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Analysis of Driver's Lane Change and Turning Behavior on Urban Highways and Street Intersections

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A Thesis in the Faculty

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for the Degree of Master of Engineering

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ABSTRACT

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Analysis of Driver's Lane Change and Turning Behavior on Urban Highways and Street Intersections

SHIV KUMAR VERMA

This study includes i) an analysis of driver's lane change and signaling behavior on urban highways and, ii) an analysis of driver's signaling behavior while turning at signalized intersections.

Analysis of lane change and signaling behavior on urban highways includes development of a mathematical model to depict the safe lane change (SLC) distance between the turning vehicle and following vehicles (in same and in adjacent lanes) on urban highways. The model includes two equations for computing SLC distances at different speeds for different perception-reaction times. Driver's lane change behavior is divided into three zones: safe zone, acceptable zone, and risk zone. This study also explores the importance of signaling as well as the appropriate signaling time before a driver starts turning to make a lane change. Field data were collected to analyze the actual driver performance on a given urban expressway with the help of the proposed model.

Analysis of driver's behavior while turning at signalized intersections includes the statistical and theoretical analysis of driver's signaling behavior. Statistical analysis examines factors such as sex, age, light phase, queue position, type of car, number of passengers, presence of pedestrians, the lane turned to, and hour of the day using one way analysis of variance at 90 % confidence level. Theoretical analysis of signaling behavior was carried out taking the speed of the vehicle as a major factor. Field data were collected and compared with the theoretical results. The results obtained give recommendations to improve the law regarding signaling distance given in the driver's handbook of the province of New Brunswick and other provinces of Canada.

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ABBREVIATIONS

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D_{1B} = Distance travelled by vehicle B while vehicle A travels from position 1 to position 2.

D_{2B} = Distance between vehicles A and B when A enters the adjacent lane(During moment 2).

D_{1C} = Distance travelled by vehicle C while vehicle A travels from position 1 to position 2.

D_{2C} = Distance between vehicles A and C when A enters the adjacent lane (During moment 2).

D_{3C} = Distance travelled by vehicle C while vehicle A travels from position 2 to position 3.

D_{4C} = Distance between vehicles A and C when A completes the maneuver.

D_{4C} = Distance between vehicles A and C when A completes the maneuver.

D_{4C} = Distance between vehicles A and C when A completes the maneuver.

D_S = Minimum required signaling distance.

D_{S1} = Minimum required signaling distance for left turns during the green the light phase.

D_{S2} = Minimum required signaling distance for right turns during the green light phase.

D_{S3} = Minimum required signaling distance for left as well as right turns during red light phase.

F = F - Test ratio.

f = Coefficient of friction.

g = Acceleration of gravity.

L = Horizontal distance travelled by vehicle A between positions 1 and 2 or between positions 2 and 3.

P = Probability.

R = Radius of curve.

t = Time taken by vehicles to travel distance X (given below).

T_S = Signaling Time.

V = Speed of the vehicle on urban highways. Also this is speed of the vehicle while crossing the stop line at an intersection.

V_0 = Initial speed of the vehicle at the moment it starts decelerating.

Vmax = Maximum speed a vehicle can have while turning into an intersection.

W = Weight of the cars.

X = Distance travelled by the vehicle from the moment it starts decelerating to the moment it starts turning into an intersection.

X_B = SLC distance between vehicles A and B when A starts the maneuver.

X_C = SLC distance between vehicles A and C when A starts the maneuver.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

CHAPTER I

CHAPTER I

INTRODUCTION

Background

Since the beginning of the 20th century about three million people have lost their lives on roadways in the U.S. alone, and many millions more have suffered injuries. As population increases, traffic activities and accidents increase as well. Accident records generated so far clearly indicate the magnitude of the problem on highways, roads, and intersections. Most of the traffic accidents are caused due to driver's improper behavior. On a TV serial known as "At the Wheel" was shown by CBC (July, 1987) regarding the causes of traffic accidents. It was found that 90 % of the accidents occur due to human errors.

There are about 160-180 million licenced drivers in North America, but because of the markedly different licence standards among the Provinces or States, there is a little homogeneity in the driving ability of these drivers. Most drivers received no formal training, and those who did, received very little. By far the bulk of driving skill has been learned on a trial and error basis. This means that the street facilities must accomodate all levels of competence, ranging from beginners to the most experienced skillful drivers. Therefore, it is clear that adequate communication is required among the drivers on the roads, so that drivers with less than average skills and strength can successfully accomplish the maneuvers they wish to perform.

Recently, the controversial issue of changing the speed limit from 55 mph to 65 mph has been approved in the U.S. federal legislature. This new speed limit is slightly higher than the Canadian speed limit which is 100 km/hr or 62.5 mph. However, many states in the U.S. still maintain the same speed limit of 55 mph because of safety reasons. With a larger speed limit, the time provided for drivers to react to a potentially hazardous situation will be reduced. Consequently, the risk of accidents for road users could be significantly increased.

Lane change movements, particularly on urban highways,and turning movements at intersections might be the most frequent maneuvers with the risk of collision. In order to complete the maneuvers safely, the drivers must clearly show their intentions to the surrounding drivers. Similarly not only signaling prior to make turn or while changing lane an important safety practice, but also it is required by law in all provinces in Canada. However, communication among drivers is difficult because they are isolated inside the body of the vehicle. Concerning the communication among the drivers, vehicle signals are the only source of information available to other drivers about the driver's intentions. Therefore, proper lane change movements on urban highways and proper signaling while turning at street intersections can be considered important behavior of drivers.

Literature Review

The overview of the previous research on driver's lane change and signaling behavior on urban highways and drivers signaling behavior while turning at intersections indicates that relatively little research has been done on this topic. A computer search was performed by using the Transportation Research Information Service (TRIS) system. Also a manual search was conducted using the Psychological Abstracts containing all material published in the last ten years.

Jamieson (1977) found that in general women yielded the right of way more often than men and there was a gender- related interaction between the two drivers facing each other. That is women generally yielded the right of way more often to male drivers than to female drivers. Barach, Trumbo, and Nangle (1957) examined driver's signaling behavior including signaling or not, the direction of turn, presence of another car and sex of driver. They found that the drivers signaled more often when the preceding car signaled. They also found no sex related differences among drivers. Since this study was conducted in 1957, many of the results obtained may not hold up today, due to present day changed traffic conditions.

Bristow, Kirwan and, Taylor (1982) classified drivers into two categories; safe and unsafe. They further classified unsafe drivers into "dissociative active" and "dissociative passive" based on their overtaking behavior and whether they made use of mirrors. In addition, Papacostas (1984) examined the signaling behavior of drivers and its effect on the following driver's lane lane choice. This study showed that a considerable number of left turners failed to indicate their turns, this had a significant effect on the following through vehicles. Also, lane change choice was affected by both the merging lane on the far right side and the traffic signal phase.

The results of the literature review indicate that no previously published paper has studied the topic of driver's lane change behavior and signaling behavior on urban highways.Those who conducted a study on signaling behavior concentrated only on the use or non-use of signals and its effects on drivers.

Need for Study

The fatal accident reports from the National Highway Traffic Safety Administration [Transportation and Traffic Engineering Handbook, 2nd Ed., 1982] indicate that improper driving is one of the dominating factors causing accidents. Inadequate and improper lane change and signaling behavior are major parts of improper driving. A study on driver's lane change behavior on urban highways and driver's signaling behavior at intersections was needed because there are two major problems. These are listed below:

i) Vague information in the Driver's Handbook:

The traffic manuals of 9 provinces in Canada state that drivers must anticipate the potentially dangerous moves of other motorists and adjust their own speeds to maintain *a sufficient distance* to be able to perform the necessary safety maneuvers. They also state that "the driver should signal for a sufficient distance to show his (or her) intentions before making any move[Drivers Handbook, 1983]. However,*a sufficient distance* is a considerably vague term for it can mean different distances for different drivers. In the Province of New Brunswick the law regarding signaling states that "the drivers must signal continously for at least the last hundred feet travelled" ("Motor Vehicle Act", 1973). This is an improvement over the regulations in the other Provinces as this is less vague. But this statement may be true only for vehicles travelling at low speeds. At a high speeds, 100 feet will be covered in a short time not giving other drivers enough time to perceive the situation.

ii) No published articles provide information about safe lane change and signaling distances:

As discussed previously, a study carried out on the published articles on driver's safe lane change and signaling distances shows that they have not been given adequate attention as yet. Also results of literature review indicate that the correct signaling distance before making a turn is still unknown.

Objectives and Scope

Due to high traffic volume urban highways and street-intersections are important places concerning the movements of the drivers. This study has been divided into two major parts to understand the drivers' behavior and to provide recommendations to improve safety for all road users. First part deals with the driver's lane change and signaling behavior on urban highways, and the second part deals with the driver's signaling behavior while turning at signalized intersections. Because of the high speeds of the vehicles and the continous flow of the trafiic, lane changes are the most critical movements on urban highways. Proper signaling is also important, but only required while changing the lanes. On the other hand on urban streets the lane change maneuvers are not as critical as on urban highways because of the lower speeds of the vehicles and because of the small sections between the street intersections. But turning into an intersection is a critical maneuver on streets due to the interrupted traffic flow, opposing traffic, and pedestrians crossing the streets. Therefore, proper signaling time or signaling distanc prior to making a turn is important to show intentions to other road users. Since, the traffic situation on urban highways is different from the traffic situation on the street intersections, these two major parts of the study were analyzed using different methodologies.

The major objective of this study is to understand driver's behavior so that safety measures can be applied to reduce the risk of accidents on urban highways and street intersections.

The specific objectives of the analysis of driver's behavior on urban highways are:

i) to identify problems and needs associated with driver's lane change and signaling behavior;
ii) to determine the safe lane change distance between turning and following vehicles at different speed levels with variation in perception-reaction time, and
iii) to calculate the appropriate time to signal while changing lanes.

The specific objectives of the analysis of driver's behavior on street intersections are:

i) to identify the effect of factors such as sex, age, number of passengers in the vehicle, light phase, queue position, etc. on driver's signaling behavior while turning at signalized intersections, and

ii) to find appropriate signaling distance before turning into an intersection while making a right or left turn considering all the factors mentioned above.

This study concentrates only on urban highways and signalized intersections. Urban highways in this study are highways across the urban area used mainly by commuters. These highways usually have high variation in vehicle speeds and traffic volumes during different hours. The intersections which are controlled by stop or yield signs are not included in this study. Signalized intersections probably represent the most important location of accidents in urban streets due to improper signaling. This is because two or more streets share the same space of an intersection, and there are a several conflicts generated by different traffic movements.

CHAPTER II

CHAPTER II

ANALYSIS OF LANE CHANGE AND SIGNALING BEHAVIOR ON URBAN HIGHWAYS

2.1 DEVELOPMENT OF A SAFE-LANE-CHANGE DISTANCE MODEL

Assumptions and Definitions

In order to develop a realistic and solvable model of the driver's lane change behavior, three assumptions are made. The assumptions are listed below:

1. Vehicles are travelling about the centre of the lanes;
2. The lane change maneuver consists of two simple circular curves of the same radius (there might be a small linear segment between the curves which is neglected for simplification); and,
3. The speeds of turning and the following vehicles remains constant for a short time during lane change maneuver (i.e.from the moment turning vehicle starts to make lane change to the moment it completes the lane change).

There are three definitions used for this study.They are:

1. Turning Vehicle: A turning vehicle is one which is making a lane change movement to its adjacent (left or right) lane.
2. Following Vehicle: A following vehicle is one which is following the turning vehicle in the same lane, or in the adjacent lane into which the turning vehicle is entering.
3. Safe Lane Change Distance (called "SLC distance" below) : The minimum distance between the turning and the following vehicle at the beginning of the lane change maneuver, so that the turning vehicle can enter the adjacent lane and complete the maneuver safely.

Definition of Variables

The model is developed considering three vehicles in two lanes as shown in Figure1. Vehicle "A" is the turning vehicle, vehicles "B" and "C" are the following vehicles in the same and in the adjacent lane, respectively.

