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Development of a Collision Avoidance Algorithm Using Elastic Band Theory

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Abstract: This paper presents a new Collision Avoidance (CA) Algorithm which uses Elastic Band Theory. Researchers tried to develop warning systems to avoid collisions which warn drivers of possible collision risk with audio and or visual signs. However, these systems are not sufficient for avoidance of a collision in situations where the driver gives no response to the warnings. CA System is a kind of Active Safety System which takes control of the vehicle for a couple of seconds and applies emergency maneuver when the collision is unavoidable through driver action alone. The proposed CA algorithm uses *Elastic Band Theory* which is an obstacle avoidance method used in robotics. This paper aims to introduce this theory applied with modifications to road vehicle based systems and presents realistic simulation results using high fidelity vehicle models with several different collision scenarios.

1. INTRODUCTION

Traffic crashes cause deaths of millions of people every year. Researchers tried to overcome this fatal problem by developing passive safety systems like seat belts, air bags and crash zones. Although these passive measures helped a lot, there must be more effective ways of holding accidents at acceptable levels. This goal is closer to realization through advances in preventive and active safety systems (Ararat and Güvenç, 2005). Collision Warning (CW) System is an important jump from passive to active safety systems. CW System tries to detect any collision risk between two vehicles by means of radar and internal vehicular sensor information. If the system detects collision risk, it will warn the driver so that a possible accident can be avoided (Ararat et al., 2006). Although a CW System is an efficient way of avoiding possible accidents, these systems become useless when the driver gives no response to the warnings. Collision Avoidance (CA) System takes action and applies emergency maneuver in these kinds of situations.

The first exported obstacle avoidance method from robotics to vehicle based applications is *Artificial Potential Field* Method which was proposed by Khatib (1986). This method appoints an artificial potential field to all the obstacles in the environment. The goal point which is the point where the robot wants to reach applies negative force to the robot where the obstacles in the environment apply positive forces that point the robot to the goal point. Reichardt et. al. (1994), Schiller et al. (1998) and Gerdes et al. (2001) used potential field method in vehicle based applications. Although this method gives adequate results, final configuration of the vehicle with applied potential forces is unpredictable which may lead to hazardous situations. Another drawback of this method is kinematical constraints. Since the dynamics of the vehicle has constraints, it is not possible to point vehicle to any desired direction.

Elastic Band method uses physical analogy similar to the potential field method to deform the predefined global path which is called *Elastic Band* (Quinlan and Khatib, 1993). Since the elastic band method does not only use the physical analogy resulting from the potential field but also the command information from the deformed path, it is called a hybrid method. Elastic Band Method was applied to the vehicle based applications by Hilgert et al. (2003). However, that application did not consider implementation issue for vehicle based applications. Moreover, since this paper only considers the automated vehicle, it may be defined as a lane change assistance system for automated vehicles.

This paper is organized as follow: In Section 2, the theory of Elastic Band is introduced. Section 3 describes the implementation issues for vehicle based applications. Section 4 introduces the proposed Collision Avoidance Algorithm. Section 5 presents simulation results. The paper is concluded by conclusion in the last section.

2. ELASTIC BAND THEORY

Elastic Band is a kind of obstacle avoidance method used in robotics which was first proposed by Quinlan and Khatib (1993). A deformable predefined path is modified by internal and external forces acting on the band. Internal forces are like spring forces which hold the band together while external forces are like artificial potential forces which keep the band away from obstacles. Figure 1 presents the schematic representation of the elastic band with internal and external forces acting on the band.

