

Performance of Driver-Vehicle in Aborted Lane Change Maneuvers

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Abstract

A "lane change crash" is defined as a family of collisions that occurred when a driver attempts to change lane and strikes or is struck by a vehicle in the adjacent lane. One type of maneuver that is commonly used to avert a lane change crash involved aborting the intended lane change, and returning the vehicle to the original lane of the subject vehicle. This study addresses the performance of driver-vehicle systems in aborted lane change maneuvers. We first compared the recorded steering command of an experienced driver in executing a lane change maneuver with that determined via solving a suitably formulated optimization problem, and found them to be qualitatively comparable. This finding allows us to analytically assess whether an experienced driver can successfully avert a lane change crash if he responded to the warning from a collision detection system T_e seconds after the initiation of the lane change maneuver. Quantitative relations between pre-crash vehicle variables, including the nominal speed of the subject vehicle, the closing speed between the subject vehicle and principal other vehicle, the longitudinal and lateral gap distances, and T_e are determined. Results obtained can be used to guide the development of collision warning devices and other lane change/merge crash avoidance counter-measures.

Introduction

A "lane change crash" is defined as a family of collisions that occurred when a driver attempts

to change lane and strikes or is struck by a vehicle in the adjacent lane. There were more than 240,000 lane change or merge crashes that occurred in 1991.¹ Even though this represents only about 4% of all crashes, it is estimated that these crashes account for about 10% of all accident-caused delay.^{1,2} Statistics on lane change crashes that are used in this study include:

- most lane change/merge crashes involved two vehicles traveling at speeds that are within 5 mph (8.3 km/hr) of each other.
- about 75% of lane change/merge crashes occurred on roads with speed limits of less than 55 mph (91.7 km/hr).
- about 68% of lane change crashes were simple lane changes, as opposed to merge, exit, passing, or weave maneuvers.
- passenger vehicles are equally likely to be involved in left-to-right and right-to-left lane change crashes.

This study addresses the performance of driver-vehicle systems in attempting to avoid a lane change crash. The scenario considered is depicted in Fig. 1. In that figure, the driver of the subject vehicle (SV) has just initiated a lane change maneuver when he detected a fast approaching vehicle (called "principal other vehicle" or POV) in the destination lane. Even though there is a longitudinal gap between the SV and POV prior to the start of the lane change maneuver, this gap is being closed very rapidly. If the SV driver does not initiate evasive maneuvers quickly, a lane change collision will occur.

One family of maneuvers that is commonly used in averting a lane change crash involved aborting the intended lane change, and returning the SV back to the initiation lane. Since the longitudinal gap between the vehicles involved could be small (in Fig. 1, the POV is within the "blind zone" of the SV), the fast-approaching vehicle must be detected quickly and the evasive maneuvers made reflexively. Unfortunately, most drivers are not familiar with the "aborted" lane change maneuver, and the evasive steering commands used might be incorrect. It is in this situation that a collision warning device might save the day. However, to be useful, the collision warning system must detect and warn the SV driver "early enough" in order to give the SV driver a chance to successfully avert the collision.

The objective of this study is to quantify the performance of driver-vehicle systems in an aborted lane change maneuver. Relations between pre-crash vehicle variables (such as the nominal speed of the subject vehicle, the closing speed between the vehicles, the longitudinal and lateral gap distances) and the detection time of the collision warning device will be established. These results can be used to guide the developments of collision detection and warning devices and other counter measures for lane change/merge crashes.

Vehicle Dynamic Model

Consider a vehicle moving over a flat and level road surface (Fig. 2). When the forward speed, U , is kept constant, this vehicle model has two degrees-of-freedom, the side velocity, v , and the yaw-rate, r . The cornering forces acting on the front and rear axles are denoted by F_f and F_r , respectively. Apart from these forces, there are the relatively small aligning torques, camber angle effects, etc. that are neglected in our study.

In Fig. 2, a and b define the location of the vehicle's e.g. between the axles, and M_s and I_{zz} denote the mass and the yaw moment of inertia of the vehicle, respectively. Furthermore, if C_{α_f} and C_{α_r} denote the cornering stiffnesses of each front and rear tire, respectively, and if δ_f denotes the front tire angle, then the vehicle's equations

of motion are:³

$$I_{zz}\dot{r} + \frac{2(a^2C_{\alpha_f} + b^2C_{\alpha_r})}{U}r + 2(aC_{\alpha_f} - bC_{\alpha_r})\frac{v}{U} = 2aC_{\alpha_f}\delta_f, \quad (1)$$

$$M_s\dot{v} + \left\{M, U + \frac{2(aC_{\alpha_f} - bC_{\alpha_r})}{U}\right\}r + 2(C_{\alpha_f} - C_{\alpha_r})\frac{v}{U} = 2C_{\alpha_f}\delta_f. \quad (2)$$

The following vehicle parameters are used in our study: $[a, b] = [1.2, 1.6] \text{ m}$, $I_{zz} = 2200 \text{ kg}\cdot\text{m}^2$, $M_s = 1700 \text{ kg}$, $[C_{\alpha_f}, C_{\alpha_r}] = [960, 1100] \text{ N/deg}$.

In our study, the vehicle dynamic model is augmented with the following first-order actuator dynamic model:

$$\tau_a\dot{\delta}_f + \delta_f = \delta_{fc}. \quad (3)$$

Here δ_{fc} is the command to the steering actuator, and τ_a is the time constant of the actuator. The assumed bandwidth of the steering actuator is 4 Hz. Similarly, we use the following driver's neuromuscular model:³

$$\tau_d\dot{\delta}_{fc} + \delta_{fc} = \delta_{driver}/N_s. \quad (4)$$

Here δ_{driver} denotes the steering wheel command from the driver, and τ_d is the time constant of the driver response. The parameter N_s is the steering ratio ($N_s = 15$). The bandwidth of the driver response is assumed to be 2 Hz.

The validity of this vehicle model begins to deteriorate in maneuvers with lateral accelerations that exceed 0.3 g's, including those found in high-speed lane change maneuvers. However, the situation is mitigated somewhat by the fact that these high-g conditions only lasted for a short time. What follows does not depend on the "linear" vehicle model assumption which was used only for convenience. Nonlinear vehicle models that can better predict vehicle responses in high-g maneuvers should be used if available.

