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Intelligent Model for Traffic Safety Applications

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Abstract: Problem statement: This study presents an analysis on road traffic system focused on the use of communications to detect dangerous vehicles on roads and highways and how it could be used to enhance driver safety. **Approach:** The intelligent traffic safety application model is based on all traffic flow theories developed in the last years, leading to reliable representations of road traffic, which is of major importance in achieving the attenuation of traffic problems. The model includes also the decision making process from the driver in accelerating, decelerating and changing lanes. **Results:** The individuality of each of these processes appears from the model parameters that are randomly generated from statistical distributions introduced as input parameters. **Conclusion:** This allows the integration of the individuality factor of the population elements yielding knowledge on various driving modes at wide variety of situations.

Key words: Driving modes, road traffic, traffic safety application, intelligent safe, dangerous vehicle, detect dangerous, traffic system, non-recurring congestion, merging maneuver

INTRODUCTION

There are several research projects on cooperatively detecting vehicles from approaching ramps, invisible corners, intersections, vehicles in the wrong lane, vehicles traveling at extremely dangerous speeds and vehicles wrongly stopping or running on a motorway shoulder.

Before going to Safety against Dangerous vehicle and situations, generally we make use of Traffic Data for Predicting where roads should be built or expanded in future, To Design bridges and pavements to withstand predicted traffic, To Analyze air quality in urban areas, To Alert drivers about congestion and accidents and to control traffic signals. But it can also be used for Real Time Traffic Control and archived.

Then it can be focused on the use of ad hoc communications to detect dangerous vehicles on roads and highways in order to have intelligent safe transportation.

System analysis: The study of traffic behavior in highways is a subject of interdisciplinary interest both to do with the real problems of congestion in highways and as an example of a complex system that is far from being completely understood. This system has special characteristics that limit the capability to perform experiments. There are various terms which are to be known before entering into traffic system design (Mannering *et al*., 2008).

Congestion: Jamming or blocking of road due to overwhelming traffic is called as congestion. Congestion can be classified into recurring and non-recurring congestion. Recurring congestion occurs at same location at same time every day, but Non-Recurring congestion occurs when a crash or unusual event occurs. Recurring congestion can be solved by proper trip planning but it cannot solve Non-Recurring congestion (Al-Mutairi *et al.*, 2009).

Capacity of the road: The theoretical number of vehicles that can use a segment of highway. The capacity of a lane at ideal condition is 2400 Vehicles Per Hour (VPH) (Schadschneider, 2000).

In case of incidents, there is tremendous impact on capacity. Even if one lane is blocked, the capacity decreases heavily because of “Rubber Necking” and “Merging Maneuver”. Rubber Necking occurs because of people slowing down to look at a crash. Merging Maneuver section occurs due to additional turbulence during merging (Kiencke and Nielsen, 2005).

When we think about solution for this problem, the situation is so that building new roads to increase the capacity cannot compete with the increasing congestion.

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So we have to maximize operational efficiency of existing facilities by providing real-time traveler Information.

Communications: Now it is focused on the use of communications to detect dangerous vehicles on roads and highways and how it could be used to enhance driver safety (Mejri *et al*., 2010).

Safety application is based on Dedicated Short Range Communications (DSRC).

5.9 GHz Band with communication range of 1000 meters is being used in USA. As shown in Fig. 1. Vehicles can communicate with each other (V2C) and with roadside infrastructure (V2I).

Communication messages: There are several data needed for different safety applications to handle various situations (Vegni and Little, 2010). The Safety Applications include periodic and event-driven messages. The Table 1 describes the difference between them in detail.

Data elements: There are several data elements needed for different safety applications to complete their jobs. For example data elements like speed, Acceleration, position. For efficient exchange of data elements, redundancy has to be avoided. Some data that change their values quickly like Position of the vehicle must be sent frequently.

The various data elements and their requirements for various Safety applications (Marques and Neves-Silva, 2005) are listed in Table 2.

