{H_0} + at_{LLC} = 22.22 + (3.5 \times 1.254)$$

$$V'_H = 26.609 m/s^2$$

Headway time at the end is given by,

$$t_H = t_{H_3} = \frac{\Delta d_{L_{2-3}} + (0.8 V_{H_0}) - \Delta d_{H_{2-3}}}{V'_H} = \frac{27.8 + 17.78 - 30.61}{26.609}$$

$$t_H = t_{H_3} = 0.56s$$

### *D.5. Passing Phase*

During this phase, ACC and straight path FLC are activated. Once the HV moves to adjacent lane, the passing phase starts in which the HV rides in straight path until it crosses the LV with sufficient gap. During this phase the velocity of the LV must be constant. This phase occurs during $t_3$ - $t_4$.

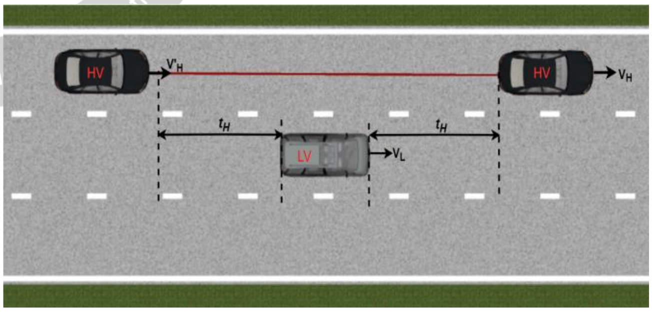


**Fig 4.4.5 Passing Phase**

HV accelerates until it reaches its desired velocity maximum acceleration. Time required ($t'_{3\text{-}4}$) for this calculated by:

$$V_H = V'_H + a\Delta t'_{3-4}$$

Distance travelled by HV during this time,

$$\Delta d'_{H_{3-4}} = (V'_H \times \Delta t'_{3-4}) + \frac{1}{2} \times a \times a\Delta t'^2{}_{3-4}$$

Consider, the HV requires additional time to acquire the needed headway time ($t_H$ = - 0.5), which is given by:

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$$t_H = \frac{\Delta d_{L_{3-4}} + Distance\ travelled\ during\ lane\ change - \Delta d_{H_{3-4}}}{V_H}$$

$$-0.5 = \frac{[V_L \times (\Delta t'_{3-4} + \Delta t''_{3-4})] + [\Delta d_{L_{2-3}} + (0.8 \times V_{H_0}) - \Delta d_{H_{2-3}}] - [\Delta d'_{H_{3-4}} + V_H \Delta t''_{3-4}]}{V_H}$$

Total time for passing is,

$$t_{Passing} = \Delta t'_{3-4} + \Delta t''_{3-4}$$

Time at $t_4$ is given by,

$$t_4 = t_3 + t_{Passing}$$

**Analytical Verification:**

Consider,

$t_H$ = -0.5s

$V_H$ = 27.78m/s

$V_L$ = 22.22m/s

HV accelerates until it reaches its desired velocity maximum acceleration. Time required ($t'_{3-4}$) for this calculated by:

$$V_H = V'_H + a\Delta t'_{3-4}$$
$$27.78 = 26.609 + 3.5\Delta t'_{3-4}$$
$$\Delta t'_{3-4} = 1.171s$$

Distance travelled by HV during this time,

$$\Delta d'_{H_{3-4}} = (V'_H \times \Delta t'_{3-4}) + \frac{1}{2} \times a \times a\Delta t'^2_{3-4}$$
$$\Delta d'_{H_{3-4}} = (26.609 \times 1.171) + \frac{1}{2} \times 3.5 \times 1.171^2$$
$$\Delta d'_{H_{3-4}} = 33.55m$$