In addition to these dynamic equations, the following kinematical relations are used to compute the resultant vehicle trajectory:

$$\dot{\psi} = r, \quad (5)$$

$$\dot{x} = U \cos \psi - v \sin \psi, \quad (6)$$

$$\dot{y} = U \sin \psi + v \cos \psi. \quad (7)$$

in Fig. 2, (x, y) is the recti-linear coordinates of the vehicle's e.g. relative to an arbitrary reference. The angle ψ is that between the vehicle's geometrical axis of symmetry and the x-axis, and is defined positive in the clockwise direction.

Performance of Driver-Vehicle System in Lane Change Maneuvers

The performance of a driver-vehicle system in lane change maneuvers is difficult to evaluate because one must take both the vehicle's directional characteristics as well as the limitations of driver responses into consideration. Several collision avoidance scenarios had been studied in the literatures [1-2, 4-6].

In Ref. 6, Lee considered the lane change maneuver illustrated in Fig. 3. As pictured, a vehicle is travelling at a constant speed on a straight two-lane roadway when an object dashes onto the vehicle's path and stops. Representative time histories of steering wheel excursions made by both experienced and inexperienced drivers in such a scenario are given in Fig. 4.4 The initial steering angles used by both driver groups are on the order of 200 degrees. The initial steering command must be followed by an "equal-and-opposite" steering in order to arrest the diverging vehicle's heading angle, and return it to the desired straight-ahead heading.

With regard to the steering commands used by experienced drivers in lane change maneuvers, Lee conjectured that driver's evasive steering commands can be determined via solving a suitably formulated optimization problem. The cost functional of that optimization problem is a weighted sum of the lane change time, vehicle's squared heading angle and tire's excursion at the end time, and the time integrals of the vehicle's squared lateral acceleration and driver's steering rate. Steering commands obtained via solving such an optimization problem were found to be qualitatively comparable to those recorded from road tests. This finding allows us to analytically assess the performance of driver-vehicle systems in "aborted" lane change maneuvers.

An Aborted Lane Change Maneuver

The aborted lane change maneuver depicted in Fig. 1 begins with a "normal" lane change maneuver. The driver attempts to make a lane change to get to an adjacent lane. Not under the pressure of time he plans to complete that lane change in three seconds (T_{LC}). An optimization problem is formulated to analytically generate the steering commands. The end conditions of the optimization problem are given as follow: Before the lane change maneuver, the vehicle is in its straight-ahead cruising condition. To make the lane change maneuver, the vehicle must be displaced a lateral distance. Also, it is desirable to end the lane change with zero vehicle's yaw rate, side velocity, heading angle, and tire excursion angle. To bring the vehicle from the given initial to the desired terminal conditions, we seek $\delta_{drive}(t)$ that minimizes the following cost functional:

$$J = \frac{1}{2} \int_0^{T_{LC}} \left\{ \left(\frac{a_{yy}}{a_{yyN}} \right)^2 + \left(\frac{\dot{\delta}_{fc}}{\dot{\delta}_{fcN}} \right)^2 \right\} \left(\frac{dt}{T_N} \right). \quad (8)$$

To make this cost functional dimensionless, all variables are normalized by quantities denoted with a subscript "N". Values selected for these normalizing quantities, and other scenario parameters are tabulated in table 1. Note that these scenario parameter values were selected to be consistent with the lane change crash statistics mentioned in the introduction section. Throughout the lane change maneuver, driver's comfort and workload are improved by inducing both the vehicle's lateral acceleration (a_{yy}) and the steering rate ($\dot{\delta}_{fc}$) in the cost functional. The formulated optimization problem was solved using the algorithm described in Ref. 7. Time histories of the steering angle, vehicle heading angle, lateral acceleration, and the resultant vehicle trajectory are given in Fig. 5. The root-sum-squares values of the lateral acceleration and steering wheel rate are 0.17 g's and 56.7 deg/sec, respectively. The corresponding cost functional for this three-second maneuver is given by $3 \times 0.5 \times \{(0.17/0.2)^2 + (56.7/150)^2\} \approx 1.3$.

Table 1 Scenario Parameters

Parameter	Value(s)
S-v speed(u)	100<111/11
speed differential (AU)	6-21 km/h
lateral gap (D)	3.6 m
vehicle width (W)	2.0 m
side mirror to rear bumper (S)	3.0 m
inner blind zone angle (β)	16 deg
steering ratio (N_S)	15
detection and warning time (T_e)	0.40-0.85 sec
lane change time (T_{LC})	3 Sec
normalized time (T'_N)	1.0 sec
normalized angle (θ_N)	2.0 deg
normalized acceleration (a_{yyN})	0.2 g's
normalized steering rate (δ_{fcN})	150/ N_S deg/sec

Many lane change crashes occurred because the driver of the SV fails to see the POV. This could be because the POV is inside the blind zone of the SV, as depicted in Fig. 6. If the SV is equipped with a collision warning system, let it be turned on the moment the lane change is initiated. Let T_e be the total time it takes the warning system to detect the POV and the time it takes the driver to recognize and react to the generated (audio or visual) warning. If the POV speed is higher than that of the SV by ΔU , the maneuver time (T_m) available to avert the lane change crash is:

$$T_m = L/\Delta U - T_e, \quad (9)$$

where L is longitudinal gap between the SV and POV. From Fig. 6, $L = (D - W/2)\cot\beta - S$. Using data given in Table 1, the available maneuver time is only $(2.2 - T_e)$ seconds if $AU = 10$ km/h. Obviously, the faster the collision warning system can detect the POV and warn the SV driver about the impending crash, more time will be available for the SV driver to execute the needed evasive maneuver. The initial condition of this evasive maneuver also depends on T_e . If T_e is small, the magnitudes of the vehicle's yaw rate, side velocity, and lateral acceleration at the start

of the aborted lane change maneuver are relatively small (see Fig. 5). Hence, it will be easier and quicker to return the vehicle back to the initiation lane. To avert the lane change crash, the y-coordinate of the SV's e.g. at the end of the maneuver must be:

$$y(T_m) \leq D - W. \quad (10)$$

Also, we must end the lane change with zero vehicle's yaw rate, side velocity, and heading angle. To steer the vehicle from the given initial to final conditions, we seek a $\delta_{driver}(t)$ that minimizes a cost functional that is similar to that given in (8):

$$J = \frac{1}{2} \{ \delta_f(T_m) / \theta_N \}^2 + \frac{1}{2} \int_0^{T_m} \left\{ \left(\frac{a_{yy}}{a_{yyN}} \right)^2 + \left(\frac{\delta_{fc}}{\delta_{fcN}} \right)^2 \right\} \left(\frac{dt}{T_N} \right). \quad (11)$$