If we ignore the dynamics of the system, variation of the internal forces can be modelled as follows;

$$\vec{F}^*_{ii} - \vec{F}_{ii} = k_s(\vec{u}_{i+1} - \vec{u}_i) \tag{1}$$

where F^*_{ii} and F_{ii} are final and initial internal forces in the i^{th} spring part, u_i is a displacement of the i^{th} knot and k_s is a spring constant. The force balance equation for each knot can be defined as;

$$\vec{F}_{ei} = -[k_s(\vec{u}_{i+1} - \vec{u}_i) + k_s(\vec{u}_{i-1} - \vec{u}_i)] \tag{2}$$

where F_{ei} is an external force acting on the i^{th} knot. If we divide the terms into their components we obtain the simplest elastic band model as follows;

$$F_{ex,ey} = k_s K u_{x,y} \tag{3}$$

where

$$K = \begin{bmatrix} -1 & 2 & -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 2 & -1 & 0 & \cdots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & & -1 & 2 & -1 \end{bmatrix}, \quad u_{x,y} = \begin{bmatrix} u_{x1,y1} \\ u_{x2,y2} \\ \vdots \\ u_{xn,yn} \end{bmatrix} \quad and \quad F_{ex,ey} = \begin{bmatrix} F_{ex1,ey1} \\ F_{ex2,ey2} \\ \vdots \\ F_{exn,eyn} \end{bmatrix}$$

Since the band has to be held on the predefined global path, the first and the last knot are static and the model is transformed to;

$$k_s \begin{bmatrix} 2 & -1 & 0 & \dots & 0 \\ -1 & 2 & -1 & \cdots & 0 \\ \ddots & \ddots & \ddots & & \\ 0 & \cdots & & -1 & 2 \end{bmatrix} \begin{bmatrix} u_{x2,y2} \\ u_{x3,y3} \\ \vdots \\ u_{xn-1,yn-1} \end{bmatrix} = \begin{bmatrix} F_{ex2,ey2} \\ F_{ex3,ey3} \\ \vdots \\ F_{exn-1,eyn-1} \end{bmatrix} \tag{4}$$

where

$$u_{x1,y1} = [0,0] \quad and \quad u_{xn,yn} = [0,0].$$

External forces acting on the band can be written as;

$$F_e = \begin{cases} -k_e(\|r_i\| - r_0)\dfrac{r_i}{\|r_i\|} & ; \quad (\|r_i\| - r_0) \le 0 \\ 0 & ; \quad (\|r_i\| - r_0) > 0 \end{cases} \tag{5}$$

where r_i is the position vector between the obstacle and the i^{th} knot, r_0 is the threshold distance and k_e is the external force constant.

This simple model neglects the dynamics of the band. However, since the band takes its final form in second or third iteration, this assumption gives adequate results which are very close to exact band model. Moreover, since the band model is transformed into a matrix inverse operation and both stiffness matrix and the external force vector are sparse (Several knot points satisfy threshold distance), this model is not a time consuming model which requires heavy computations.

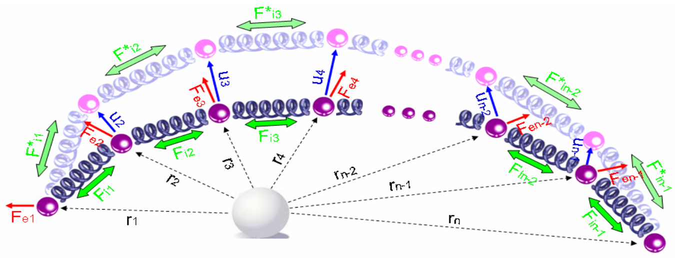

Fig. 1. Schematic Representation of Elastic Band.

3. IMPLEMENTATION ISSUES

Elastic Band Theory introduced in previous section has very successful applications in mobile robot platforms. However, the method has to be modified for vehicle based applications that are realized in highly dynamic environments with different road conditions. Following subsections present these modifications.

3.1 Modifying Repulsive Force

Repulsive force formulation described in (5) does not give uniform results in the vicinity of the obstacle. Formulation is modified for close distance to the obstacle. Figure 2 gives the comparison of two formulations.