Message dispatcher: As shown in Fig. 3, these data elements have to be gathered and compressed into one packet to be sent to nearby vehicles and infrastructure. Using data element compression and single hop broadcast communication, the number of messages to be sent will be reduced significantly improving channel utilization. SAE (Society of Automotive Engineers) has identified 70 standard elements which can also be extended if needed. There are few fields to define each element.

Fields:

- Standard name
- Unique Identifier
- Unit of Measure
- Accuracy of measure
- Range of measure
- Description

Related data elements can be combined to single value to be stored in one data frame in specific order.

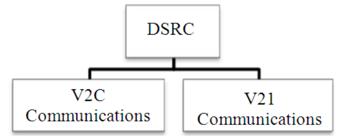

Fig. 1: Dedicated short range communications

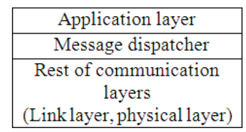

Fig. 2: Layers of message communication

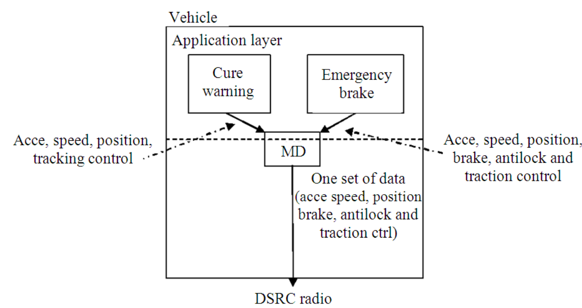

Fig. 3: Message dispatcher architecture

Table 1: Comparison of periodic and event-driven messages

Periodic messages	Event-driven messages
Awareness of environment	Detection of unsafe situation
To inform nearby vehicles about vehicle's current status like speed, position and direction	These are very high priority msgs like location, time and event type
This data helps other vehicles to avoid unsafe situations even before they occur	This data helps other vehicles to avoid unsafe situations after occurrence of an event for one vehicle
These messages are broadcasted frequently	This is sent only when some serious situation occurs
Such messages cause broadcast storm problem, leading to contention, packet collisions and inefficient use of wireless channel	The challenge is that all vehicles intended to benefit from these messages receive them correctly and quickly

Message construction: As shown in Fig. 2, message dispatcher divides message into 3 parts (Burks, 1966):

- Data frames for Physical and Link Layer
- Data elements for Message Dispatcher layer and
- Newly defined terms for Application Layer

Advantages:

- Not single vehicle based technology (Eg: Parking Sensors)

Table 2: Data elements required for safety applications

Data element	Signal violation	Curve warning	Emergency brake	Precrash warning	Collision warning	Turn assistant	Lane warning	Stop sign assistant	No. of uses
Acceleration	√	√	√	√	√	√	√	√	8
Airbag count					√				1
Antilock brake state	√		√		√				3
DSRC message ID	√	√	√	√	√	√	√	√	8
Elevation		√		√					2
Heading	√	√	√	√	√	√	√	√	8
Speed	√	√	√	√	√	√	√		7
Vehicle length				√	√	√	√	√	5
Vehicle mass	√	√	√	√					4

- Vehicles need not be in Line of Sight
- Vehicles share data

MATERIALS AND METHODS

Design of intelligent safety applications: There are 5 categories of Intelligent Safety Applications (Araki *et al*., 1996) such as:

- Intersection collision avoidance
- Public safety
- Sign Extension
- Vehicle diagnostics and maintenance
- Information from other vehicles

Vehicular mobility modeling: There is always a tradeoff between complexity and precision during modeling (Hoogendoorn and Bovy, 2001). There are 3 mobility models based on the trade off. They are:

- Macroscopic models-Vehicular Traffic is considered as continuous flow. Density or mean velocity of cars are modeled using fluid dynamics theory
- Macroscopic models-Individual mobile entities are modeled at an aggregate level, exploiting gas kinetic and queuing theory results
- Microscopic models-Each vehicle's movement is represented in great detail, its dynamics treated independently from those of other cars, except for those near enough to have a direct impact on the driver's behavior. Produces fine grained real world situations, such as front-to-rear car interactions, lane changing, flows merging at ramps and interactions