The first term in this cost functional accounts for the driver's desire to return the tire angle back to "zero" at the end time as closely as possible. The normalized angle θ_N is given in Table 1. Physical interpretations of the terms under the integral had been given above. For ranges of T_e and AU values, the formulated optimization problem, with both equality and inequality terminal conditions was solved using the technique described in Ref. 8. The variations of the cost functional (per unit maneuver time) with AU, for a range of T_e are depicted in Fig. 7. The corresponding variations of the terminal lateral displacements with AU are given in Fig. 8.

Discussions

In Fig. 7, the magnitude of the cost functional represents the '(degree of difficulty)' of making the evasive steering maneuver. If the driver executes the maneuver with, on the average, 0.3 g's of lateral acceleration and 150 deg/scc of steering rate, the resultant per unit time cost functional is $0.5 \times \{ (0.3/0.2)^2 - 1 + (150/150)^2 \} \approx 1.63$. If a horizontal line that represents $J/T_m = 1.63$ is drawn in Fig. 7, its intersections with various ΔU -to- J curves give the maximum allowable speed differential ΔU_{max} below which the SV can successfully avoid the collision. Since the cost functional increases very rapidly with AU for larger T_e , the

resultant ΔU_{max} becomes very small. A plot between T_e and ΔU_{max} is given in Fig. 9. A first-order approximation of the data given in that figure is:

$$\Delta U_{max} = 25.5 - 15T_e, \quad (12)$$

where T_e is in units of seconds and ΔU_{max} is in units of km/hr. When the above described analysis is repeated for the case when the SV speed is 90 km/hr (instead of 100 km/hr), the corresponding relation is: $\Delta U_{max} = 25.2 - 14.9T_e$, which is close to (12). Looking at these relations, it is obvious that the magnitude of the warning time T_e plays a critical role in deciding whether the SV driver can successfully avert an accident.

The presence of the POV in the SV'S blind spot might be detected by the SV driver himself. Let us assume that the detection time is one second. Else, the SV driver might be aided by a collision detection device. Ultrasonic, radar, and Doppler technologies have been used in commercially available proximity detection systems which could be used for this purpose. In this study, we assume that the combined detection and diagnostic processing time for the system used is 0.1 seconds. The processed information must then be presented to the driver in a manner that elicits appropriate collision avoidance maneuver.

Driver warning recognition time is a strong function of the type of display used. A comparison between the recognition times of a head-up display (HUD) and a conventional instrument panel head-down display (HDD) was made in Ref. 9. In that reference, the recognition time is the time it takes the driver to focus on and recognize the displayed warning sign. For straight line driving at 100 km/hr, the recognition time of a HUD system is about 0.3 seconds (that of a HDD is 0.5 seconds). From Ref. 10, the delay time in the driver's steering response is on the order of 0.15 seconds. Hence, the overall detection and warning time $T_e = 0.1 + 0.3 + 0.15 = 0.55$ seconds, which is about half that of the driver. Using (12), the maximum allowable speed differentials for the driver-based and warning system-based scenarios are 10.4 and 17.2 km/hr, respectively. If the POV

is approaching the SV with a AU of 11 km/hr, a collision will result if the driver is not aided by a collision warning system.

Another way to interpret the result given in (12) is as follows. Consider the scenario when the speed differential between the vehicles is 5 mph (8.3 km/hr, see also the Introduction section). The question is: how quickly must the POV be detected so that the SV driver needs only to perform lane change maneuver of "moderate" degree of difficulty having a cost functional of 1.63. Using (12), we estimate that T_e must be less than $(25.5 - 8.3)/15 \approx 1.2$ seconds. This level of response time is generally achievable by most drivers. Hence, most drivers can successfully avert a lane change collision with a 5-mph speed differential. This conclusion is consistent with our general driving experience.

The parameter T_{LC} given in Table 1 denotes the time duration within which the SV driver plans to complete the attempted lane change maneuver. This time is a function of the following factors, among others: (a) nominal speed of the SV, (b) traffic density, and (c) the "aggressiveness" of the SV driver's lane change maneuver. If the SV driver is cautious, he might decide to complete the lane change with a longer T_{LC} . To study the effects that T_{LC} has on our results, we repeated the analyses with a $T_{LC} = 4$ seconds (instead of 3 seconds). The resultant $U_{max}-T_e$ relation is:

$$\Delta U_{max} = 29.2 - 17.8T_e. \quad (13)$$

This approximate relation is also depicted in Fig. 9. Using (13), the maximum allowable speed differentials for the driver-based (with $T_e = 1$ second) and warning system-based (with $T_e = 0.55$ seconds) scenarios are now 11.4 and 19.4 km/hr, respectively. Hence, for a cautious driver, if the POV is approaching the SV with a AU of 11 km/hr, a collision will not result even if the driver is not aided by a collision warning system. These analyses indicate that, from the view point of averting a lane change collision, it is advisable to make a lane change as '(cautiously)' as the traffic permits.

The variations of the terminal lateral displacements with ΔU . For a range of " T_e " values, are given in Fig. 8. Looking at the curve with a detection time of 0.4 seconds, we note that the larger the speed differential ΔU , the smaller is the terminal lateral displacement. The same trend is also observed in results obtained for all other detection times. Note also that in all cases the terminal lateral displacements are always less than $D - W$ ($= 1.6$ meters, see (10)). This ensures that the SV and POV do not collide at the end time of the lane change maneuver.