Whenever a vehicle wants to make a lane change under normal traffic conditions, it is affected mainly by the vehicles following it and less by those ahead of it. This is because the drivers can judge the gap distance more accurately and can react to any change in situation quicker for the vehicles ahead of them than for the vehicles behind them. Therefore, a simple and common case involving three vehicles is considered.

The lane change maneuver of vehicle A is divided into three key moments as shown in Figure1.

These are:

1. The moment vehicle A starts turning;
2. The moment vehicle A just enters the adjacent lane with half of its body in the same lane and half in the adjacent lane; and,
3. The moment vehicle A completes the maneuver.

Figure1 also depicts the expected relative positions of the vehicles during the maneuver from position 1 to position 3.

Variables shown in Figure 1 are defined as follows:

x_B = SLC distance between vehicles A and B when A starts the maneuver.

x_C = SLC distance between vehicles A and C when A starts the maneuver.

D_{1B} = Distance travelled by vehicle B while vehicle A travels from position 1 to position 2.

D_{1C} = Distance travelled by vehicle C while vehicle A travels from position 1 to position 2.

D_{2B} = Distance between vehicles A and B when A enters the adjacent lane (During moment 2).

D_{2C} = Distance between vehicles A and C when A enters the adjacent lane (During moment 2).

D_{3C} = Distance travelled by vehicle C while vehicle A travels from position 2 to 3.

D_{4C} = Distance between vehicles A and C when A completes the maneuver.

L = Horizontal distance travelled by vehicle A between positions 1 and 2 or between positions 2 and 3.

The line of action of vehicle A during the lane change maneuver is shown in Figure 2 from position 1 through position 3.

Because of the assumptions listed previously, the line of action includes two simple circular curves only. On a level road, only the side friction force between the tires and the road is taken into consideration. The path adopted by the vehicle should be such that the centrifugal force and the friction force counterbalance to avoid any danger of skidding. On the verge of skidding,

Centrifugal force = friction force

$$\frac{WV^2}{gR} = Wf$$

OR

$$R = \frac{V^2}{gf}$$

where g = acceleration of gravity (9.8 m/sec^2 or 32.2 ft/sec^2);

f = coefficient of friction ;

W = weight of the cars (newtons or lbs);

V = Velocity of the vehicle (km/hr);and

R = radius of curve (meters or feet).

Thus,

$$R=\frac{V^2}{127f}\ , \text{ R in meters, V in km/hr.} \tag{1}$$

Therefore, the safe curved path travelled by a vehicle with velocity V should be of radius R.

From Fig. 2.

M = One half of the lane width.

L_C = Length of the curve

Therefore, $$L = \sqrt{R^2 - (R - M)^2} \tag{2}$$

The approximate length of the curve can be taken as:

$$L_C \approx \sqrt{L^2 + M^2} \tag{3}$$

From (2) and (3)

$$L_C \approx \sqrt{R^2 - (R - M)^2 + M^2}$$

Simplifying above equation

$$L_C \approx \sqrt{2RM} \tag{4}$$

<u>SLC Distance Between vehicles A and B</u>

From Fig. 1:

$$X_B = D_{1B} + D_{2B} - L$$

D_{1B} is the distance travelled by vehicle B while vehicle A travels from position 1 to 2 .

Therefore $\dot{D}_{1B} \doteq V_B \cdot \frac{\sqrt{2RM}}{V_A}$ (5)

where V_B = Velocity of vehicle B;

V_A = Velocity of vehicle A ; and,

$\frac{\sqrt{2RM}}{V_A}$ = Time taken by vehicle A from position 1 to position 2 ,

D_{2B} is the gap between vehicles B and A when vehicle A just enters the adjacent lane. The gap should be such that B can make judgement and have sufficient time to avoid any collision. Therefore, the gap should be a minimum distance equal to the perception-reaction distance.

Therefore $D_{2B} = V_B \cdot t$ (6)

where t = perception-reaction time for driver B.

From Equation (2),

$$L = \sqrt{R^2 - (R - M)^2} \tag{7}$$

Combining (5), (6), (7) into the equation for X_B

$$X_B = V_B \cdot \frac{\sqrt{2RM}}{V_A} + V_B \cdot t - \sqrt{R^2 - (R - M)^2} \tag{8}$$

Simplifying (8)

$$X_B = \frac{V_B}{V_A}\sqrt{2RM} + V_B \cdot t - \sqrt{2RM - M^2} \tag{9}$$

Since M^2 is relatively small as compared to 2RM ,

the magnitude of $\sqrt{2RM}$ and $\sqrt{2RM - M^2}$ are approximately the same.

Letting $K = \sqrt{2RM} = \sqrt{2RM - M^2}$

Equation (9) becomes

$$X_B = (\frac{V_B}{V_A} - 1) K + V_B \cdot t \tag{10}$$

Using the minimum safe radius, R, from Equation (1),an average lane width (w) of 3.64m (or 12ft.) and a coefficient of friction (f),

$$K = \sqrt{2RM} = \sqrt{2 \cdot \frac{V_A^2}{127 \cdot f} \cdot \frac{w}{2}}$$

i. e.

$$K = 0.170 \frac{V_A}{\sqrt{f}}$$

Thus,the SLC distance between vehicles A and B can be calculated as

$$X_B = 0.170 \frac{V_A}{\sqrt{f}} (\frac{V_B}{V_A} - 1) + V_B \cdot t \quad , X_B \text{ in meters and } V_B, V_A \text{ in km/h} \tag{11}$$

<u>SLC Distance Between Vehicles A and C</u>

It is necessary to derive separate equations for X_B and X_C, because the effects of a lane change movement in both cases are different. As shown in Figure 1, when vehicle A starts the lane change maneuver, vehicle B is concerned for safety, only while vehicle A is in the same lane. Once vehicle A enters the adjacent lane, vehicle B has less danger. But for vehicle C, the safety problem starts once vehicle A enters that lane. Vehicle A is out of the picture for vehicle B once vehicle A enters the adjacent lane, but in the adjacent lane, vehicle A is entering and joining the traffic stream. Therefore, the situation for vehicle C becomes different from that of vehicle B.

To determine the SLC distance between vehicles A and C, from Figure 1

$$X_C = D_{1C} + D_{2C} - L$$

also

$$D_{2C} = D_{3C} + D_{4C} - L$$

so

$$X_C = D_{1C} + D_{3C} + D_{4C} - 2L \qquad (12)$$

D_{1C} and D_{3C} can be determined in the same way as D_{1B} and D_{2B}.

Therefore $$D_{1C} = V_C \cdot \frac{\sqrt{2RM}}{V_A} \qquad (13)$$

also $$D_{3C} = V_C \cdot \frac{\sqrt{2RM}}{V_A} \qquad (14)$$

As it is assumed that both curves in Figure1 are of the same radius and length.

The moment vehicle A finishes the lane change maneuver, the gap between vehicles C and A should still be sufficiently wide so that even if vehicle A takes some emergency action, vehicle C would perceive and react to the situation. Therefore, the gap D_{4C} should be a minimum distance equal to the perception-reaction distance.

Therefore $$D_{4C} = V_C \cdot t \qquad (15)$$

Where

V_C = Velocity of vehicle C ; and,

t = Perception-reaction time for driver C .

Putting Equations (13), (14), (15) into Equation (12)

$$X_C = 2\ V_C \cdot \frac{\sqrt{2RM}}{V_A} + V_C \cdot t - 2L$$

or
$$X_C = 2\frac{V_C}{V_A}\sqrt{2RM} + V_C \cdot t - 2\sqrt{2RM - M^2}$$

As discussed previously, $K = \sqrt{2RM} = \sqrt{2RM - M^2} = 0.170\frac{V_A}{\sqrt{f}}$

$$X_C = 2\left(\frac{V_C}{V_A} - 1\right)K + V_C \cdot t \tag{16}$$

Thus, the SLC distance between vhicle A and C can be calculated as

$$X_C = 0.340\frac{V_A}{\sqrt{f}}\left(\frac{V_C}{V_A} - 1\right) + V_C \cdot t\ , \quad X_C \text{ in meters and } V_C, V_A \text{ in km/hr} \tag{17}$$

<u>Discussion</u>

In order to gain insight into Equation (11) and (17), three cases when $V_B = V_C$, at a constant f value are demonstrated below:

<u>Case 1</u>: $V_B = V_C > V_A$

Thus, $\frac{V_B}{V_A} = \frac{V_C}{V_A} > 1$

From Equations (11) and (17), we can derive the following inequality:

$$X_C > X_B \tag{18}$$

This inequality indicates that the minimal gap between vehicles A and C should be greater than that between vehicles A and B in order for vehicle A to complete the lane change maneuver safely. Therefore, when the speeds of both following vehicles are higher than the speed of the turning vehicle, X_C is more critical than X_B.

Case 2: $V_B = V_C = V_A$

Thus, $\dfrac{V_B}{V_A} = \dfrac{V_C}{V_A} = 1$

Also, $\left(\dfrac{V_B}{V_A} - 1\right) = \left(\dfrac{V_C}{V_A} - 1\right) = 0$

Hence,

$$X_B = X_C = V_B \cdot t = V_C \cdot t = \text{perception -reaction distance} \quad (19)$$

This case explains that as long as gaps X_B and X_C are equal to or larger than the perception-reaction distance, the lane change maneuver is safe.

Case 3: $V_B = V_C < V_A$

Thus, $\dfrac{V_B}{V_A} = \dfrac{V_C}{V_A} < 1$

So, $\left(\dfrac{V_B}{V_A} - 1\right) = \left(\dfrac{V_C}{V_A} - 1\right) < 0$

In the case that X_B or X_C might be negative,which indicates that in this case vehicle A can change lanes safely without any trouble.

Hence,when $X_B \geqslant 0$ and $X_C \geqslant 0$,

$$X_C < X_B < \text{perception-reaction distance} \quad (20)$$

In practice,vehicle A can complete the maneuver safely when $V_B = V_C < V_A$ ($X_B \geqslant 0, X_C \geqslant 0$) is true. However, vehicle A should still travel a greater distance along the curve as compared to straight line distance travelled by vehicles B and C in order to maintain a small gap in case of any unexpected emergency.

2.2 ANALYSIS OF THE MODEL

Variation of Side Friction Value

Coefficient of friction f depends mainly upon speed of the vehicle,condition of tires and roadway surface.The coefficient of friction has been found to decrease with increasing initial speed. At high speeds and on a wet surface, variation in f is very small . As a rule of thumb, f is approximately equal to 0.6 when the pavement is dry and about 0.3 when the pavement is wet[Papacostas, 1987].

It can be noticed from equations (11) and (17) that the SLC distance is inversely proportional to square root of f. Since the value of f depends upon vehicle speed, the variation of SLC distance with f value leads to the fact that a larger value of SLC distance is required at higher speeds than at lower speeds.

Variation of Perception-Reaction Time (Called" P-R Time" below)

Under average driving conditions the P-R time is generally taken as 1.5 sec.[Papacostas, 1984].The P-R time varies from driver to driver depending upon age, sex and other factors. But on urban highways inside the city, the drivers are under a lot of pressure during rush hours. The average P-R time during these times is a fraction of a second[Toates, 1972]. But for design purposes, taking into account the factor of safety, the average minimum P-R time is taken as 1.0 sec.[Chan and Thomas, 1987].

In this model, 1.5 and 1.0 sec. are taken as the two limits of the P-R time. Below 1.0 sec. the driver is classified as an 'quick driver'; and above 1.5 sec., the driver is classified as a 'slow driver'; between 1.0 sec. and 1.5 sec., the driver is a 'average driver'. Graphs are drawn depending upon these values of P-R time and taking into consideration the speed of the following vehicles B and C i.e. V_B equal to $0.9V_A$, $1.0V_A$, and $1.1V_A$ as well as V_C equal to $0.9V_A$, $1.0V_A$, and $1.1V_A$, respectively as shown in Figure 3 to Figure 8. The figures are drawn taking average lane width of 3.64 meters (12 ft.), coefficient of friction f=0.30 (under wet conditions).