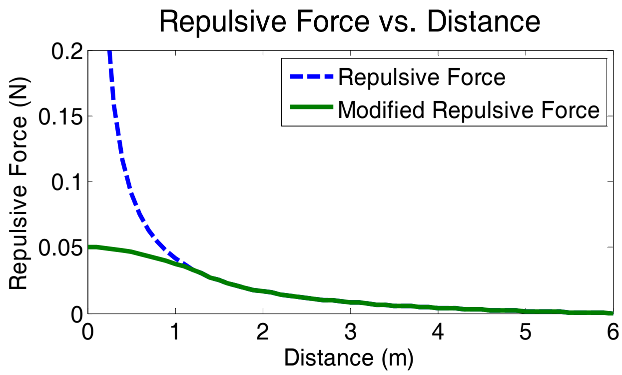

Fig. 2. Variation of Repulsive Force with Distance.

Second issue about the repulsive force is continuity and smoothness. Since the host vehicle and the other road users move with high velocities, elastic band has to be moved and modified. To be able to obtain continuous path and smooth trajectories, the band has to show harmonic characteristics. Figure 3 shows one of the unintended behaviours of the band. When the obstacle approaches the band too much, repulsive forces acting on the band show non-uniform distribution. Method is modified for this kind of situations. If the obstacle is too close to the band, algorithm searches for the parts that have similar kind of properties. Parts that have similar characteristics are grouped together. Forces acting on the groups are modified according to the characteristics of the group.

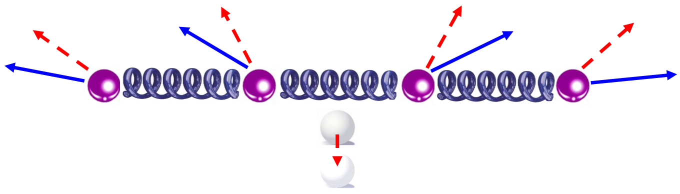

Fig. 3. Non-uniform Repulsive Force Distribution in the vicinity of the Band.

3.2 Modifying Predefined Path

In vehicle based applications, predefined global path is the road data for the middle of the lane. However, since vehicles do not follow the lane exactly, elastic band can be modified for the wrong direction that may drag the host vehicle to the outside of the road. To solve this problem, the algorithm defines two alternative paths for right and left lane directions. Connections to the alternative paths are made with cycloids;

$$y = \frac{a}{1 + e^{-b(x-c)}} \tag{6}$$

where a describes the desired lateral offset and c describes the longitudinal point where the lateral offset takes half of its final value. b is used to change the slope. Figure 4 shows the right alternative path that the algorithm creates.

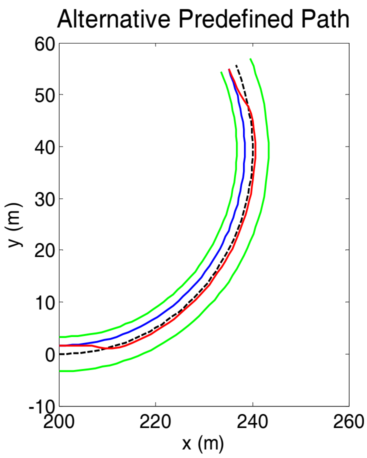

Fig. 4. Alternative Predefined Path.

3.3 Corrupting Elastic Band

Collision Avoidance Algorithm needs error detection subsystems that control possible errors with road limits and other road users. Following subsections describe these subsystems.

Path Error Detection The bubble concept in robotics is relatively much more time consuming for vehicle based applications than for mobile robot platforms. It is also simpler to track defined trajectory for mobile robots than for vehicles. Hence, the bubble which is defined for vehicle based applications should be larger than the bubble defined in robotics. Instead of defining bubbles around the vehicle, the algorithm uses distances to the obstacles to determine any path error. Distance threshold for the path error;

$$d_{pt} = d_{mo} + d_{mv} + 0.5 \tag{7}$$

where d_{pt} is the threshold distance, d_{mo} is the maximum detected width of the obstacle, d_{mv} is the maximum width of the host vehicle. Figure 5 shows an example situation for the path error.