Summary and Caveats

This study addressed the performance of driver-vehicle systems in shorted lane change maneuvers. An optimization problem was formulated to allow us to analytically assess whether an experienced driver can successfully avert a lane change crash if he responded to the threat T_e seconds after the initiation of the lane change maneuver. Results obtained in this study can be used to quantify how fast a collision detection and warning system must work in order to be effective. However, note that the present study assumed that the SV was traveling at a constant longitudinal speed throughout the entire lane change maneuver. The potential benefit of using longitudinal acceleration (or deceleration) in the evasive maneuver was not considered in this study. Similarly, we assumed that the POV driver did not make any complementary crash avoidance control maneuvers (such as braking). Hence, "results obtained are for the 'worst case' scenario we used in this study". Accordingly, a lane change crash predicted by this study might not happen if, for example, the POV driver brakes and slows down his vehicle.

In some situations, the POV'S speed might be so fast that it is unlikely that the SV driver can avert a lane change crash on his own. In these situations, it becomes necessary for the collision avoidance system to detect, warn, and even assume temporary (and partial) control of the vehicle in order to avert the crash. A coordinated control of the vehicle's steering, braking, and throttling is likely needed in these emergencies, together with a capability to generate an optimal

evasive trajectory on-board. This is an interesting research topic for future study.

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References

1. Wang, J.S. and Knipling, R. R., "Lane Change/Merge Crashes Problem Size Assessment and Statistical Descriptions," DOT HS 808075, Final Report, January 1994.
2. Chovan, J. D., Tijerian, L., Alexander, G., and Hendricks, D. L., "Examination of Lane Change Crashes and Potential IVHS counter-measures," DOT HS 808071, DOT-VNTSC-NHTSA-93-2, Final Report, March 1994.
3. Lee, A. Y., "Vehicle Stability Augmentation Systems Designs for Four Wheel Steering Vehicles," ASME Journal of Dynamical Systems, Measurements and Control, Vol. 112, No. 3, pps. 489-495, September 1990.
4. Maeda, T., Irie, N., Hidaka, K., and Nishimura, H., "Performance of Driver-Vehicle System in Emergency Avoidance," SAE 770130, 1977.
5. MacAdam, C. C., "Development of Driver-Vehicle Steering Interaction Models for Dynamic Analysis," US Army Tank-Automotive Command RD&E Center Technical Report No. 13437, December 1988.
6. Lee, A. Y., "Performance of Four-wheel-steering Vehicles in Lane Change Maneuvers," SAE 950316. See also SP-1074, "New Developments in Vehicle Dynamics, Simulation, and Suspension Systems," pp. 161-174, 1995.
7. Lee, A. Y. and Bryson, A. E., Jr., "Neighboring Extremals of Dynamic Optimization

Problems with Parameter Variations," Optimal Control Applications and Methods, Vol. 10, pps. 39-52, 1989.

8. Lee, A. Y., "Dynamic Optimization Problems with Bounded Terminal Conditions," Journal of Optimization Theory and Applications, Vol. 52, No. 1, January 1987.
9. Okabayashi, S., Sakata, M., Fukano, J., and Daidoji, S., "Development of Practical Heads-up Display for Production Vehicle Application," SAE 890559, 1989.
10. Allen, R. W., "Stability and Performance Analysis of Automobile Driver Steering Control," SAE 820300, 1982.