Model's formal definition:

Where:

I = Vehicle under investigation

I ±1 = Front (+) and back (-) vehicles in current lane

$X_i(t)$ = Position of vehicle i at time t

$V_i(t)$ = Speed of vehicle i at time t

$\frac{dV_i(t)}{dt}$ = Instantaneous acceleration of vehicle i

$\Delta X_i(t)$ = Front bumper to back bumper distance between i and i+1

$\Delta V_i(t)$ = Relative speed $V_{i+1}(t)-V_i(t)$ If this is positive, distance of car i from car i+1 is growing

j-1, j+1 = Back and front cars on left lane with respect to vehicle i

k-1, k+1= Back and front cars on right lane wrt vehicle i

$Lane_i$ = Representation of i^{th} Lane

n_i = Number of vehicles in Lane i

Model input parameters:

Parameter	Symbol
Acceleration	a
Deceleration	b
Maximum allowed/desired speed	v_{max}
Minimum allowed/desired speed	v_{min}
Bumper to bumper safety distance	Δx_{safe}
Safety time headway	Δt_{safe}
Driver's reaction time	τ
Time step (Discrete-Time Models)	Δt
Space step (Discrete Space Models)	Δx
Initial velocity of X_{ij}	u_{ij}

The Intelligent safety application System is a distributed intelligent control system that ensures safe vehicle maneuver on road and intersections. The system ensures that no two vehicles coming from different roads collide or interfere during transit or at the intersection region. It ensures that the time taken by any two vehicles on transit are separated by at least Δx_{safe} (which depends on the length of the road section region and velocity of vehicles), by giving commands to adapt their velocities appropriately.

In other words, it ensures that no two vehicles will be present in the particular point away from intersection region at any given instant of time. This system involves: (i) determining the Sequence i.e., order in which vehicles move in the region (ii) ensuring safety at intersection region and (iii) achieving an optimization goal such as minimizing the maximum (Δt, Discrete time taken by a vehicle to reach the intersection region) our goal is to ensure safe vehicle maneuver sections of road which involves the above mentioned three sub problems.

We have made following assumptions while formulating the optimization problem:

- An intelligent (communication + computation) infrastructure node is situated road-side near the intersection region. It performs all computations and perceives the information to be given by each vehicle.
- A suitable communication infrastructure exists for vehicles and roadside infrastructure node to communicate with each other.
- Initially, all the vehicles are at least Δx_{safe} distance apart (safety distance) from their respective leading vehicle.
- Each vehicle has an intelligent control application which takes v_{max} and time as input and ensures that the vehicle reaches the intersection region in that time periods by maintaining the speed below given v_{max}
- Only those vehicles which are inside the Area of interest (AoI) are part of the system i.e., their profiles (velocity, acceleration and distance) will be tracked by roadside infrastructure node and commands can be given to those vehicles to accelerate or decelerate (Umedu *et al*., 2010)

Specification of the Δt optimization problem: In this part, we give the formulation of the optimization function subject to constraints ensuring their safety. Consider a section of road with three lanes, as shown in Fig. 4 where vehicles are represented by rectangles (Knospe *et al*., 2000). It is assumed that $Lane_i$ contains m_j vehicles where $1 \le i \le 2$ (Lane Index) and $1 \le j \le 2$ (Vehicle Index).