Effect of Perception-Reaction Time

In Figure 3 through Figure 8, the lower line and upper line are drawn using a P-R time of 1.0 and 1.5 sec., respectively. These two lines divide each graph into three zones.Three zones have been identified as shown in the figures in each category. The three zones are:

i) Safe zone;

ii) Acceptable zone; and

iii) Risk zone.

The safe zone is the zone above the line that was drawn using a P-R time of 1.5 sec. The gaps between the lead and the following vehicle within this zone are large. These gaps will provide the driver of the following vehicle (i.e. vehicle B or C) with at least 1.5 seconds to perceive and react to the lane change maneuver of the lead vehicle (i.e. vehicle A) at different speeds. Thus,even if the driver of vehicle A does not signal or the driver of vehicle B or C does not perceive the signal before vehicle A starts the lane change movement,there is still time and distance for the driver of vehicle B or C to take proper action to prevent any collision. However, this situation is difficult for drivers to achieve on urban highways, particularly during rush hours.

The acceptable zone is the range between the lines of 1.0 and 1.5 seconds. The gaps within this zone are smaller than those in the safe zone. These gaps provide the driver of vehicle B or C with 1.0 to 1.5 seconds to react to the lane change movement at different speeds. The P-R time of 1.0 to 1.5 seconds is appropriate for drivers on urban highways to take proper action. Thus, if driver A signals for an appropriate length of time before he starts the maneuver, driver B or C should be able to take adequate action to avoid a collision. Hence, any gap within this zone is acceptable for most drivers.

The risk zone is the area below the 1.0 second line. The gaps within this zone are so small that driver A provides driver B or C with less than 1.0 seconds to react to the lane change movement at different speeds. Thus, if driver A does not show his intentions by signaling for an appropriate length of time, there exists a high risk of collision. Hence, quick drivers might fall in this zone, as they make sharp turns.

Sometimes driver A is in the process of completing the lane change maneuver, and then realizes that the distance between his(or her) vehicle and vehicle C is too short to complete the maneuver safely and decides to remain in the same lane. It might be difficult for driver A to return to the same lane because the gap between his(or her) vehicle and vehicle B, at that moment, has become too short to return. At this position the driver can neither continue in the same lane nor change lanes. This can be termed as the "dilemma situation". Such a situation can occur if the lane change movement is carried out in the risk zone.

Need for Appropriate Signaling

The problem just explained above brings up the need for appropriate signaling on highways, particularly for the cases in the risk zone. The model was developed assuming the worst condition, i.e. when the driver does not signal before starting the lane change maneuver.

The use of signals should be such that the following drivers have sufficient time to understand the driver's intentions and can react to the situation accordingly.Therefore, before the driver of vehicle A starts turning, he(or she) should signal for a minimum time equal to the P-R time. For safety consideration, the P-R time in this section is taken as the sum of the P-R time of both drivers B and C .The sum of P-R time is proposed, considering the fact that the drivers in the adjacent lane, far from vehicle A, and coming with high speed, will have adequate time to perceive the situation. Greater P-R time of two drivers with some factor of safety could be taken, but how much safety should be considered, has not been defined.

Thus, the driver should signal for at least the sum of the two P-R times before turning and should signal continuously until the centroid of the vehicle reaches the dividing line between the lanes. Therefore, the minimal signaling time (T_S) before vehicle A starts to turn;

$$T_S = t_B + t_C \text{ sec.} \tag{21}$$

where

t_B = P-R time for driver B; and,

t_C = P-R time for driver C.

Based on the P-R time this study recommends that there can be three cases as explained below:

<u>Case 1</u>: If the driver is in the safe or acceptable zone ,

$$t_B + t_C = 1.0 + 1.0 = 2.0 \text{ seconds.}$$

This means that driver of the vehicle should signal at least 2.0 seconds before starts to turn. In this case, the P-R time for each driver is taken as 1.0 second because the vehicle is already in the safe or the acceptable zone, and it just needs to show the intention of turning.

<u>Case 2</u>: If the driver is in the risk zone and the gap between the turning and the following vehicle is small, the driver should signal continuously until he (or she) gets a sufficient gap to make the turn safely. By signaling continuously, the situation can be changed from the risk zone to the acceptable zone. The reasons are:

i) Vehicles B and C might slow down and provide a longer gap;and,

ii) The P-R time will be reduced to a smaller value because while observing the signals, the perception time of the following drivers (B and C) becomes smaller and only the reaction time will constitute the major part of the P-R time.

Case 3: If the driver is in the risk zone and in a " Must turn" condition, i.e., the driver has to turn (e.g. if driver has to take an exit), then the driver should signal at least ;

$$t_B + t_C = 1.5 + 1.5 = 3.0 \text{ seconds}$$

Normally, driver A should continue signaling until vehicles B and C slow down and provide a gap within the acceptable zone. But if vehicles B and C don't provide a gap then driver A should signal at least for 3.0 seconds. This signaling time will reduce the required P-R time of the following drivers to a smaller value, and hence the risk of accident can be reduced.

2.3 APPLICATIONS OF THE MODEL

Major Applications

The developed model includes Equations (11) and (17) which can be used to determine the SLC distances. The goal of this study is to improve driver's lane change and signaling behavior in order to reduce the risk of highway accidents. The major applications of the developed model are discussed below:

i) Evaluation of Driver's Performance in Lane Change and Signaling Maneuvers.

In order to prevent highway accidents, government authorities can use the developed m~~odel to calcul~~ate the safe lane change distance under current driving situations such as speeds and weather conditions.The actual lane change distance and signaling time of drivers can also be measured on the highway. By the comparisons of actual and safe lane change distance,the percentage of drivers falling into each of three categories--the safe zone,acceptable zone,and risk zone can be obtained. Furthermore, the percentage of drivers did not signal, signaled for insufficient time, and signaled for sufficient time can be calculated.

This study provides an example of data collection and an example of data analysis.They are discussed in details in the next two sections.The purpose of the examples is to illustrate procedure not only for collecting necessary data in the field, but also for analyzing the data.The results of the data analysis will be a good indication to identify the potential risk of accidents due to the driver's lane change and signaling maneuvers at any particular highway or segment of the highway. In addition, the results of the data analysis can also be used for before-and-after study in order to evaluate the effectiveness of any safety improvement project.

ii) Education and Traffic Regulation Enforcement.

Government authorities can use the developed model to create the awareness among drivers about the significant change in SLC distance due to the change in vehicle speed, pavement conditions, and perception-reaction time. For example,Table 1 provides the values of SLC distance between vehicles A and C at different speeds and with variation of coefficient of friction, assuming that vehicle A is turning to the faster traffic lane and V_C is equal to 1.1 V_A. In Table 1, the P-R time of 1.5 second was taken considering the average drivers. From Equations (11) and (17) it can be noticed that in general, SLC distance $X_C > X_B$. From the data collected for the example discussed in the next section, it was observed that the ratios of speeds of most vehicles (i.e.V_B / V_A and V_C / V_A) varied from 1.0 to 1.1.Therefore, for the safety considerations Equation (17) with $V_C / V_A = 1.1$ was used to calculate values given in Table 1. If vehicle A is turning to the slower traffic lane, then the SLC distance values provided in Table 1 could be smaller. However, in order to make a safe lane change at any time, this study recommends, the drivers should assume that the following vehicles are travelling with greater speed or can accelerate any moment.

Also the part of study carried on the signaling behavior suggests that the drivers should signal 2-3 seconds before turning.This rule can be enforced to improve the performance of drivers and hence to improve safety on urban highways.Traffic signs can also be posted indicating the minimum distance, the drivers should keep with other vehicles during wet and dry pavement conditions in order to carry out safe lane change maneuvers.

Example of Data Collection

The data were collected on sections of Decarie expressway between Van Horne and Vezina streets in Montreal, Canada. This Expressway is an open-channel type of urban highway. It is a divided two way highway with three lanes in each direction. A video camera was used to record lane change movements . The video camera was installed on one of the bridges on Van Horne Street. The data were collected during the morning and afternoon non-rush hours, as well as evening rush hours in order to have different levels of vehicle speed.

The following measurements were taken:

i) Distances between the lead vehicle and the following vehicles (in the same and in the adjacent lane) the moment the lead vehicle starts the lane change maneuver;

ii) Velocities of the lead vehicles and the following vehicles;and,

iii) Length of time the lead vehicle signaled before starting the maneuver.

To determine the velocities of the vehicles the simple principle of distance/time was used. The length of the white stripes constituting the dividing line between the two lanes and the gaps between them were measured at the time the data were collected. To determine the velocity, the vehicle is stopped at one point by pausing the videotape using the remote control. At this point, the stop watch and the videotape are started at the same time and paused at another point on the screen. The distance between these two points is calculated by counting the number of white stripes and number of gaps between the white stripes. The time is recorded from the stop watch. In this manner, the velocity of each vehicle can be calculated by dividing the distance by the time. The process is repeated three to four times in order to assure accuracy.

About 300 lane change movements were analyzed from recorded videotapes. The distances measured from vodeo tape recordings were plotted on graphs (Figure 3 to Figure 8) according to the different speed levels. These Figures are graphs plotted between X_B and velocity V_A (Figure 3 to Figure 5), and between X_C and velocity V_A (Figure 6 to Figure 8), respectively.

Example of Data Analysis

Since the model developed in this study is used to analyze the performance of the drivers, therefore, f value was used depending upon the average vehicle speed and surface condition at the time of data collection. At the time of data collection the road surface was wet due to snow and rain, and average speed of vehicle was 70-100 km/hr(appx.45-60 miles/hr), therefore a constant value of f=0.3 was taken.

From the data plotted in Figure 3 to Figure 8, it was found that of the total lane change maneuvers recorded,12% were in the safe zone and 75% were in the acceptable zone. Therefore, out of 300 drivers, 87% made the safe lane change maneuver and 13% made the aggressive or unsafe maneuver. Although, there were no accidents in the field, the potential risk of an accident for these drivers in the risk zone was always present.

Out of 300 vehicles observed, 152 (51%) failed to signal while changing lanes. Of the 49% who signaled, 3.3% signaled for 1.0 sec. or less, 8.3% signaled between 1.0 and 2.0 sec., 3.7% signaled between 2.0 and 3.0 sec. but less then 3.0 sec.,and 33.7% signaled more than 3.0 sec. These data indicate that of the 49% who signaled, 12% failed to signal properly. From the overall observation, it was found that 63% of the drivers did not signal or failed to signal for an appropriate length of time.

CHAPTER III

CHAPTER III

ANALYSIS OF DRIVER'S SIGNALING BEHAVIOR WHILE TURNING AT SIGNALIZED NTERSECTIONS

3.1 STATISTICAL ANALYSIS OF SIGNALING BEHAVIOR

EXPERIMENTAL DESIGN AND DATA COLLECTION

The site selected for this study was the intersection of Sherbrooke street and Atwater avenue. The intersection (Figure9) in both directions contained three lanes : a right turn lane, a through lane and a left turn lane. Both left turn and right turn vehicles were observed. Prior to beginning the experiment a distance of 60 meters was measured, from the stop line away from the intersection. Every 10 meters was marked off with red tape for visibility purposes. The observer was situated on the corner of the intersection from where it was possible to observe the traffic.

Data were collected for two weeks. 395 vehicles were surveyed for left turn and 400 vehicles were surveyed for right turn . The data were analyzed by ANOVA using the Statistical Package for the Social Science (SPSS) program. The independent factors examined were: 1) position in queue, 2) traffic light phase, 3) type of car, 4) sex of the driver, 5) number of passenger on the car, 6) age of the driver, 7) lane the driver turns to after making the turn, 8) number of pedestrians crossing the streets and, 9) hour of the day. All factors were the same in the left turn and the right turn experiment except factor 5) which was investigated for right turn only, and factor 8) which was investigated for left turn only. Combined analysis was also done by combining left turn and right turn data to confirm the significance of all the factors except for factors 5), 7), and 8).