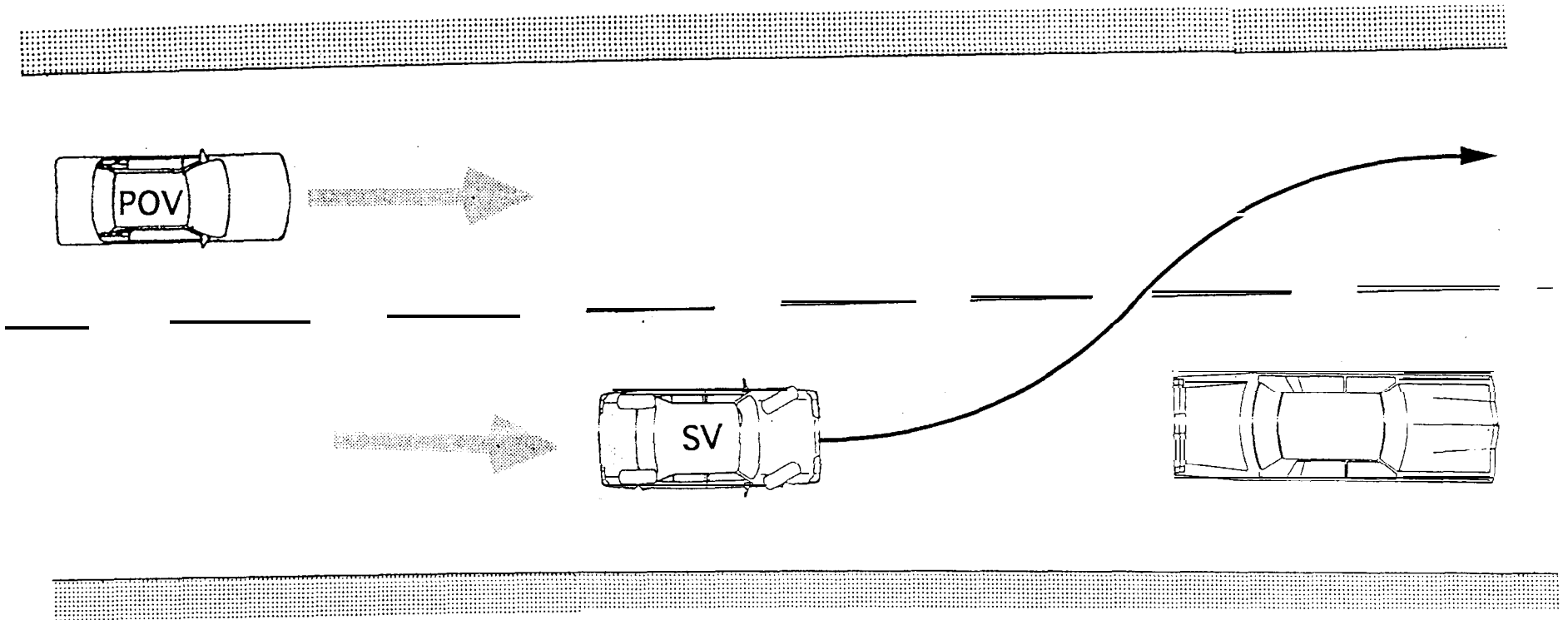


Fig. 1 A lane change crash scenario

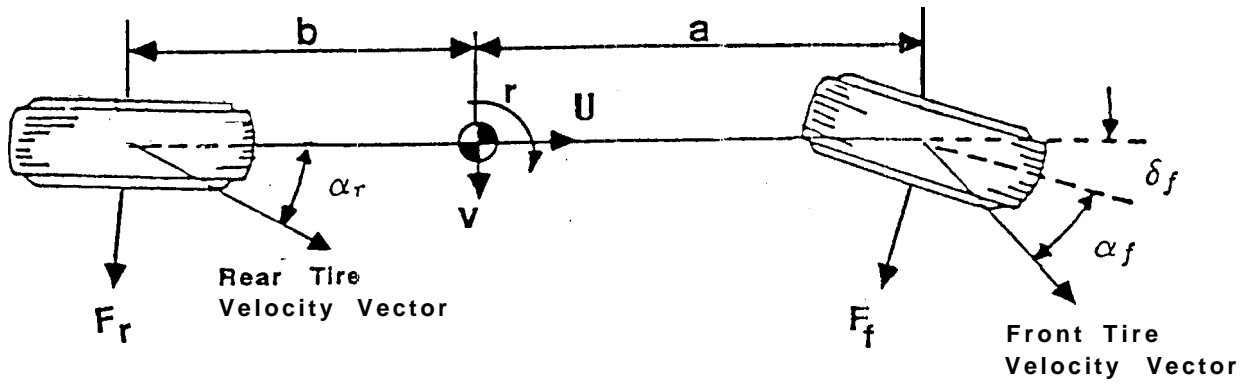


Fig. 2 Schematic of a vehicle handling model

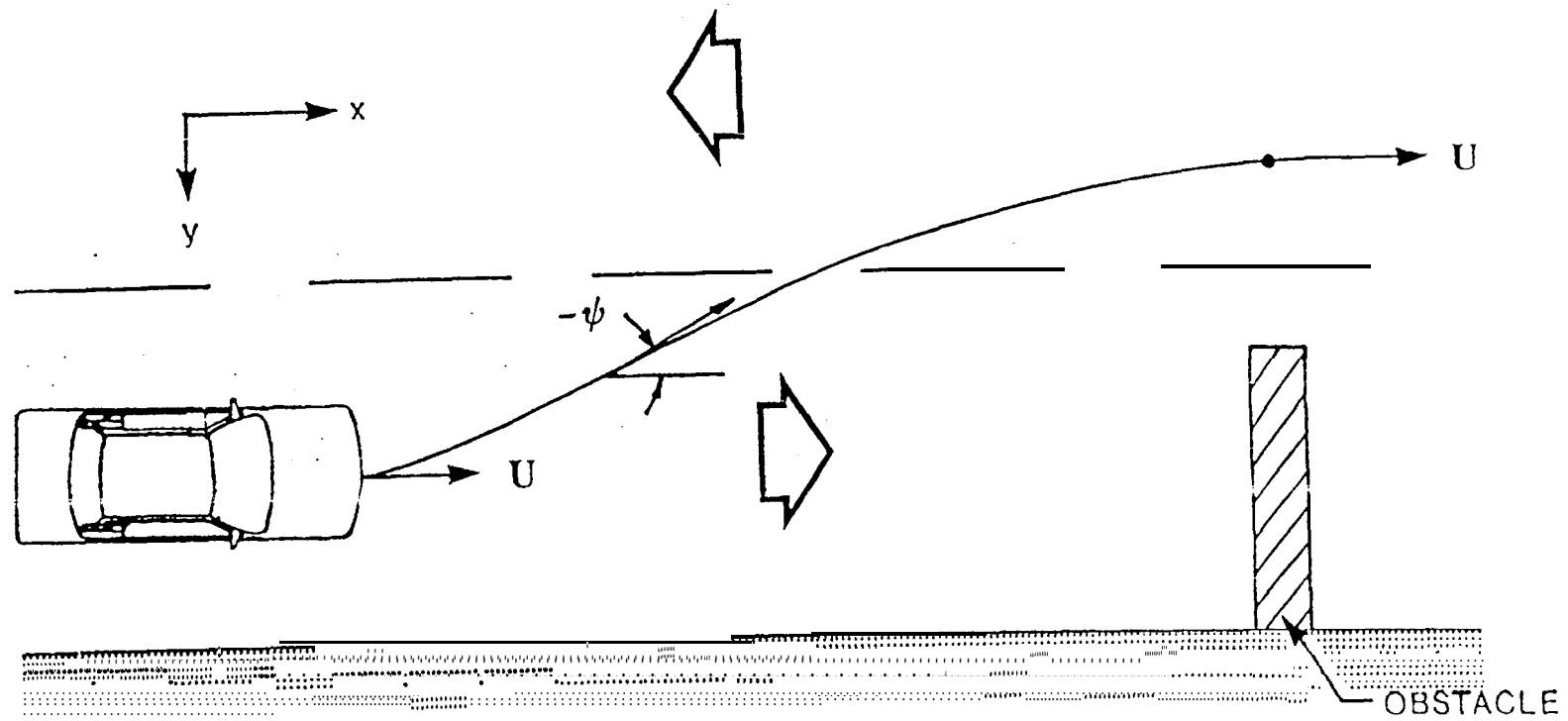