Consider, the HV requires additional time to acquire the needed headway time ($t_H$ = - 0.5), which is given by:

$$-0.5 = \frac{[V_L \times (\Delta t'_{3-4} + \Delta t''_{3-4})] + [\Delta d_{L_{2-3}} + (0.8 \times V_{H_0}) - \Delta d_{H_{2-3}}] - [\Delta d'_{H_{3-4}} + V_H \Delta t''_{3-4}]}{V_H}$$

$$-0.5 = \frac{[22.22 \times (\Delta t'_{3-4} + \Delta t''_{3-4})] + 14.9 - [\Delta d'_{H_{3-4}} + V_H \Delta t''_{3-4}]}{V_H}$$
$$\Delta t''_{3-4} = 3.821s$$

Total time for passing is,

$$t_{Passing} = \Delta t'_{3-4} + \Delta t''_{3-4} = 1.171 + 3.821$$

$$t_{Passing} = 4.992s$$

The time at $t_4$ is

$$t_4 = t_3 + t_{Passing} = 50.41 + 4.992$$
$$t_4 = 55.402s$$

*D.6. Start of right lane change*

Once there is adequate distance between the LV and the FV the right lane change phase starts using the FLC. This phase completes its operation at $t_5$

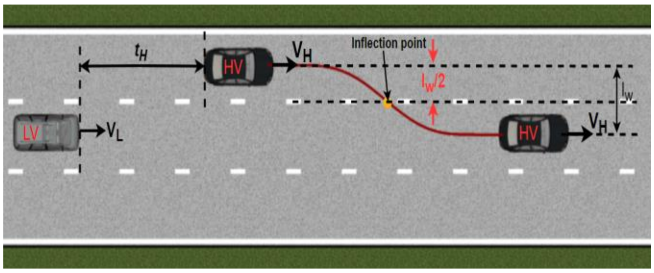


**Fig 4.4.6 Right lane change**

Where,

$l_W$ = Lane width (lateral shift for the lane change, 3.5m)

$V_H$ = Host vehicle speed at the end of passing phase (desired speed)

$t_{RLC}$ = Time taken by host vehicle for the right lane change.

For again changing the lane to right lane, HV has to orient the steering angle. Yaw rate of the HV during the lane change is given by,

$$\Psi_H = \frac{V_H}{L_H} \times \tan \delta_H = \frac{V_H}{L_H} \times \delta_H$$
$$\Psi_H = \frac{V_H}{L_H} \times \delta_H \times t$$

Applying small-angle estimation for Ψ and $\delta_H$:

$\sin(\Psi_H) \approx \Psi_H$

$\cos(\Psi_H) \approx 1 - \frac{\Psi^2_H}{2} \approx 1$

$\tan(\delta_H) \approx \delta_H$

$\tan(\Psi_H) \approx \Psi_H$

Where, LH = HV wheelbase = 2.94m

$\delta_H$ = 10 deg/s

By integrating the Yaw rate, we get Yaw angle,

$$\Psi_H = \int_0^t \Psi_H \, dt$$
$$\Psi_H = \int_0^t \left[\frac{V_H}{L_H} \times \delta_H \times t\right] dt$$
$$= \frac{V_H \delta_H}{L_H} \left[\frac{t^2}{2}\right]_0^t$$
$$\Psi_H = \frac{V_H \delta_H}{L_H} \left[\frac{t^2}{2}\right]$$
$$V_{Hy} = V_H \times \Psi_H$$

Time required ( $t_{RLC} = t_5 - t_4$) for changing to right lane can be calculated as,

$$\Delta d_{Hy} = \int_0^{t\frac{RLC}{2}} [V_{Hy}] \, dt = \int_0^{t\frac{RLC}{2}} [V_H \times \Psi_H] \, dt$$

The headway time ($t_5$) at the end of the lance changing process,

$$t_H = t_{H_5} = \frac{V_L t_{RLC} - (0.5V_H) - V_H t_{RLC}}{V_H}$$

Total time for the overtaking maneuver is given by,

$$T_{OT} = t_5 - t_2 = t_{LLC} + t_{Passing} + t_{RLC}$$

Hence, the overtaking maneuver is finishes safely.