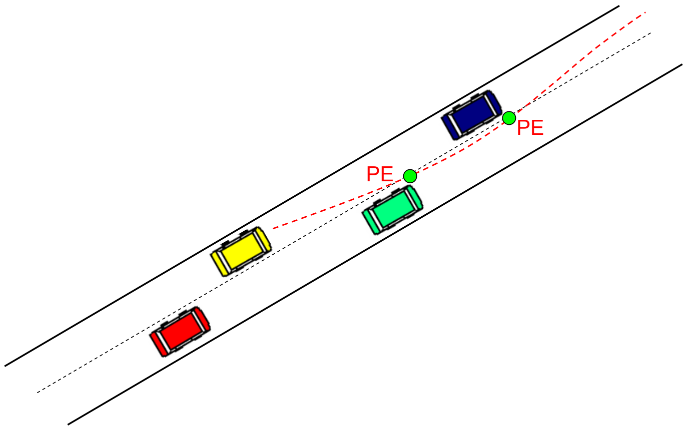

Fig. 5. Example Situation for the Path Error.

Road Error Detection Algorithm also has to detect any road error of the band. For this purpose, road data is divided into parts. These parts are grouped together and parts satisfy predefined threshold linked together linearly. Global points that represent the knot positions are compared with these linked parts. Elastic Band is corrupted at the point where the knot and road limit intersect. Figure 6 shows an example situation for the road error.

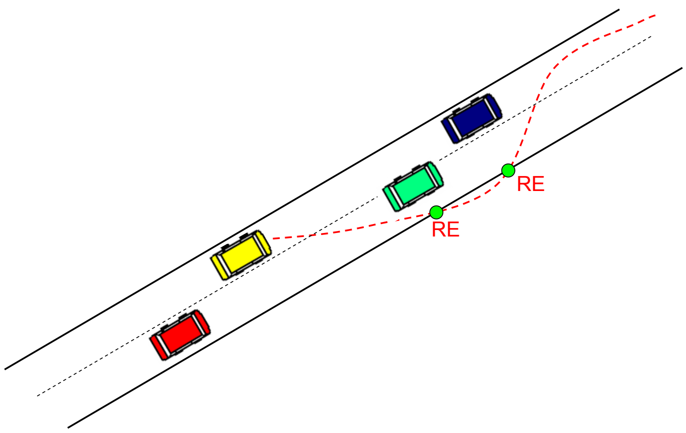

Fig. 6. Example Situation for the Road Error.

Route Error Detection Algorithm needs an extra error detection subsystem for intersection points and lane change maneuvers. Lateral movements in an application area constitute important problems if the velocity of the object is high. Modifying repulsive forces might solve the problem.

Objects having lateral movements might apply repulsive forces proportional to their velocities. However this solution destroys the uniformity of the band. Another solution is an error detection subsystem. Time to collision is calculated for the obstacles that cut the band and compared with the arrival time of the host vehicle to the cutting point. If the time difference is less than the predefined threshold value than route error detection subsystem gives an error for that point. Figure 7 shows an illustrative figure for that subsystem.

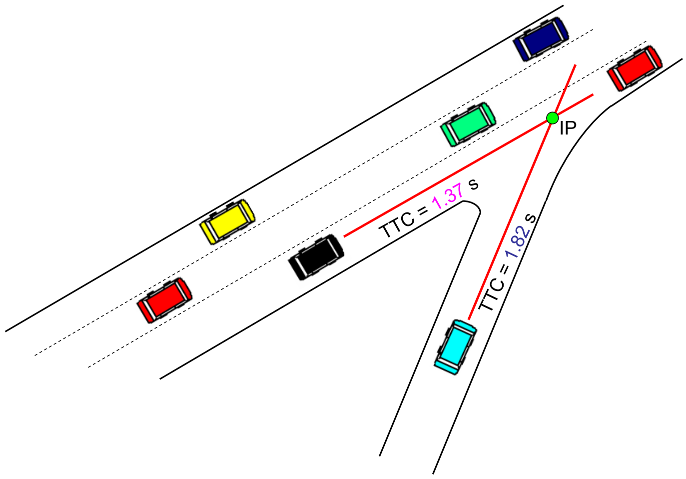

Fig. 7. Example Situation for the Route Error.