Fig. 3 Schematic of an accident-avoidance lane change maneuver

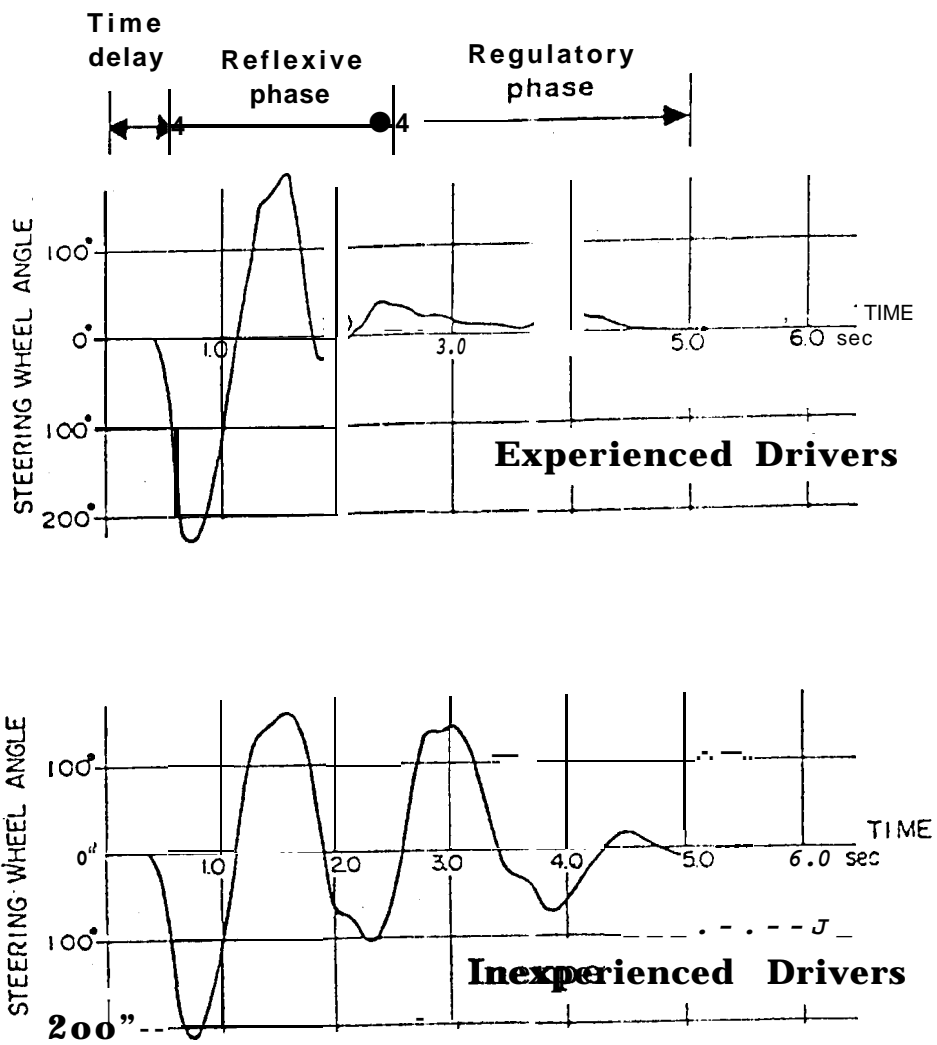
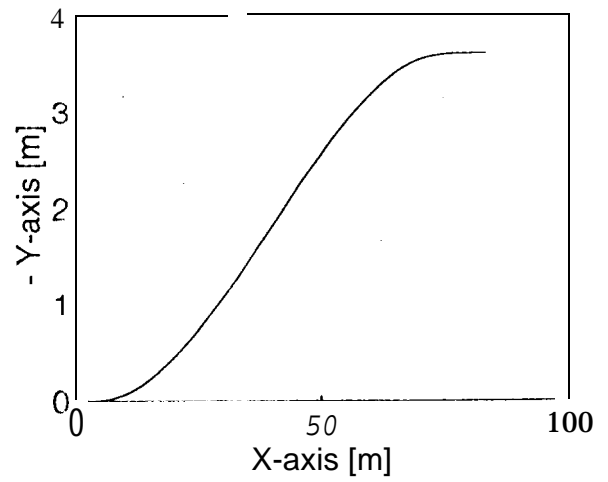
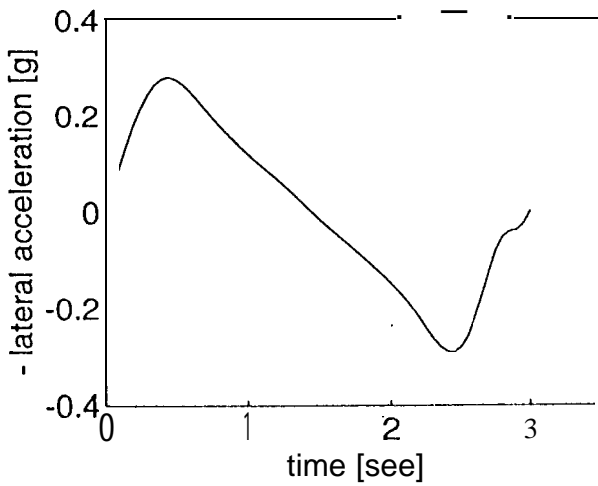
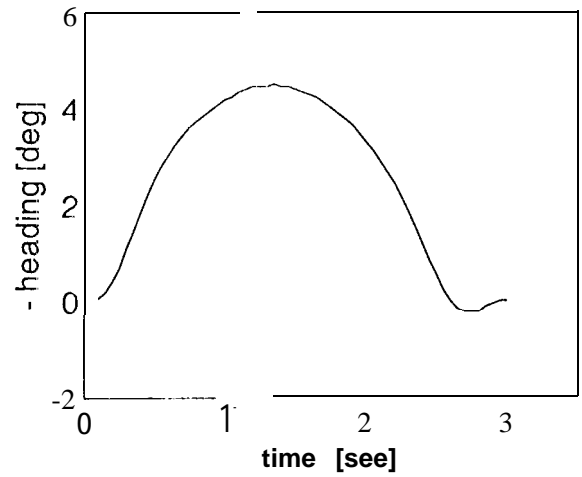
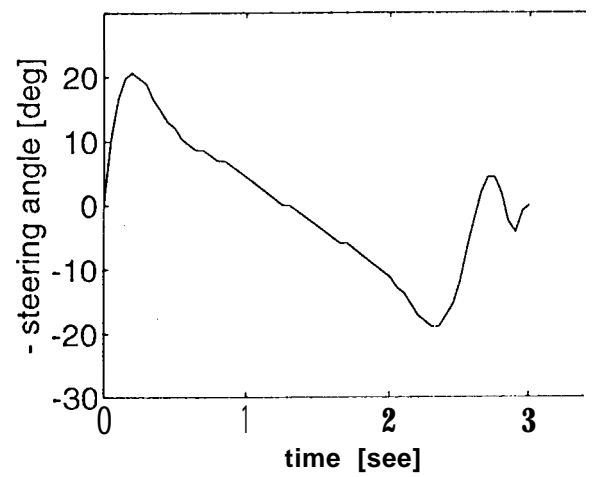