The Signaling distance was measured from the stop line to the point on the street at which the driver first puts on the signal lights. This was divided into 9 possible values: -20, -05, 05, 15, 25, 35, 45, 55, and 65. For all possible values the midpoint of the particular category of signaling distances was assigned to the driver. For example if a driver signaled between 10-20 meters into the intersection a value of 15 was assigned as the signaling distance. Therefore, for drivers who signaled at approximately 0-10 meters after passing the stop line of the intersection a value of -5 was assigned to them. Furthermore, -20 was the value assigned to drivers who did not signal at all. This value was used because not signaling at all is the same as signaling after crossing the stop line on the other approach. 20 meters was the approximate curved diagonal distance between the stop lines on Sherbrooke and Atwater streets as shown in Figure 9. This study compares the significance of the factors on signaling distances for right turn and for left turn. Therefore, for consistency, value of -20 was also provided to those drivers who did not signal at all during right turn.

DATA ANALYSIS

The signaling distances observed at the intersection were analyzed only to determine the effect of the factors mentioned previously. An F-test was carried out to identify the significance of these factors. The F-ratio i.e. $F(\nu_1, \nu_2)$ shows the degree of freedom between groups (ν_1), and within the group (ν_2). The data were collected from the actual traffic and there was no control on any of the factors. Because behavior varies widely from person to person, only a 90 percent level of confidence was considered for determinig the significance of the factors. The results of the data analysis are discussed below.

1) Position in Queue

It was hypothesized that the signaling distance would not be different depending on the car's position in the queue. That is, the signal distance would be greater as the position in the queue increased. A one way Anova was performed comparing the signal distance of drivers according to their position in the queue. For both left turning and right turning vehicles variance was not significant with $F(5, 389) = 1.66$, $P > .1$, and $F(4, 390) = .774$, $P > .1$, respectively. Also for combined data the variance was not significant with $F(5,789) = 1.71$, $P > .1$.This indicates that signaling distance is not significantly different for drivers in the various positions in the queue, at a 90% confidence level.

Figure 10 illustrates the mean signaling distances of left turning and right turning drivers, and for the combined data according to their queue position . As it can be seen, the signaling distance increases as the queue position increases for left turns and the opposite is true for right turns. This shows that during left turns, the tendency of the drivers is to start signaling as soon as the preceding car signals. The trend for right turns shows that the reason for this behavior may be because there is no traffic coming from the opposite direction, and drivers do not have to be as careful about the opposing traffic as in case of left turns . Also for right turns, as the queue position increases, the chance of confrontation with pedestrians decreases, and hence the drivers tend to signal for shorter distances at higher queue positions. Line for the combined data in Figure 2 shows that the overall tendency of the drivers is to signal for longer distances as the queue positions increase. However, the effect of queue position is not significant on driver's signaling behavior.

2) Light Phase

It was hypothesized that signaling distances would not be greater during the green light phase than during the red light phase. For left turns and right turns the variance was significant with $F(2, 394) = 9.97$, $P << .1$ and $F(2, 399) = 146.63$, $P << .1$, respectively. Also, for combined data the variance was significant with $F(2, 794) = 64.7$, $P << .1$. This indicates that light phase is a highly significant factor which affects signaling distances.

Figure 11 shows the mean signaling distance for left turns, right turns, and the combined data. During the green phase, the signaling distance is greater than during the red phase in all cases. This result can be expected because during the green phase drivers are travelling at higher speeds and have less time to show their intentions, and hence signal for a longer distance than during the red phase.

3) Car Type

An analysis of variance was performed to compare the signaling distances of different vehicle types. The vehicles that were included in the analysis were 1), small cars, 2) large cars, 3) vans or pickups, and 4) trucks or buses. For left turns, right turns, and for combined data the analysis were significant with $F(3, 392) = 2.07$, $P < .1$, $F(3, 397) = 3.5$, $P < .1$, and $F(3, 792)$, $P < .1$. This shows that the vehicle type is a significant factor affecting driver's behavior.

Figure 12 illustrates the mean signaling distances for each vehicle type. As shown in figure, during all periods of time the mean signaling distance is greater for 'trucks or buses' and for 'vans or pickups' than the distance for 'small' and 'large cars'. This may be due to the actual size of the vehicle. The vans, pickups, trucks, and buses are bigger than both small and large cars; therefore, they require more time to execute the maneuvers. Thus, they signal earlier as they prepare for the turn.

Drivers of commercial vehicles are individuals who drive for a living; thus, they may have more driving experience probably making them better drivers.

4) Sex of the Driver

Another analysis of variance was performed to compare the signaling distances of male and female drivers. For left turns the difference was not significant with $F(1, 394) = .415$, $P > .1$, and for right turns the difference was significant with $F(1, 399) = 14.27$, $P < .1$. Results obtained from the combined data show that the difference was significant with F

(1, 794) = 4.2, P < .1. This shows that sex is a significant factor affecting signaling distance.

Figure 13 reveals that the mean signaling distances for male drivers is greater than for female drivers during left turns and the opposite is true for right turns. The results obtained from the combined data shows that females signal for longer distances than males. This finding is similar to the results seen in other studies where women generally comply more with traffic regulations and are less likely to take risks when driving (Bararach, Trumbo, and Nangle, 1957). Although, the driving education, rules, and regulations are applicable for both males as well as females, there is a difference in their signaling behavior. Therefore, sex has significant effect on driver's signaling behavior.

5) Passengers In The Car

An analysis of variance was performed to compare the signaling distance of drivers with passengers in the car and drivers without passengers. This analysis was done only for left turning vehicles. The difference was not significant with F(.1,198) = .6862, P > .1.

Figure 14 reveals the mean signaling distances of drivers with or without passengers. Though the difference is not significant, the trend shows that the signaling distance is greater when there are no passengers in the car. This is due to the fact that the presence of the passengers diverts the attention of the driver. This findings also demonstrate that the overall concentration of drivers in executing such routine varies in such a way that as signaling before making a turn is not adversely affected by the presence of passengers in the car.

6) Age of the Driver

An analysis of variance was performed to compare the signaling distances of older and younger drivers. Drivers were classified as young if they were between 16 and 50 years old, and drivers were classified as old if they were over 50. This judgment was based on a visual inspection of drivers as they approached the intersection. Thus, it is only an estimate based on certain distinguishing features of the drivers, such as hair, allure, and skin. This analysis was not significant during left turn with $F(1, 394) = .098$, $P > .1$, but the analysis was significant during right turn with $F(1, 399) = 4.6$, $P < .1$. Results obtained from the combined data show that the variance is significant with $F(1, 794) = 3.7$, $P < .1$, and hence age is a factor that affects signaling behavior.

Figure 15 reveals that for right turns, for left turns, and for combined data the mean signaling distance for older drivers is longer than that for younger drivers. This may be due to the fact that older drivers can be more experienced and less aggressive. These findings are similar to those found in other studies i.e. Bristow, Kirwan, and Taylor (1982) who found differences in the driving styles of older and younger drivers. They found that younger drivers often made cognitive errors which involved taking risks such as speeding, and older drivers were more likely to make cognitive errors such as not making a stop.

7) The Lane to be Turned To

This one way analysis was performed to compare the signaling distance of drivers who turned into the center lane (the correct lane for left turns and incorrect lane for right turns) and drivers who turned to the right lane (the incorrect lane for left turns and correct lane for right turns). For the left turn the difference was significant with $F(1, 198) = 3.54$, $P < .1$, but for the right turn the difference was not significant with $F(1, 198) = .29$, $P > .59$.

Figure 16 illustrates the mean signaling distance for drivers who turned to the correct lane and incorrect lane. Figure 8 shows that for both left turn and right turn the drivers who turned into the correct lane had a greater signaling distance than those drivers who turned into the incorrect lane. Although this finding was not significant, there is a trend for the drivers who turn to the correct lane to signal for a longer distance than those turning to the incorrect lane. This may be due to the fact that the drivers who turn into the correct lane, are obviously more aware of the traffic rules and regulations.

8) Number of Pedestrians

An analysis of variance was performed to compare the signaling distance of cars when there were pedestrians crossing the street, and when there were not any pedestrians crossing the street. This analysis was done for right turns only. The difference was not significant with $F(1, 398) = 1.67$, $P > .1$.

Figure 17 illustrates the mean signaling distance of cars when there were pedestrians crossing and when no pedestrians were crossing. As can be seen the signaling distance was greater when pedestrians were not crossing than when they were crossing, but the difference is small. Thus, presence or absence of pedestrians is the factor which does not significantly affect signaling distance of cars when making a right turns.

9) Hour of the Day

Analysis of variance was performed to see the driver's behavior during peak and offpeak hours. The difference between peak and offpeak hours for both left and right turn was significant with $F(1, 394) = 6.52$, $p < 0.1$ and with $F(1, 399) = 4.75$, $p < .01$. Analysis of variance done for the combined data shows that the difference between peak and offpeak hours is absolutely insignificant with $F(1, 794) = .037$, $p >> .1$.

Figure 18 reveals the mean signaling distance for left turn, right turn, and combined data during peak and offpeak hours. It can be observed from Figure 18 that the mean signaling distance for left turn is smaller during offpeak hours than during peak hours, while the result is opposite for right turn. For the combined data the difference between signaling distance during peak and offpeak hour is negligible. This shows that the hour of the day has little or no effect on driver's behavior. During rush hours drivers might have a tendency to signal for longer distance than during nonrush hours due to heavy traffic and to the pressure of getting home or work on time.

3.2 SIGNALING DISTANCE AS A FUNCTION OF VELOCITY

3.2.1 REQUIRED SIGNALING TIME

Tables 2 and 3 give the mean signaling distances, standard deviations, F-ratios, P-values, and the significance of the factors for left turn and right turn, and for combined data respectively. The results from this study with a 90 % confidence level indicate that the light phase, vehicle type, sex of the driver, age, and pedestrians are the major factors which significantly affect the driver's signaling distance. It can be observed from Tables 2 and 3 that the average signaling distance varies from 4.0 meters to 28.0 meters. If the vehicles are travelling at higher speeds, then signaling distances of 4.0 meters to 28.0 meters will give the following drivers, pedestrians, or other street users, insufficient time to perceive and react accordingly. Urban streets are full of hazards because of the different types of vehicles using the road and the number of pedestrians crossing the streets. Therefore, before turning into an intersection, drivers should signal in such a way that the following drivers, pedestrians, and the traffic coming from the opposite direction can see and understand the driver's intentions.

This study recommends that drivers should signal for a time lapse equal to the perception-reaction time of at least 2.0 seconds (Pignataro, 1973) so that the following drivers can perceive and react to the situation in time. In addition drivers should signal for a time lapse at least equal to 1.0 seconds (Pignataro, 1973) so that the opposing traffic and pedestrians can understand the driver's intentions. Therefore, drivers should signal for at least a time lapse equal to 3.0 seconds before turning into an intersection. It is difficult for drivers to measure the time while turning into an intersection, but it is easier for drivers to judge the distance of their vehicles from the stop line. Therefore, it is preferred to make recommendations in terms of the distance.

3.2.2 MINIMUM REQUIRED SIGNALING DISTANCE

When drivers make a decision to turn, they start decelerating in order to make a safe turn into an intersection. Therefore, assuming a constant deceleration rate, the distance travelled by the vehicle from the point it starts decelerating to the point where it starts turning into an intersection can be given as :

$$X = \{ \frac{V_0 + V}{2} \}.t \tag{22}$$

where,

X = distance (meters) travelled by vehicle from the moment it starts decelerating to the moment it starts turning,

V_0 = speed (meters / sec.) of the vehicle when it starts decelerating,

V = speed (meters / sec.) of the vehicle at the point it starts turning into an intersection, and;

t = time (seconds) taken by the vehicle to travel distance X.

In this study, the stop line is considered to be the point where vehicles start turning into an intersection. The driver should turn on the vehicle signals the moment he (or she) decides to make a turn. Therefore, the driver should start decelerating and signaling at the same time. As mentioned before, the driver should signal for at least equal to 3.0 seconds. Therefore, the minimum required signaling distance in meters, D_S, can be given as :

$$D_S = \{ \frac{V_0 + V}{2} \} . 3 \qquad (23)$$

There are several factors which affect driver's signaling behavior as found from the statistical analysis described previously. Light phase is one of the highly significant factors, minimum required signaling distance depending upon the traffic light phase is as explained below.