Threshold value for the time difference can be calculated with the following formulation;

$$d_{vt} = \frac{v_v}{\sqrt{2}} \tag{8}$$

where d_{vt} is the threshold value for the time difference, v_v is the velocity of the host vehicle.

Route error detection subsystem works both in the algorithm and in the collision detection system. This subsystem detects error with predefined path and the obstacles in the collision detection system while it detects error with modified path and the obstacles in the algorithm. This system detects error in lane change maneuvers of the obstacles as well as detecting error with intersection points.

4. COLLISION AVOIDANCE ALGORITHM

Collision Avoidance Algorithm (CAA) is composed of main algorithm, error detection subsystem and the decision algorithm. Algorithm uses laser, digital map and driver as an input source. Laser data gives obstacle data where digital map satisfies the predefined path. Algorithm uses driver data in decision part. Collision Detection Algorithm (CDA) which is introduced in ([2]) is a kind of kinematical based algorithm that provides Time to Collision (TTC) information.

Algorithm is initialized with the collision risk data which comes from CDA. CDA calculates TTC with the preceding vehicle via kinematical analysis based algorithm and with the intersection object via route error detection subsystem. If TTC is lower than the total delay time which means there is nothing to do even if driver becomes aware of the crash possibility, CAA is initialized.

Algorithm first defines the alternative right and left paths. Firstly, left alternative path is sent to the deformation process. If the deformation process gives error with this path, the algorithm passes through the right alternative path. If this path also is not an adequate path, algorithm gives an error at a point which is the minimum value of the errors for left and right path given by error detection subsystems.

Deformation process is composed of modification of the elastic band with the repulsive and external forces resulting from objects around the vehicle and the spring forces. Deformed path is sent to the error detection subsystems. These systems which are defined in previous sections detect path, road and route errors and send the minimum value of knot number which gives error.

Decision Algorithm is the last part of the algorithm. Algorithm first searches for an alternative modified path without any error. If algorithm finds a path, it assigns this path as a maneuver path and puts a trajectory on this path. If driver gives no response, final velocity is defined as zero. If algorithm can not find any modified path without error, it searches for the path with maximum of the minimum of knot points which gives error. If obtained value is higher than the predefined threshold, algorithm selects this path and assigns the trajectory to be followed as this path whose velocity values at the error knots is zero. In this way, it is possible to search for an alternative path at the next time step. Threshold value is calculated as;

$$d_{at} = \frac{v_v}{\sqrt{2}/2} \tag{9}$$

where d_{at} is the threshold value for the decision algorithm, v_v is the velocity of the host vehicle.

Since it is not possible to avoid collision with the emergency braking because of the inadequate time, emergency braking is the last choice for the algorithm. If decision algorithm can not find a path without error or a path which gives error before the predefined threshold, algorithm decides on emergency braking. Figure 8 shows the flowchart of the algorithm with connected systems.

5. SIMULATION STUDY

Since simulations should be done in an environment close to reality with advanced vehicle models, Carsim 6.05 is used for testing purposes. Carsim provides connection with Simulink to realize testing of control algorithms developed in Simulink. Conventional controllers are used at the first step for trajectory tracking. Three different configurations with different scenarios are tested with developed algorithm. Following subsections give detailed results of the algorithm for these configurations.