Fig. 4 Recorded steering time histories in a lane change [4]

Fig. 5 Computed time histories of vehicle variables in a lane change



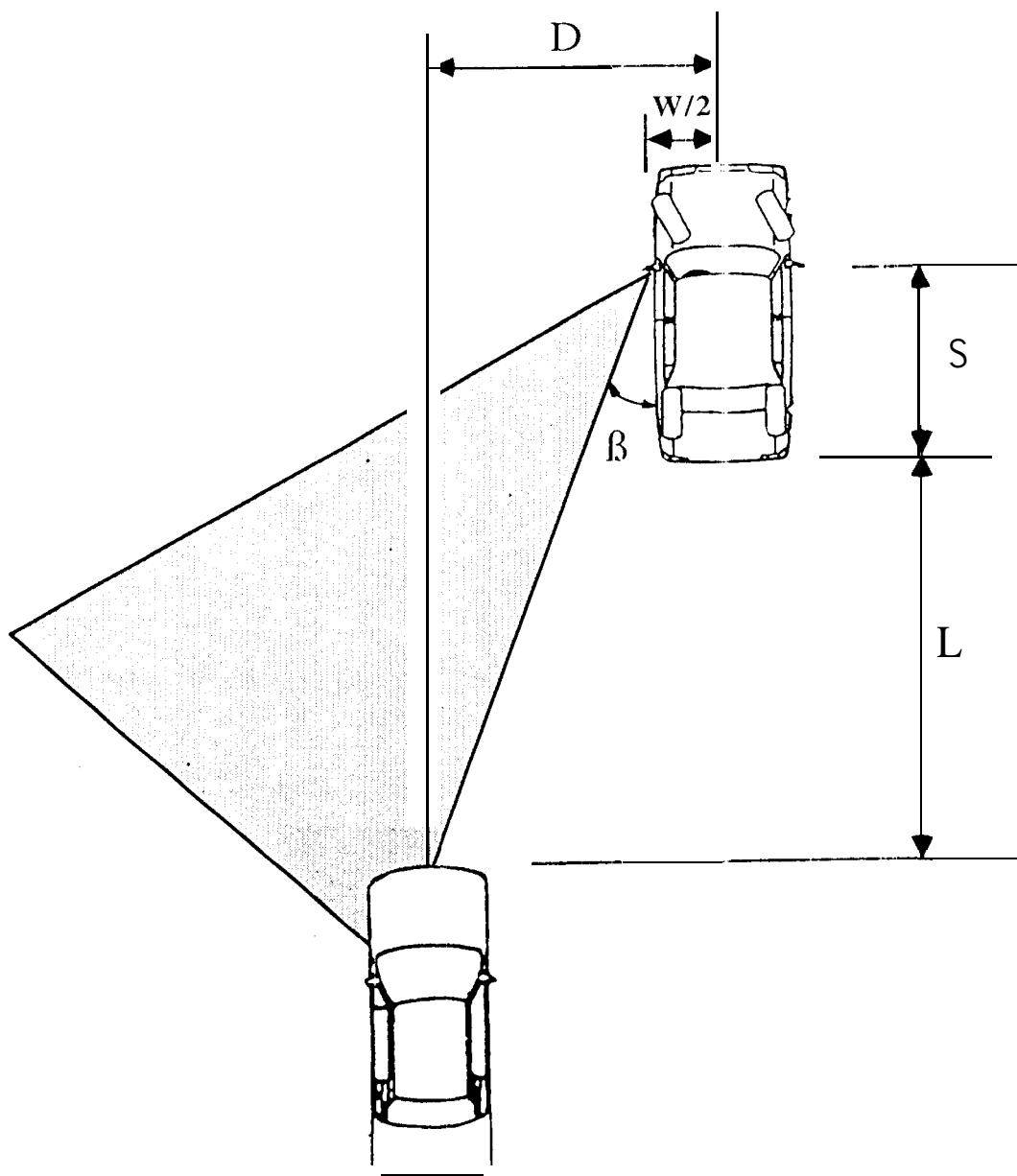


Fig. 6 SV initiates a lane change not knowing that the POV is inside its blind zone