(A) Minimum Required Signaling Distance During Green Phase :

a) Left Turning Vehicles :

While approaching the intersection during green phase, the speed of the vehicle is higher. Due to the high approaching speed, the rate of deceleration should be smaller so that driver can turn into an intersection without skidding and also he (or she) should be able to stop the vehicle completely when required. It was observed from the traffic at Sherbrooke and Atwater intersection that while turning into the intersection, the speed V at which drivers cross the stop line varies approximately from 20 km / hr to 50 km / hr. This variation in speed depends upon the presence of pedestrians, queue position, opposing traffic, geometry of the intersection, and initial approaching speed V_0 of the vehicle and it can be different at different times of the day. Geometry of an intersection is a major factor which causes variation in speed with which drivers cross the stop line. This is because at some intersections, the streets cross each other at approximately 90 degrees and hence forcing drivers to slow down to make a safe turn.

The estimated value of the radius of the curved distance along which vehicles made left turn into Sherbrooke and Atwater intersection was about 30.0 meters. Therefore, the maximum speed at which vehicles should turn into the intersection safely can be given by :

$$V_{max} = \sqrt{127 \times 30 \times f} \tag{24}$$

where,

V_{max} = maximum turning speed in km / hr, and;

f = coefficient of friction.

Since, all the data and measurements were done under dry conditions of pavement, and the variations in the vehicle speeds were significant, a constant value of f equal to 0.6 was taken. Therefore, from Equation (24);

$$V_{max} \doteq 50.0 \text{ Km / hr.}$$

Therefore, substituting speed Vmax for speed V in Equation (23), the minimum required signaling distance in meters for left turning vehicles during green phase, D_{S1}, is given as follows ;

$$D_{S1} = \{\frac{V_0 + 50.0}{2}\}.3 \tag{25}$$

b) <u>Right Turning Vehicles</u> :

For the right turning vehicles also, the approaching speed during the green phase is higher. Due to the high approaching speed, the rate of deceleration should be small to avoid any skidding , and also so that drivers can stop the vehicle when required. From the observation of traffic it was found that during the right turn, the speed with which vehicles cross the stop line varies from 10 to 30 Km / hr. This variation in speed is smaller as compared to the left turning vehicles, but may change from time to time. This may be due to the fact that right turning vehicles are in close confrontation with the pedestrians, and, also presence of bus stops near the intersections reduce the turning speeds of the vehicles significantly.

The measured value of the the radius of the curved distance along which the drivers turned into the intersection during right turns was approximately 15.0 meters. Therefore, maximum speed with which drivers should turn into the intersection can be given by ;

$$V_{max} = \sqrt{127 \times 15 \times f} \qquad (26)$$

For $f = 0.6$ under dry conditions;

$V_{max} \approx 35.0$ km / hr.

Therefore, minimum required signaling distance in meters for right turning vehicles during green phase, D_{S2}, can be given by ;

$$D_{S2} = \{\frac{V_0 + 35.0}{2}\}.3 \qquad (27)$$

(B) <u>Minimum Required Signaling Distance During Red Phase</u> :

When the drivers approach the intersection during red phase, the rate of deceleration should be such that they can stop completely before the stop line. Since drivers have to stop before the intersection at the red phase, therefore, the speed of the vehicle V with which it should cross the intersection is zero. Minimum required distances during red phase for left turns and for right turns, D_{S3}, are the same and can be given by ;

$$D_{S3} = \{\frac{V_0}{2}\}.3 \qquad (28)$$

(C) <u>Conclusion</u> :

It can be noticed from Equations [26], [27], and [28] that the minimum required signaling distance during the green phase is higher than during the red phase. The same result was found from the statistical analysis of factors as explained previously. Also, it can be noticed from Figure 3 that for left turns as well as for right turns, the signaling distance during the green phase was higher than the signaling distance during the red phase.

For safety considerations, the minimum required signaling distances from Equations [26], [27], and [28] can be given as follows :

$$\text{Minimum required signaling distance} = \text{Max}\,[\,D_{S1}, D_{S2}, D_{S3}\,] \tag{29}$$

Table 4 gives the list of approximate minimum required signaling distances based upon the approaching speeds of the vehicles.

3.2.3 RECOMMENDED SIGNALING DISTANCE

Intersections are the point where a number of activities happen at the same time such as thorough movements, left turns, right turns, pedestrians crossing the streets and jay - walkers. Therefore, while approaching the intersection drivers have to be careful of all the movements going on near the intersection. Driver's mind is occupied in such a way that it is difficult for the drivers to remember the minimum required signaling distance given in Table 4. Therefore, a simple rule as given below has been recommended for the drivers to make it easier for them to signal properly while making left or right turn ;

Drivers should signal a distance (in meters) approximately equal to the value of the speed of their vehicles (in km / hr) before turning into an intersection.

Therefore as listed in Table 3, if drivers are driving at speeds of 30 or below, 40, 50, 60, 70, or 80 km / hr, they should signal for distances approximately equal to 30, 40, 50, 60, 70, or 80 meters, respectively, before turning into an intersection. Values of recommended signaling distances are generally higher than the values of minimum required signaling distances except for speed of 30 km / hr. At 30 km / hr the minimum required distance is slightly higher (3meters) than the recommended signaling distance. Since, the recommended signaling distances are the maximum values based upon equation [8], therefore a difference of 3.0 meters is negligible. Recommended values of the signaling distances are given because, the drivers can look at their speeds, and can then decide for how long should they signal before turning into an intersection. Also it is easier for drivers to remember that they have to signal for a distance approximately equal to the value of speeds of their vehicles.

3.2.4 DRIVER'S ACTUAL BEHAVIOR IN THE FIELD

Data were collected in the field at the same intersection (Sherbrooke and Atwater streets) to see how signaling distances vary according to vehicle speeds. Data from 400 vehicles were collected, out of which 102 vehicles did not signal at all or just signaled after crossing the stop line. The other 298 data were plotted as shown in Figure 19. This figure shows a clear trend that signaling distances increase with increase in speeds. Figure 19 also shows a "field curve" drawn to show the average trend of the drivers according to the speeds of their vehicles. Another line called as a " theoretical line" in Figure 19 was drawn depending upon Equation (29). It was observed from Figure 19 that out of the 298 data plotted, 198 were below the theoretical line. As mentioned previously, Figure 19 does not include the vehicles which did not signal or signaled after the stop line. Therefore, it can be concluded that out of the 400 drivers, 300 (75 %) did not signal properly.

As can be observed from Figure 19, a few vehicles travel at a speed less than 20 km / hr. Figure 19 shows that the 'field curve' becomes almost horizontal below 20 km / hr i.e. variations in signaling distances are expected to be small at speeds of less than 20 km / hr. The slope of 'field curve' in Figure 19 shows that above 20 km / hr, signaling distances increase with increase in speed. It is rare to have a speed less than 20 km / hr on urban streets. Depending upon Equation (29), the minimum required distance at 20 km / hr is approximately 30 meters. Also, at the speed of 30 km / hr the recommended signaling distance is 30 meters. Therefore, it was recommended that at speeds of 30 km / hr or below, drivers should signal for at least 30 meters before turning into an intersection.

3.2.5 RELATIONSHIP BETWEEN SIGNIFICANT FACTORS AND THE RECOMMENDED SIGNALING DISTANCE

1. Light phase :

While approaching the intersection when the light phase is green, generally drivers do not slow down and hence speeds during the green phase are normally higher than the speeds during the red phase. The recommended signaling distances in Table 4 are given based upon the variations in speeds during different light phases, and perception reaction time. Therefore, if drivers signal according to the recommended signaling distance as given in Table 4, there is less risk of collision.

2. Vehicle size :

Drivers of the heavier vehicles should signal for longer distances because of the size of their vehicles. Also the size of the turn signals on heavier vehicles is relatively smaller making it difficult for other drivers and pedestrians to see them clearly. Since, the recommended signaling distances are greater than the minimum required signaling distances, therefore, if drivers signal according to the simple rule recommended, they can make safe maneuvers. Also, other road users will have sufficient time to understand the driver's intentions.

3. Sex and age of the drivers :

Sex and age of the drivers are psychological factors and that are hard to control. A better education can be provided to young drivers so that they signal properly in order to avoid collisions at intersections. Variation between the signaling distances for female and male drivers will diminish if they signal according to the simple rule recommended.

3.2.6 IMPROVEMENT TO THE TRAFFIC LAW OF NEW BRUNSWICK

As mentioned previously, the Driver's Handbook in the province of New Brunswick mentions that, drivers should signal for at least 100 feet (appx. 30 meters) before turning into an intersection. It can be observed from Figure 19 that 30 meters is an inappropriate signaling distance for speeds greater than 40 km / hr. In other words, this distance will be covered in a short time giving following drivers, pedestrians, and other users of the road, insufficient time to make decisions. Figure 19 also shows the line drawn according to the law of New Brunswick, and it can be observed that it does not meet the actual trend of the traffic. Therefore, this study can be used to improve the traffic law for the signaling distance in the province of New Brunswick.

CHAPTER IV

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The major objective of this study was to understand and analyse drivers' behavior on urban highways and street intersections. As mentioned in Chapter I, urban highways and street intersections are the places where importat maneuvers take place due to high traffic volume.

The behavior of driver is different on urban highways than at street intersectios due to different traffic situations. On urban highways, the lane change maneuvers are much more critical than on urban streets because of the higher speeds of the vehicles and continous flow of the traffic. Factors such as light phase, queue position, opposing traffic, and pedestrians etc. do not have any influence on drivers on urban highways. On the other hand at street intersections driver's signaling behavior is more important. On the urban highways proper signaling is required to show intentions to the following drivers only while changing lanes. On the street intersections adequate signaling is required not only to show intentions to the following drivers but also to the drivers in the opposing traffic, and for the safety of other road users such as pedestrians. Though the analysis done in chapters II and III involve different approaches, but both analysis deal with the safety of drivers and other road users.

Conclusions drawn from the analysis done on drivers' lane change and signaling behavior on urban highways are :

1. A matematical model was developed to determine the required safe lane change (SLC) distance. Equation (11) and Equation (17) are adequate to calculate the SLC distance between the turning and the following vehicle in the same lane and the adjacent lane

respectively.

2. Based on the proposed model, this study divided the driver's lane change movement into three zones: safe zone, acceptable zone, and risk zone, as depicted in Figures 3 through 8.

3. Based upon the driver's perception-reaction time, this study recommends that drivers in the safe and the acceptable zones should signal for at least 2.0 sec. before turning. The drivers in the risk zone should continue to signal until the following drivers provide them with a sufficient gap falling within the acceptable zone. If a driver in the risk zone is under "Must turn" conditions, i.e. he (or she) has to turn, then he(or she) should signal for at least 3.0 sec. before turning.

4. From the analysis of the data collected on Decarie Expressway, Montreal, Canada, it was found that 12 percent of the total drivers were in the safe zone, 75 percent were in the acceptable zone, and 13 percent were in the risk zone.

5. From the analysis of the data collected on Decarie Expressway, Montreal, Canada, it was found that 51 percent of the total drivers did not signal, 12 percent signaled for insufficient time, 37 percent signaled for sufficient time.

Conclusions drawn from the anlysis of drivers' signaling behavior while turning at signalized intersections are :

1. Light phase, type of vehicle, sex of driver, and pedestrians are the factors which significantly affect the driver's signaling distance while turning at signalized intersections at 90 % confidence level.

2. Position in the queue does not effect signaling distances of the drivers at 90 % confidence level, but the tendency of the drivers is to signal for greater distances at higher queue positions.

3. It is a tendency of the drivers to signal for greater distances at higher approaching speeds, but according to the data collected appoximately 75 % of the drivers did not signal adequately.

4. Speed is one of the major factors which should be considered to decide the signaling distances. Table 4 gives the minimum required siganling distances and recommended signaling distances for which drivers should signal at a particular speed before turning into an intersection. A simple rule depending upon the recommended signaling distances is given below, to make it easier for the drivers to remember;

Drivers should signal for a distance (in meters) approximately equal to the value of speeds (in km / hr) of their respective vehicles before turning into an intersection.