Objective function: The objective is to minimize the maximum Δt (i.e., time taken by the vehicle says X_i (t) to reach the intersection region):

$$\text{Minimize } f = MAX(\Delta t_{n1}, \Delta t_{n2}, \Delta t_{n3})$$

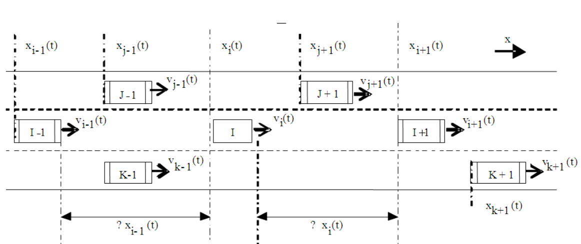

Fig. 4: Model's formal definition

This is similar to the make span of a schedule. An alternative is to minimize the average Δt:

$$\text{Minimize } f = \frac{1}{n1+n2+n3} * \left(\sum_{i=1}^{n1} \Delta t_{xi} + \sum_{i-1}^{n2} \Delta t_{xj} + \sum_{k=1}^{n3} \Delta t_{xk} \right)$$

Precedence constraint: This constraint is to ensure that the vehicles within a road reach the intersection region according to the ascending order of their distance from the region i.e., no vehicle overtakes its leading vehicle:

$$\text{For road}_i, \Delta t_{xi} < \Delta t_{xi+1}$$

Where:

$$1 \le i \le n_i\text{-}1$$

Mutual exclusion constraint: This guarantees that no two vehicles are present in a particular point on particular lane at any given instant of time. In other words, this condition ensures that before (j +1) the vehicle reaches the particular point, the j^{th} vehicle would have traveled through the region:

$$\text{For lane}_i, \Delta t_{xi+1} > \Delta t_{xi} + \frac{\Delta x_{safe}}{V_i}$$

Where:

$$1 \le j \le m_i\text{-}1$$

The above condition guarantees that no vehicles from same road will be present in the intersection region. To ensure vehicles from different roads also adhere to this safety criterion we have:

$$\forall k, l, m\left(\left|\Delta t_{kl} - \Delta t_{lm}\right|\right) \ge \frac{\Delta x_{safe}}{v}$$

where, v will take value v_{1k} or v_{2l} or v_{3m} depending on whether $\Delta t_{1k} < \Delta t_{2l}$ or $\Delta t_{2l} < \Delta t_{3m}$ or $\Delta t_{3m} < \Delta t_{1k}$ respectively and k ,l and m represent vehicle index numbers.

Safety constraint: This constraint ensures that safe distance is always maintained between consecutive vehicles on the same lane, before they enter the merge region. Consider two such consecutive vehicles x_{ij} and $x_{i(j+1)}$ on $Lane_i$. For safety, the following condition needs to be ensured:

$$\forall \Delta t \in \left(0, \Delta t_{ij}\right), s_{i(j+1)} - s_{ij} > \Delta x_{safe}$$

Distance between x_{ij} and $x_{i(j+1)}$ is given by:

$$s_{i(j+1)}(\Delta t) - s_{ij}(\Delta t) = \left(s_{i(j+1)}(0) - \left(u_{i(j+1)} * t + a_{i(j+1)} * t^2\right)\right) - \left(s_{ij}(0) - \left(u_{ij} * t + a_{ij} * t^2\right)\right) = f(t)$$

Ensuring $f_{min}(t) > \Delta x_{safe}$ will guarantee safety criteria. On simplification, the following constraint is obtained:

$$\text{For lane}_{i,} \forall j$$
$$\text{if}\left(a_{ij} > a_{i(j+1)} \text{and} \frac{\left(u_{ij} - u_{i(j+1)}\right)}{\left(a_{i(j+1)} - a_{ij}\right)} < \Delta t_{ij}\right) \text{then}$$
$$s_{i(j+1)}(0) - s_{ij}(0) - L > \frac{\left(u_{ij} - u_{i(j+1)}\right)^2}{\left(2 * \left(a_{ij} - a_{i(j+1)}\right)\right)}$$

else

Mutual Exclusion Constraint guarantees that the safety criteria will be satisfied.

Lower bound on time: This imposes lower bound on the time taken by any vehicle to reach intersection region with the help of V_{MAX}, maximum velocity any vehicle can attain:

$$\text{For Lane}_i, \forall j \Delta t_{ij} \geq \frac{s_{ij}}{V_{MAX}}$$

where, s_{ij} is the initial distance from intersection region i.e., at time instant $t = 0$.