**Analytical Verification:**

Yaw-angle of the HV is calculated as,

$$\Psi_H = \int_0^t \Psi_H \, dt$$

$$\Psi_H = \frac{V_H \delta_H}{L_H} \left[\frac{t^2}{2}\right] = \frac{27.78 \times 0.175 \times t^2}{2.94 \times 2}$$

$$\Psi_H = 0.82t^2$$

$$V_{Hy} = V_{Hset} \times \Psi_H$$

Time required ( $t_{RLC} = t_5 - t_4$) for changing to right lane can be calculated as,

$$\Delta d_{Hy} = 1.75 = \int_0^{t\frac{RLC}{2}} [V_{Hy}] \, dt = \int_0^{t\frac{RLC}{2}} [V_{Hset} \times \Psi_H] \, dt$$
$$= \int_0^{t\frac{RLC}{2}} [27.78 \times 0.82 \times t^2] \, dt$$

After solving the above equation,

$$t_{RLC} = 0.94s$$

The headway time ($t_5$) at the end of the lance changing process,

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$$t_H = t_{H_5} = \frac{V_L t_{RLC} - (0.5V_H) - V_H t_{RLC}}{V_H} = \frac{(22.22 \times 0.94) - (0.5 \times 27.78) - (27.78 \times 0.92)}{27.78}$$

$$t_H = t_{H5} = -0.668s$$

Total time for the overtaking maneuver is given by,

$$T_{OT} = t_5 - t_2 = t_{LLC} + t_{Passing} + t_{RLC} = 1.254 + 4.992 + 0.94$$

$$T_{OT} = 7.186s$$

*D.7. Two-Lane Road (Mixed Traffic)*

In this type of road, the overtaking opportunity depends on the rate of vehicles from opposite direction and also the sight range visible at that instant. Consider $d_2$ is the distance travelled by the host vehicle during the overtaking maneuver and $d_3$ is the distance travelled by the vehicle approaching from opposite direction during the maneuver. The minimum headway distance between the HV and the LV is given by:

$$HWD = 0.7V_{LV} + 6$$

Distance covered by HV during the maneuver is given by:

$$\Delta d_{H_{1-2}} = V_L + \frac{a\Delta t_{1-2}{}^2}{2}$$

Where, a = acceleration of HV

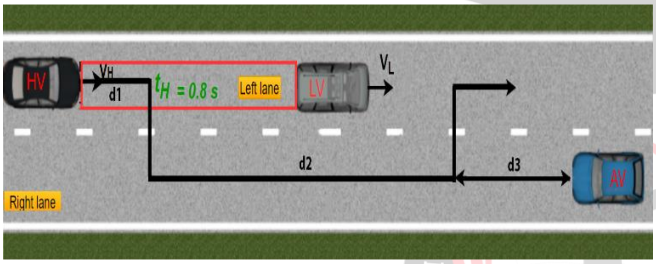


**Fig. 4.4.7 Two-Lane Road**

*D.8. Normal Driving*

After all the above steps, HV again comes back to the initial or the original lane. During this phase the LKA is activated and the vehicle travel with the desired velocity.

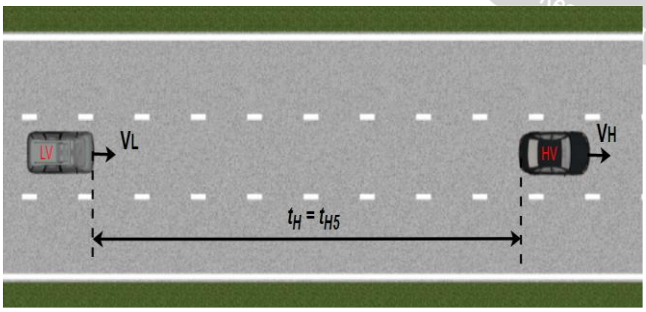


**Fig. 4.4.8 Normal Driving**

At beginning of normal driving, range between HV and LV is:

$$d_{HL_{5-6}} = V_H \times t_{H_5}$$

**Analytical Verification:**

$$t_H = t_{H_5} = -0.668$$

At beginning of normal driving, range between HV and LV is:

$$d_{HL_{5-6}} = V_H \times t_{H_5} = 27.78 \times -0.668$$

At beginning of normal driving, range between HV and LV is:

$$d_{HL_{5-6}} = V_H \times t_{H_5}$$

$$d_{HL_{5-6}} = -18.55m$$

*D.9. Following lead vehicle*

Consider a situation when a faster approaching follower car or vehicle (FV) is detected, which is moving at a faster speed than the HV. HV will only execute the overtaking procedure when the headway time is greater than 0.8s between FV and HV. If it is less or equal to 0.8s, HV will follow the LV as shown:

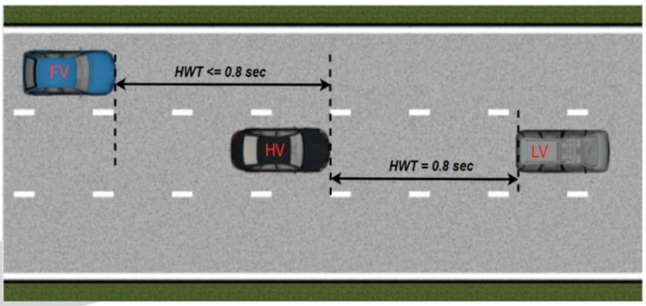


**Fig 4.4.9: Following LV**

Once the FV passes or the headway time between follower and host vehicle becomes less than or equal to -0.8s. The host will perform the overtaking as explained above from steps 4 to 6.

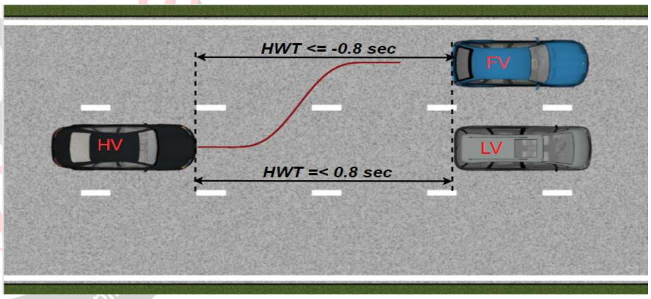


**Fig 4.4.10: Left Lane change after following LV**

## V. CONCLUSION

In this paper, an Autonomous Car Overtaking manoeuvre is observed. The problem of vehicle overtaking on the highway and an undivided road was solved. It was confirmed analytically using mathematical equations and therefore the system was tested virtually. The proposed system has many advantages:

- **Safe:** Safety was assured by safeguarding that the HV remains outside the safe time distance while overtaking. It does not exceed the safety limits of the heading angle, longitudinal acceleration, lateral velocity.
- **Comfortable:** The automation of the overtaking manoeuvre maintains the comfort level during driving.
- **Robust:** Based on the results of simulation and performance validation, it was concluded that the FLC

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was applicable in practice and even at high velocity. This makes the system robust.

- **Feasible:** The use of all the sensors and the adaptive driving assistance system ADAS which are available in the automotive market makes the system feasible. For real-time implementation, the system can be optimized.

Thus, the proposed system with the V2V communication, selected sensors, and results meet the objectives of the paper.

## VI. Future Scope

The future expansion of this paper might be the real-time implementation and verification and validation of the proposed system. The simulation model for overtaking assist will be developed which will foster the development of an autonomous car overtaking. The utilization of various control strategy and different parameters can be studied. The velocity and therefore the lateral movement of the target vehicle can be altered in the future work and its consequences can be studied. Vehicle platooning can be an interesting expansion. Platooning could be beneficial, but it comes with technical challenges which need to be tackled to become a reality. The accuracy of the object detection algorithm could be increase. High accuracy sensors could be used to get the accurate inputs.

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