5. Better education should be provided to the young drivers regarding the lane change maneuvers and the signaling since they are more aggressive and more likely to make dangerous maneuvers.

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TABLE 1- SLC Distance Between Vehicles A and C at Different Speeds and Coefficient of Friction f* When $V_C = 1.1V_A$.

SPEED		SLC DISTANCE			
		Wet Pavement		Dry Pavement	
Km/Hr	Miles/Hr (Appx.)	Meters	Feet	Meters	Feet
50	30	24.0	80.0	15.0	50.0
60	40	30.0	100.0	20.0	66.0
70	45	36.0	120.0	25.0	83.0
80	50	41.0	135.0	30.0	100.0
90	55	47.0	155.0	35.0	116.0
100	65	52.0	170.0	38.0	125.0
110	70	59.0	195.0	42.0	139.0
120	75	65.0	215.0	46.0	152.0

* A Policy on Geometric Design of Rural Highways (Washington D.C.:American Association of State Highway Officials,1965)p.136.

Table 2: Summary of Mean Signaling Distance For Left Turn and Right Turn.

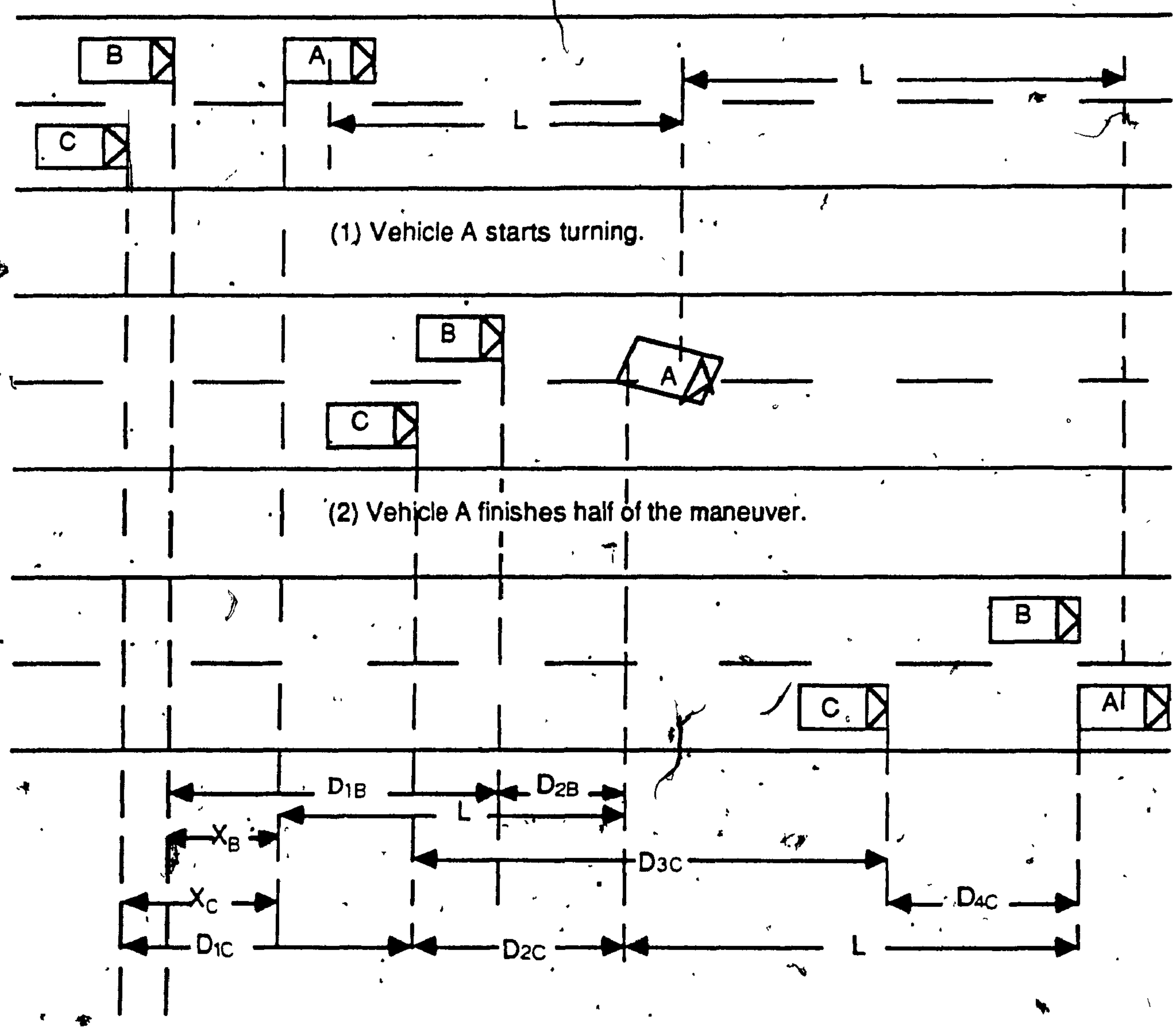
FACTOR	LEFT TURN					RIGHT TURN				
	Mean	s.d.	F ratio	P value	Significa-nt	Mean	s.d.	F ratio	P value	Significa-nt
1) Light Phase										
a. Red	11.4	19.1	9.97	0.00	yes	4.6	17.0	146.0	0.00	yes
b. Green	20.7	20.9				27.8	19.9			
2) Queue Position										
1	13.1	20.4				13.2	22.0			
2	13.8	20.0				11.9	19.1			
3	16.0	18.5	1.66	0.14	no	11.1	22.0	0.77	0.543	no
4	15.3	23.7				4.6	15.6			
5	19.4	21.7				3.7	18.4			
6	27.0	21.5								
3) Sex										
a. Male	15.3	20.6	0.41	0.52	no	10.3	20.6	14.3	0.00	yes
b. Female	13.7	21.4				20.0	21.4			
4) Type of vehicle										
a. Small Car	14.2	19.8				11.6	20.3			
b. Large Car	13.8	20.1	2.07	0.01	yes	10.6	21.0	3.5	0.01	yes
c. Van or Pickup	17.8	17.2				25.4	25.4			
d. Truck or Bus	26.2	23.6				20.2	23.0			
5) Passengers										
a. No	15.6	20.6	0.68	0.41	no					
b.More than one	13.7	20.3								
6) Age of driver										
a. Old	15.5	20.8	0.09	0.75	no	16.7	21.8	4.6	0.03	yes
b. Young	14.7	20.4				11.2	21.0			
7) Lane Turned on										
a. Center	15.6	20.7	3.54	0.06	yes	12.5		0.29	0.59	no
b. Right	9.3	17.4				9.7				
8) Pedestrians										
a. No						13.3	21.2	1.6	0.2	no
b.More than One						10.5	20.7			
9) Hour of the Day										
a. Peak Hour	17.5	21.3	6.52	0.01	yes	10.0	19.4	4.75	0.27	yes
b. Offpeak Hour	12.2	19.4				14.6	22.4			

Table 3 : Summary of Mean Signaling distance for Combined Data

FACTOR	COMBINED				
	Mean	s.d.	F-Ratio	P-Value	Significant
1) Queue Position					
1	13.3	21.4	1.71	0.13	no
2	12.8	19.5			
3	14.5	19.6			
4	11.1	22.3			
5	17.3	21.7			
6	27.0	21.4			
2) Light Phase					
a. Green	24.0	20.7	64.7	0.0	yes
b. Red	7.7	18.4			
3) Type of Vehicle					
a. Small Car	13.0	20.1	4.98	0.0	yes
b. Large Car	11.7	21.5			
c. Van or Pickup	22.3	23.1			
d. Truck or Bus	20.0	19.7			
4) Sex					
a. Male	12.7	20.1	4.20	0.04	yes
b. Female	16.3	20.3			
5) Age					
a. Old	16.2	21.3	3.72	0.05	yes
b. Young	12.8	20.6			
5) Hour of the Day					
a. Offpeak	13.4	21.0	0.04	0.85	no
b. Peak	13.7	20.7			

Table 4 : Speed of the Vehicle Vs Minimum Required Signaling Distance, and Recommended Signaling distance

Speed (km / hr)	Minimum Required Signaling Distance (Meters)	Recommended Signaling Distance (Meters)
30 or below	33.0	30.0
40	37.5	40.0
50	42.0	50.0
60	46.0	60.0
70	50.0	70.0
80	55.0	80.0



(3) Vehicle A completes the maneuver.

Figure 1- Three Key Moments of Vehicle A Completing the Lane Change Maneuver.

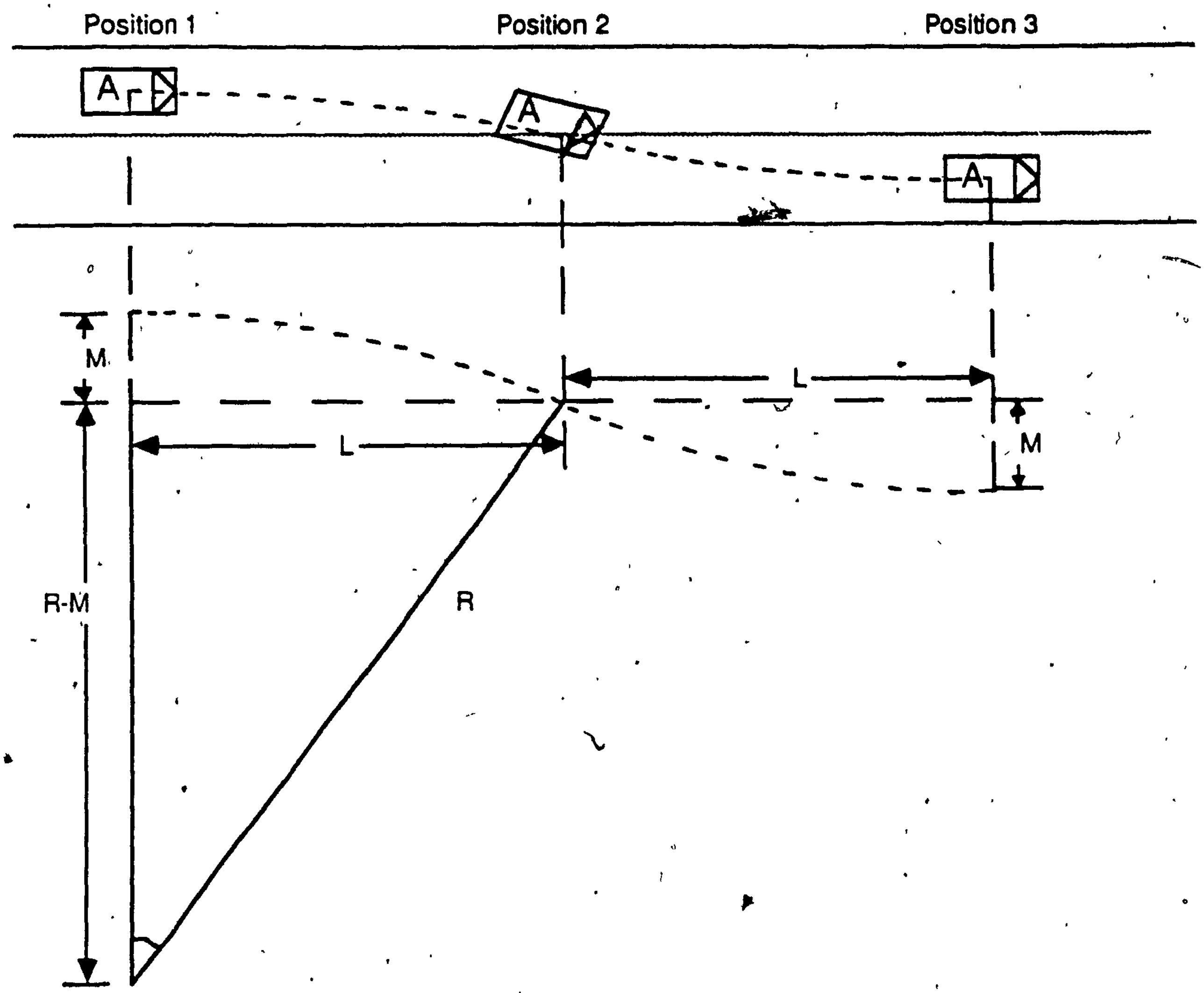


Figure 2- Line Diagram of Lane Change Maneuver.