Equality constraint on velocity: This constraint relates the velocity of vehicle at the intersection region to its initial velocity, the distance traveled and the time taken to do so (Wedel *et al*., 2009):

$$\text{For lane}_i, \forall j v_{ij} = \frac{2 s_{ij}}{\Delta t_{ij}} - u_{ij}$$

Other constraints: These constraints impose limits on the velocity and acceleration range of vehicles:

$$\text{For lane}_{i,} \forall j V_{min} \leq v_{ij} \leq V_{max}; A_{min} \leq a_{ij} \leq A_{max}$$

After replacing all v_{ij} in the above set of constraints using the equality constraint on velocity, the system is left with the following design variable (s): Δt_{ij}:

System input: $\forall_i, j$ s_{ij}, u_{ij}, Δx_{safe} and V_{MAX}.

System output: $\forall_i, j \Delta t_{ij}$. The acceleration or deceleration commands to be given to each vehicle can be computed offline from the output of system using:

$$\forall i, j a_{ij} = \frac{2 * \left(s_{ij} - u_{ij} * \Delta t_{ij}\right)}{\Delta t_{ij}^{\ 2}}$$

RESULTS

Implementation using SUMO: A car's motion is structured in trips, which are movements between vertices of the graph, referred to as destinations and randomly selected at each point in SUMO simulator.

At the beginning of each trip, a vehicle i chooses its next destination, computes the route to it by running a shortest path algorithm on the graph with link costs possibly biased by parameters such as road length, Speed limits, traffic congestion and so on.

Then it sets its speed to:

$$V_i = V_{min} + \eta (V_{max} - V_{min})$$

where, η is uniformly distributed random variable in (Mannering *et al*., 2008).

Speed update: Speed is varied by random acceleration of maximum magnitude a. If we define as η is uniformly distributed in (Mannering *et al*., 2008), then rule is expressed as:

$$V_i(t + \Delta t) = V_i(t) + \eta \, a \Delta t$$

Speed bounding: At any time, Speed of a vehicle cannot be lower than a minimum value V_{min} and cannot exceed maximum value V_{max}. This constraint is enforced as:

$$V_i(t + \Delta t) = \min\min\left\{\max\max\left[V_i(t + \Delta t), V_{min}\right], V_{max}\right\}$$

Speed reduction: In order to avoid overlapping, that is a collision situation, with the front vehicle, a minimum safety distance must be maintained:

$$V_i(t + \Delta t) = \begin{cases} V_{i+1}(t) - \frac{a}{2} \text{if } \Delta x_i(t) \leq \Delta x_{safe} \\ V_i(t + \Delta t) \text{otherwise} \end{cases}$$

Basic equation of traffic stream model: In a segment, Number of vehicles on it can vary due to vehicles entering or leaving the segment. It leads to the continuity equation:

$$\frac{\partial\rho}{\partial t} = -\frac{\partial q}{\partial x} = \frac{\partial(\rho\gamma)}{\partial x}$$

Where:
ρ = Density
dx = Small road section
dt = Small interval
q = Corresponding flow

So $\frac{\partial\rho}{\partial t} = -\frac{d}{d\rho}(\rho V(\rho))\frac{\partial\rho}{\partial x}$ assuming velocity as function of density. Speed of each car as a monotonically decreasing function of vehicular density, forcing a lower bound on the velocity when the traffic congestion reaches a critical state:

$$V_i(t+\Delta t) = \max\max\left[V_{min}, V_{max}\left(1-\frac{\rho(x,t)}{\rho_{jam}}\right)\right]$$

where, ρ (x, t) is current density of road being travelled by i.

By fluid traffic motion model:

$$\rho(x,\ t) = \frac{n}{l}$$

Where:
n = Number of vehicles on same road of i and
l = Length of the road segment itself

So by this vehicles on crowded streets are forced to slow down to minimum speed, speed of vehicles increased to maximum value when less congested roads are encountered.