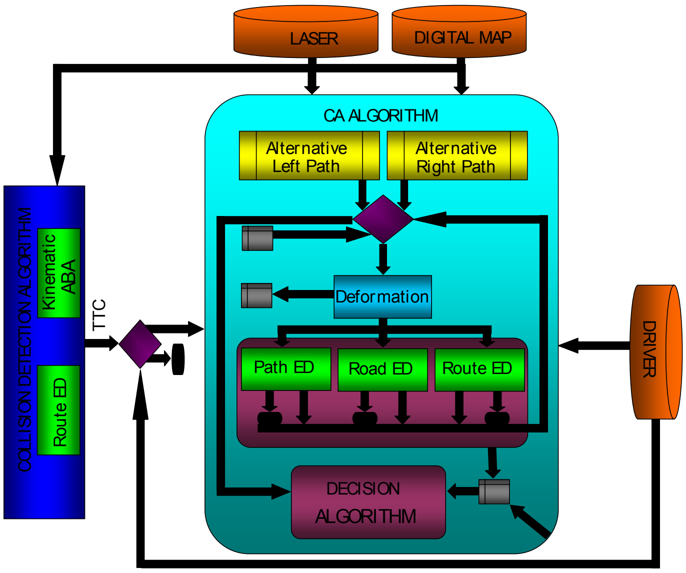

Fig. 8. Flowchart.

5.1 *Rear End Collision*

In this configuration, host vehicle approaches preceding vehicle too much which will resulted in a rear end collision. For this configuration, algorithm is tested for different positions of the vehicle driving in the next lane.

In the first simulation, preceding vehicle applies emergency braking at 4 s and the vehicle which is coming from the next lane does not let the host vehicle make an emergency maneuver for first few seconds. Host vehicle applies emergency braking first. When the vehicle coming from opposite direction moves away, host vehicle starts emergency maneuver. Figure 9 shows the stroboscopic view of the emergency maneuver which is applied after vehicle coming from opposite site moves away. Figure 10 shows velocity vs. time data for three vehicles.

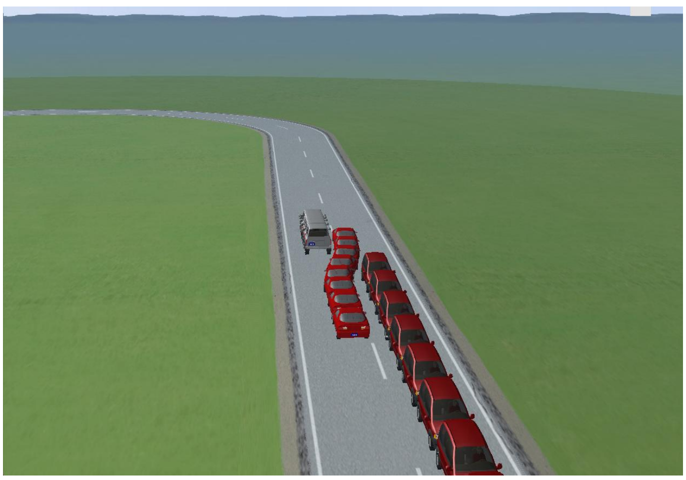

Fig. 9. Second Action: Emergency Maneuver.

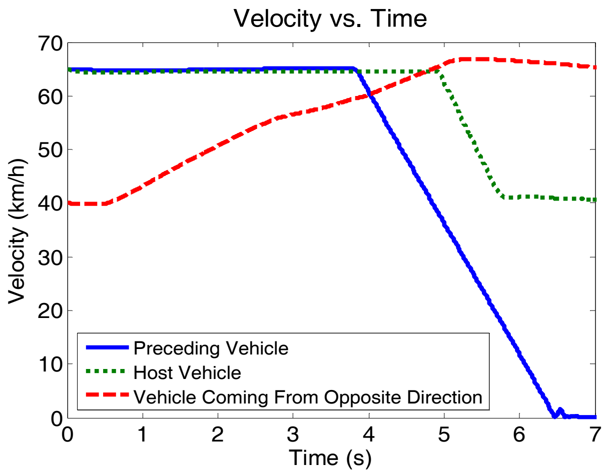

Fig. 10. Velocity vs. Time for Three Vehicles.