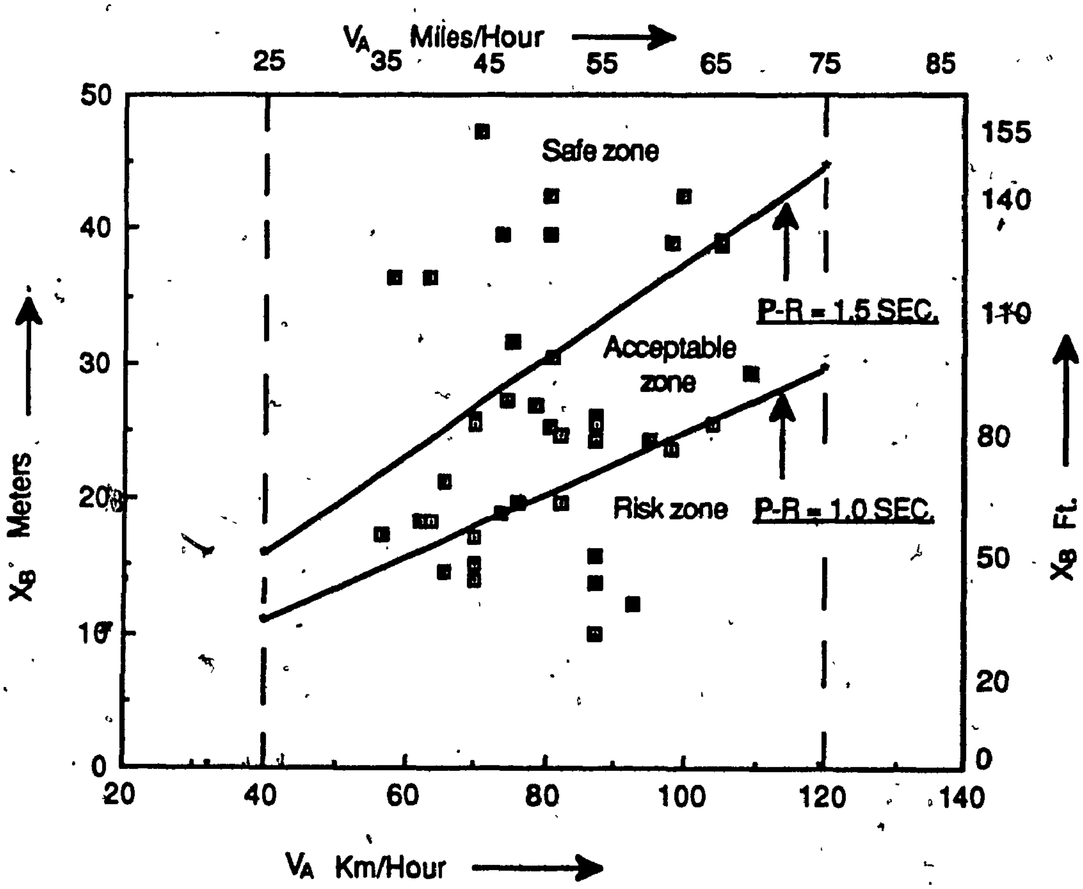


Figure 3 : SLC Distance Between A and B Vs Speed of Vehicle A When $V_B = 0.9\ V_A$

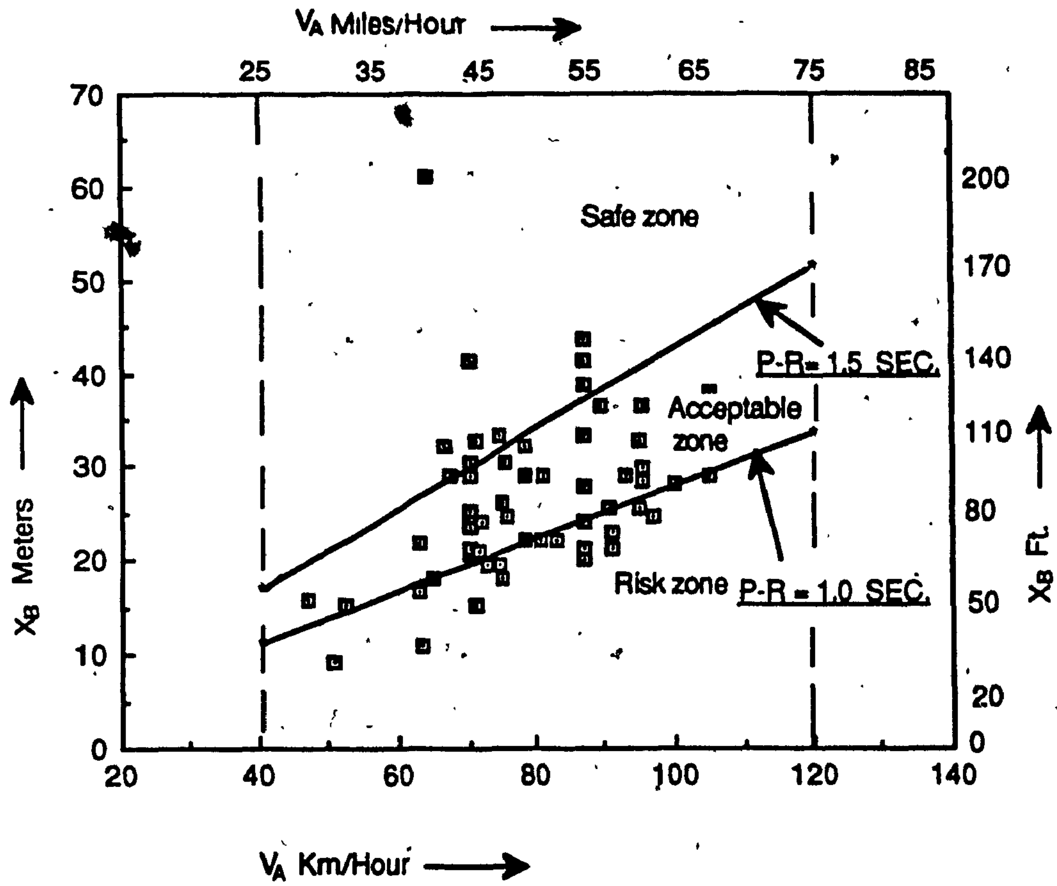


Figure 4 : SLC Dstance Between Vehide A and B Vs Speed of Vehicle A When $V_B = V_A$

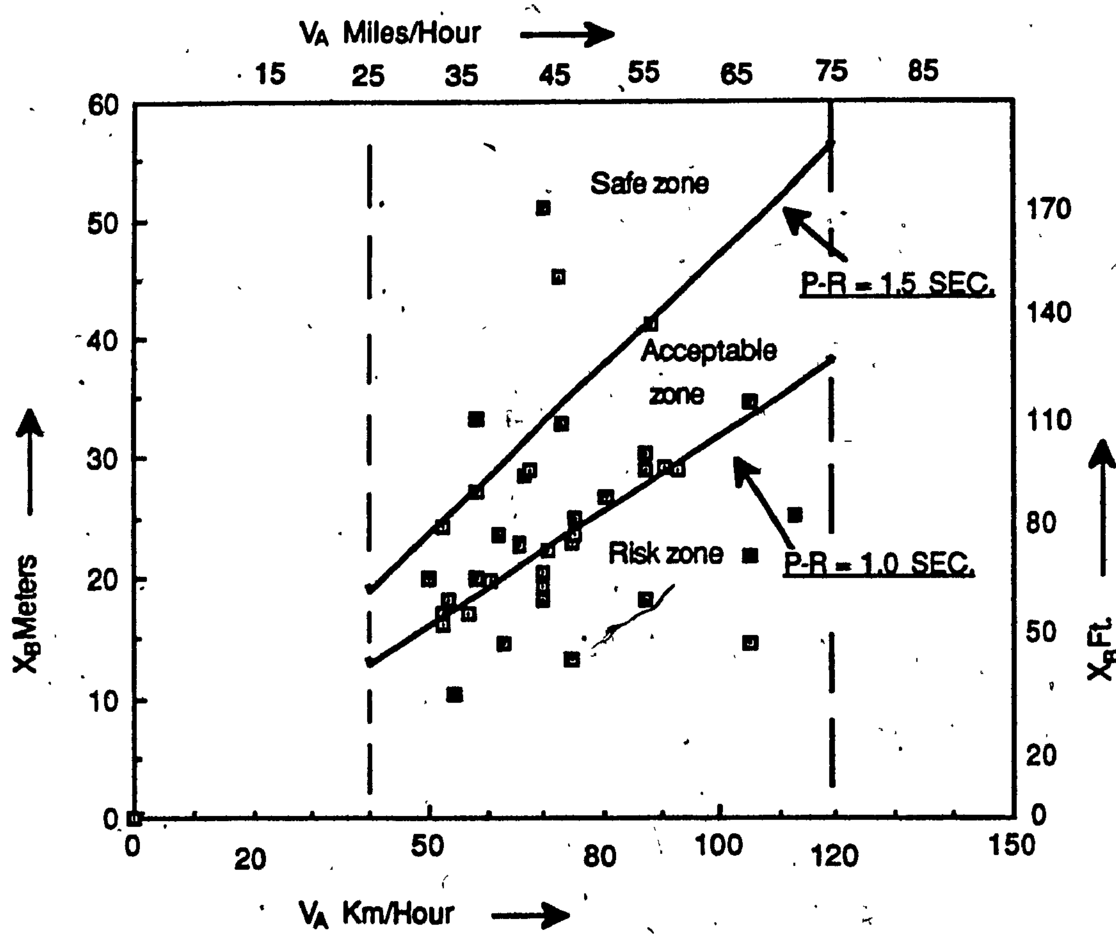


Figure 5 : SLC Distance Between Vehicle A and B Vs Speed of Vehicle A When $V_B = 1.1V_A$

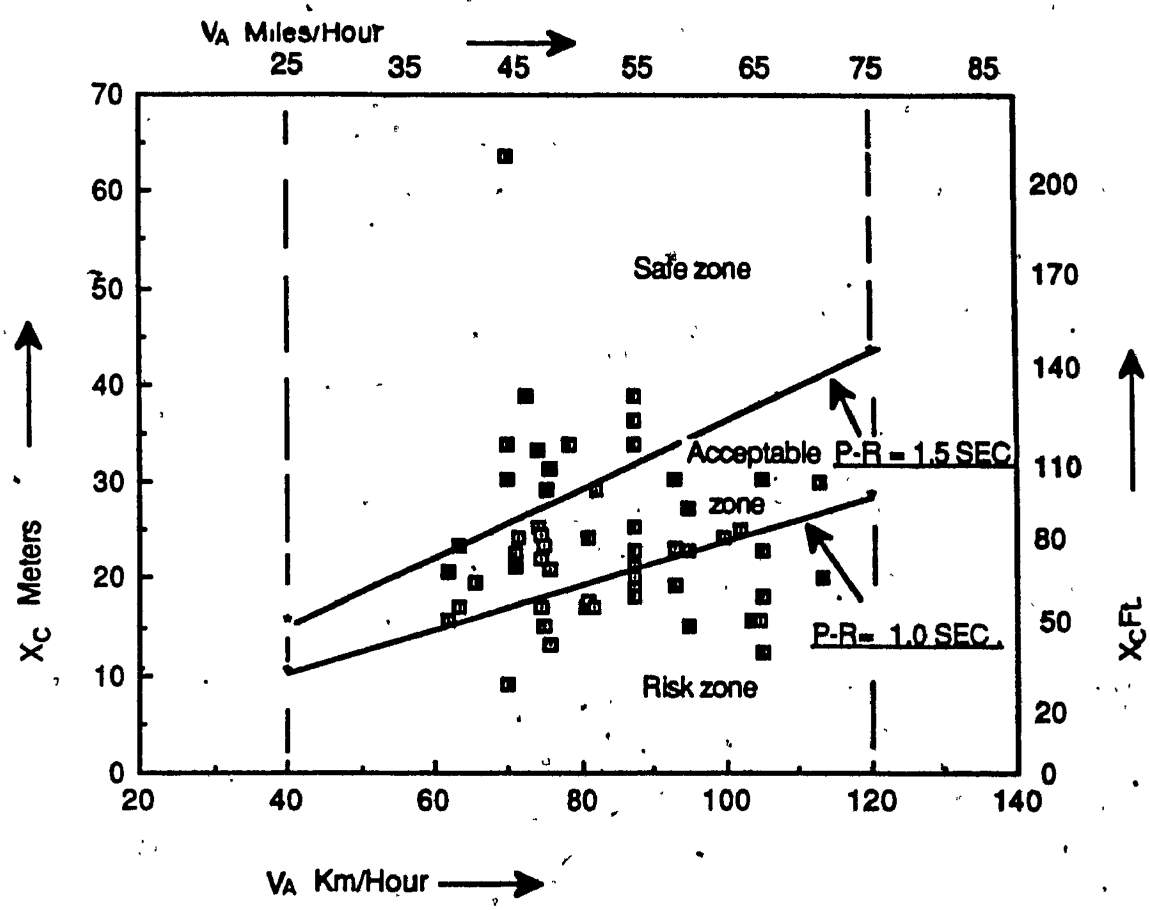


Figure 6 : SLC Distance Between Vehicle A and C Vs Speed of Vehicle A When $V_C = 0.9\ V_A$