Car following models: Describe the behavior of each driver in relation to its neighboring vehicles (Panwai and Dia, 2005).

Follow the leader model:

- It considers only the vehicle at front
- Motion of vehicle is function of the state of vehicle at front
- The speed or acceleration depend on factors such as distance from the front car, absolute and relative speed or acceleration of both vehicles

$$\frac{dV_i(t)}{dt} = -f\left[V_i(t), V_{i+1}(t), \Delta X_i(t)\right]$$

Helly's Linear Model solution to it is:

$$\frac{dV_i(t)}{dt} = K_1\Delta V_i(t-\tau) + K_2\left[\Delta X_i(t-\tau) - \Delta X_{des}(t)\right]$$

$$\Delta X_{des}(t) = K_3 + K_4 V_i(t-\tau) + K_5\frac{dV_i(t-\tau)}{dt}$$

where, k_1, k_2, k_3, k_4 and k_5 are constants to be calibrated according to traffic scenario.

Intelligent driver model: provides solution to it as:

$$\frac{dV_i(t)}{dt} = a\left[1-\left(\frac{V_i(t)}{V_{max}}\right)^4 - \left(\frac{\Delta X_{des}(t)}{\Delta X_i(t)}\right)^2\right]$$

Where:
$\frac{V_i(t)}{V_{max}}$ = Desired acceleration
$\frac{\Delta X_{des}(t)}{\Delta X_i(t)}$ = Braking deceleration:

$$\Delta X_{des}(t) = \Delta X_{safe} + \left[V_i(t)\Delta t_{safe} - \frac{V_i(t)\Delta V_i(t)}{2\sqrt{ab}}\right]$$

Where:
ΔX_{safe} = Minimum bumper to bumper distance
Δt_{safe} = Minimum safe time head
Waya = Maximum acceleration
B = Maximum deceleration

Krauss model: provides solution to it as Safe speed of vehicle i to maintain safe distance:

$$V_i^{(safe)}(t+\Delta t) = V_i(t) + \frac{\Delta X_i(t) - \tau V_{i+1}(t)}{\left[V_i(t)+V_{i+1}(t)\right]/2b+\tau}$$

Final value of speed with the stochastic noise factor η (Mannering *et al*., 2008) random of maximum % K_1.

Gibb's model: for collision avoidance Car Following Motion Minimum Safety distance at each time instant to be:

$$\Delta X_i(t-\tau) = \frac{\tau}{2}\left[V_i(t-\tau)+V_i(t)\right] + \frac{V_i^2(t)}{2b} + \Delta t_{safe}V_i(t) - \frac{V_{i+1}^2(t-\tau)}{2b}$$

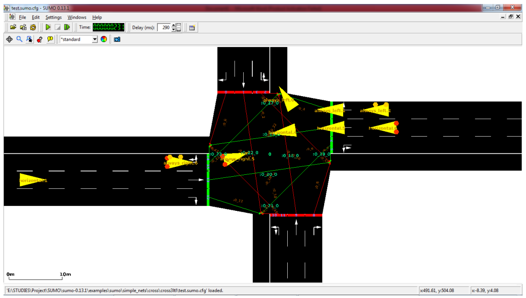

Fig. 5: Screen shot of the simulation using SUMO 0.13.1

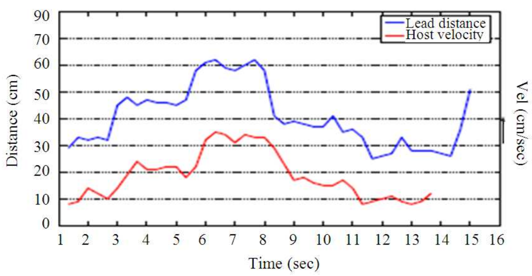

Fig. 6: Velocity response to the changes in the Lead B2B Distance

Four different tests were carried out to observe the system behavior by logging the host speed and position with time. The Fig. 5 shows the simulation performed using SUMO Vehicular simulator.

The Fig. 6 shows the Graph of results obtained.