Fig, 7 Variations of Cost Functional with Speed Differential

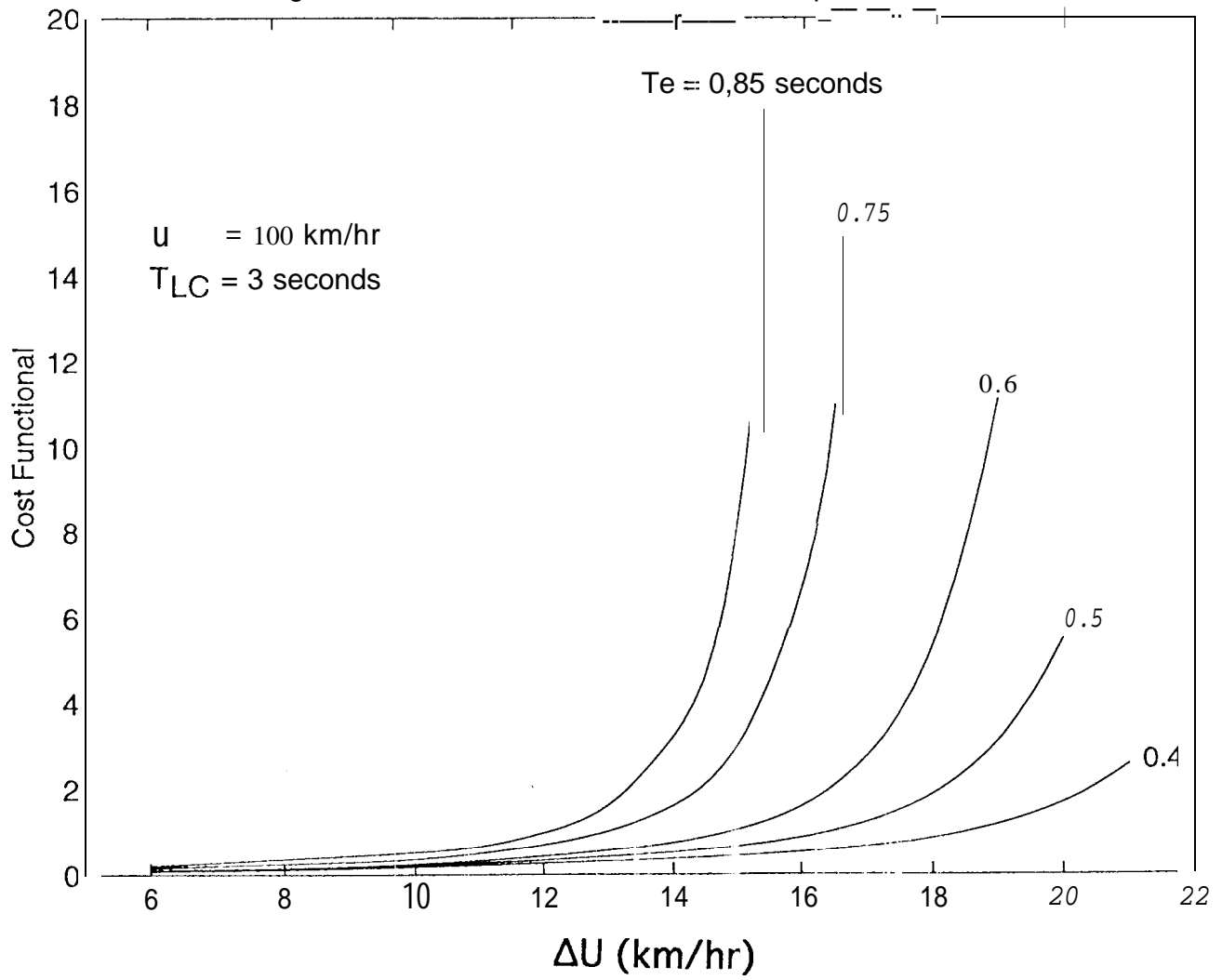


Fig. 8 Variations of Terminal Lateral Displacement with Speed Differential

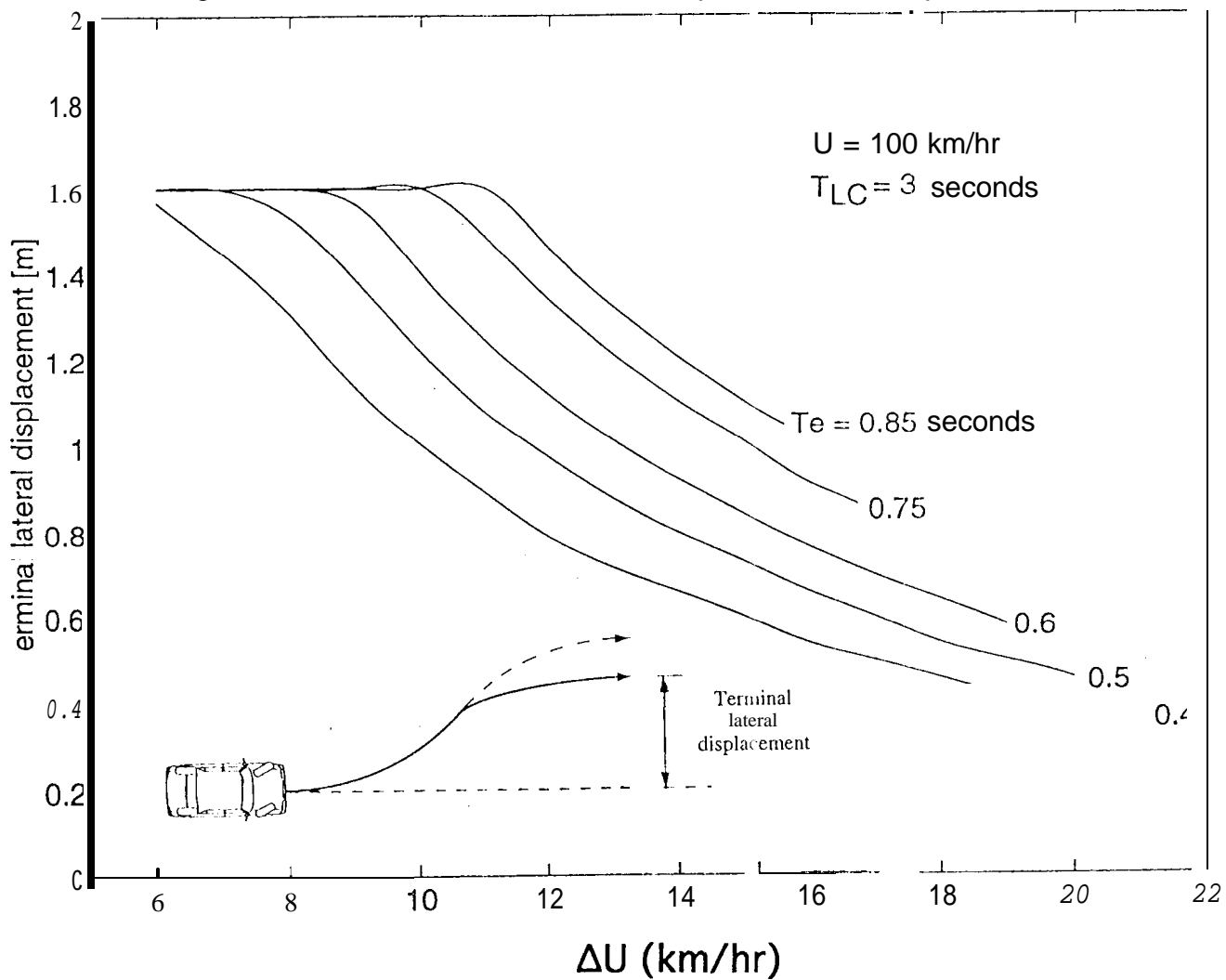


Fig. 9 Variations of Maximum Allowable Speed Differential with Detection Time