Second simulation is done for the same configuration except that vehicle coming from opposite site is far away from the host vehicle and lets host vehicle make an emergency maneuver. Figure 11 shows the stroboscopic view of the emergency maneuver.

Fig. 11. Stroboscopic View of an Emergency Maneuver.

5.2 *Lane Change Collision*

In this configuration, vehicle driving in the next lane does not recognize the host vehicle and starts to change its lane. Algorithm detects the collision risk and applies emergency braking first. Since emergency braking can not avoid collision alone, algorithm applies emergency maneuver after vehicle changing its lane comes closer to host vehicle's lane. Figure 12 shows emergency braking as a first action.

5.3 *Intersection Point Collision*

In this configuration, all three vehicles are approaching intersection point. Preceding vehicle stops at stop sign where host vehicle do not notice the sign and causes a possible collision risk. Algorithm detects available maneuver for the host vehicle. However, available maneuver causes a possible collision risk with the third vehicle. Algorithm chooses first applying emergency braking to avoid collision with third vehicle and applying emergency maneuver when it finds collision free emergency maneuver. Figure 13 shows emergency maneuver action. Figure 14 shows the path (X vs. Y data) for three vehicles.

Fig. 12. First Action: Emergency Braking.

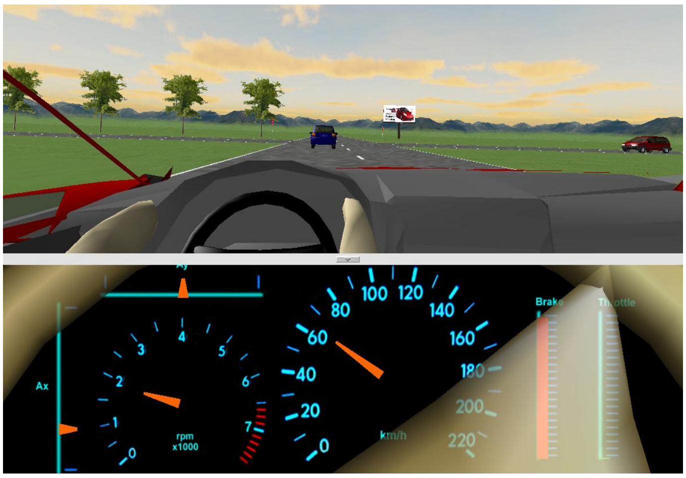

Fig. 13. First Action: Emergency Braking.

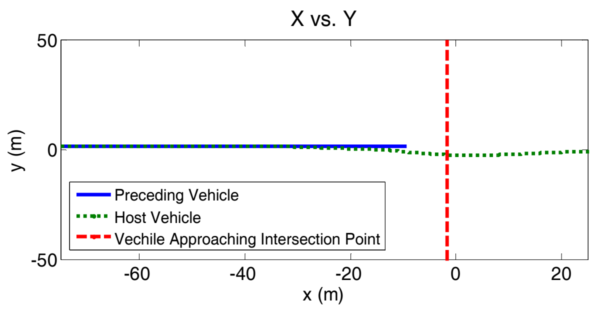

Fig. 14. X vs. Y Data for Three Vehicles.

6. CONCLUSION

Elastic Band is a strong method which combines the simplicity of the potential field method with the accuracy of the trajectory generation based methods. This strong method was modified for vehicle based applications. Reactive forces that push the vehicle away from the other objects in an environment was first modified. Uniformity of the band was satisfied by changing the method for the situation which has objects in the vicinity of the band. Alternative paths were developed considering the restrictions of the vehicle dynamics. Error detection subsystems were developed for searching available modified alternative paths. Proposed algorithm was tested with Carsim 6.05 for different scenarios and different configurations. Algorithm gave acceptable results for Rear-End, Lane Change and Intersection Point Collisions. Although conventional controllers gave acceptable results, performance of the algorithm might be increased with much more advanced trajectory following controllers. In the next stages of this work, different trajectory controllers will be tested with the proposed algorithm.

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