DISCUSSION

The experimental vehicle was able to maintain its speed equivalent to the maximum allowed speed with tolerance of ±3 m/s in Follow the Leader model case where there was one leading vehicle.

In Intelligent Driver case where leading vehicle was moving with non uniform velocity at a constant B2B, a delay of 0.5s was observed in its velocity response to the changes in the environment which can be attributed to its physical characteristics. The results of these experiments with description can be found.

The next set of experiments tested the two-level safety speed maintenance design using Krauss and Gibb's model. These experiments captured the system behavior when the speed update tasks of both directions were considered, both at front and back of the host vehicle but only when necessary.

The velocity response of the host vehicle with the use of the real-time repository where the leading and following distance increases in time intervals 0-5s and 6-7s, kept constant between 5-6s and 7-8s and then gradually reduced from 8s-12s is shown in Fig. 7.

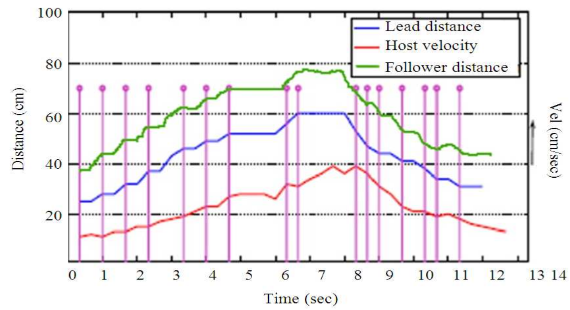

Fig. 7: Velocity response to the changes in the Lead and follower B2B Distance

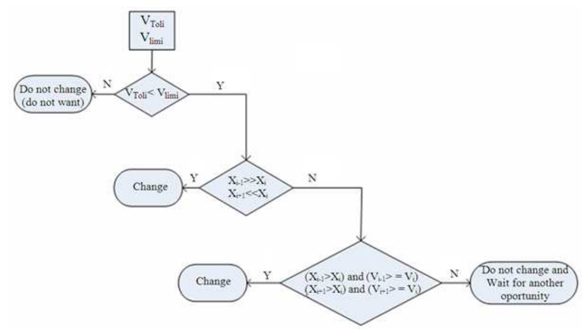

Fig. 8: Lane changing schema while vehicle i wants to change lane

We can observe from the graph that during the time interval 5-6s and 7-8s when the Distance was constant, the on demand acceleration is not invoked and during other time intervals, it is invoked whenever the Distance changes by considering threshold value in purple color (which was set to 3.5 cm sec^{-1} for this experiment).

Vehicles on the road follow the idea stated on previous sections, that is, to maintain a certain distance from their precedent and to maintain a certain value of speed, related to the imposed one. Nevertheless, there are drivers that tend to drive above the speed limit and others that tend to drive below that same speed limit (Sipper, 2002). The consequence is that drivers will change between lanes, in order to achieve a better self satisfying situation. These changes are made, by each driver, taking into consideration the position and the speed of the nearby vehicles, to avoid the occurrence of collisions. And it is shown in Fig. 8 as a schema of how these actions are implemented. Note that vehicle i is the vehicle that wants to change lane.

CONCLUSION

The proposed model implements the vehicle behavior as well as the human component of the driver. This implementation makes use of the statistical variation of the parameters that configure each one of the elements. Based on behavioral thresholds referred to as action points, the idea is that it is possible to identify space-time thresholds triggering different acceleration profile characterizations in a vehicle's driver.

Four driving modes identified so are:

- No reaction-No influence from ahead vehicle, too distant or travelling at higher speed than considered vehicle. So car under study can reach and keep desired speed
- Reaction-The vehicle is approaching the car ahead and thus has to reduce its speed to keep at a safe distance
- Unconscious Reaction-The vehicle is at short distance from vehicle in front, the speed difference is small and the two vehicles form a cluster for communication
- Deceleration-The distance is too small if compared to the current speed difference and the vehicle under consideration is forced to brake

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