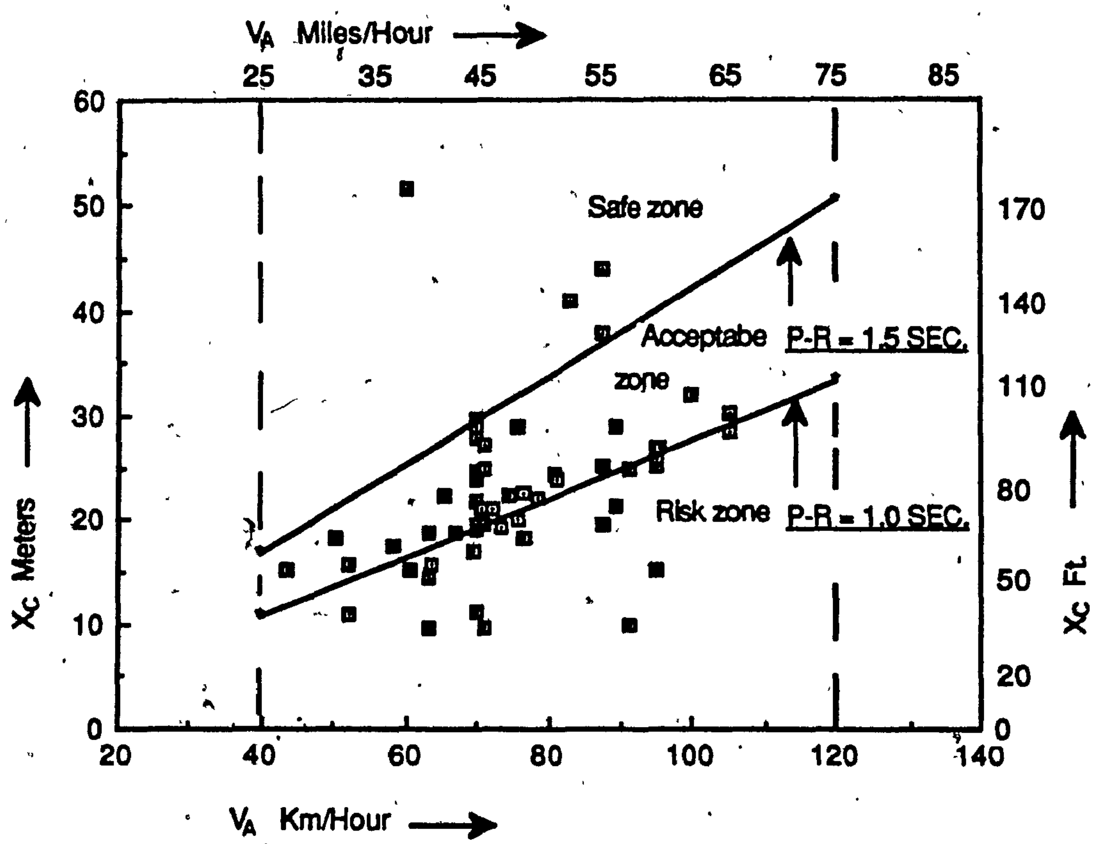


Figure 7 : SLC Distance Between Vehicle A and C Vs Speed of the Vehicle A When $V_C = V_A$

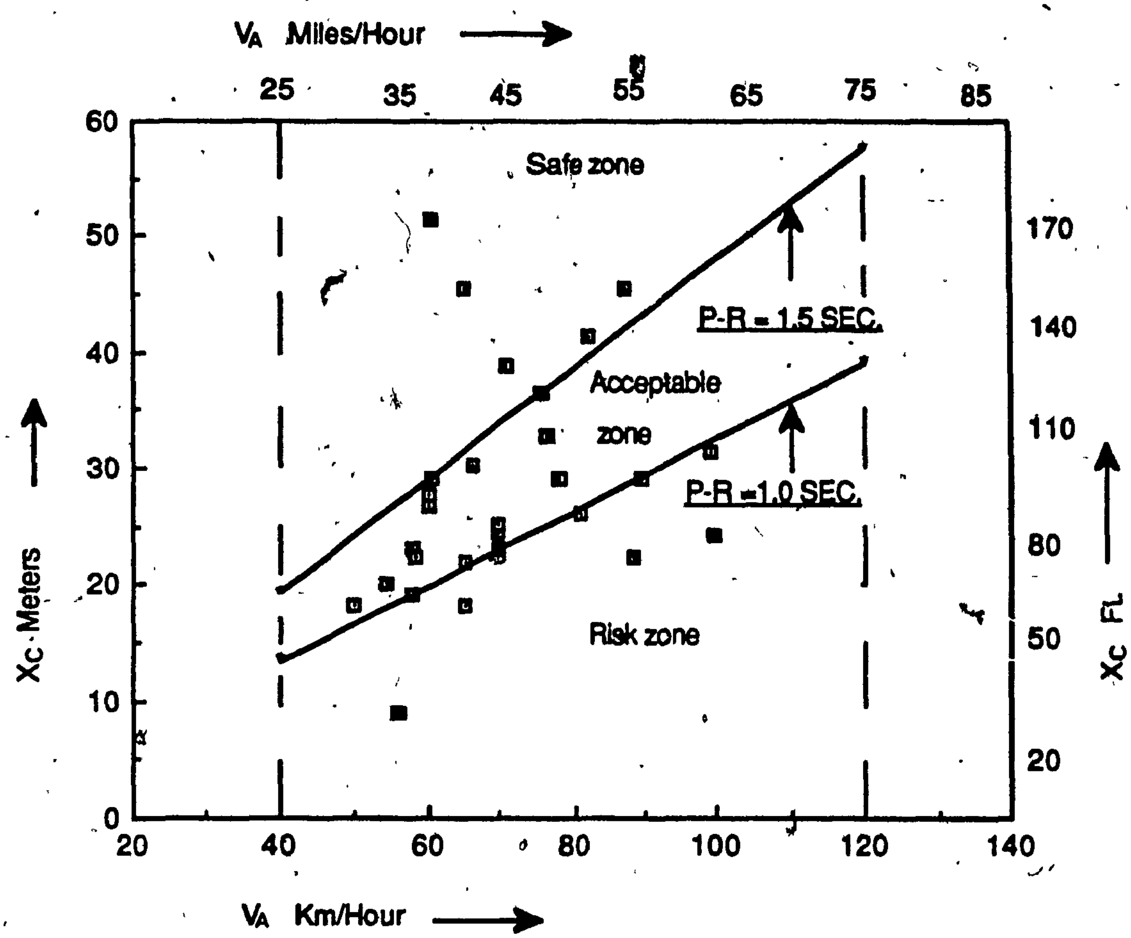


Figure 8 : SLC Distance Between Vehicle A and C Vs Speed of the Vehicle A When V_C=1.1V_A

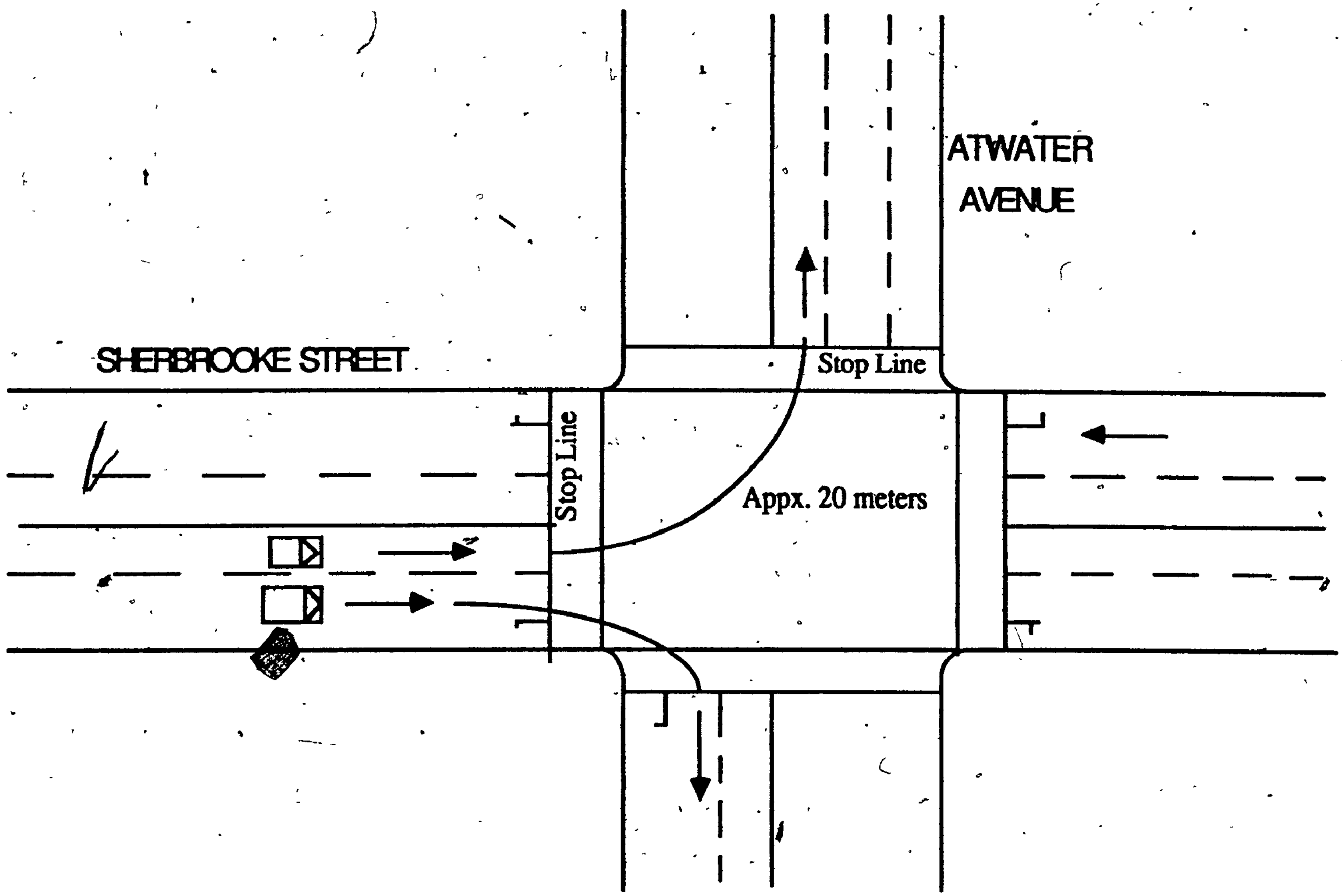


Figure 9 : Sherbrooke and Atwater Intersection

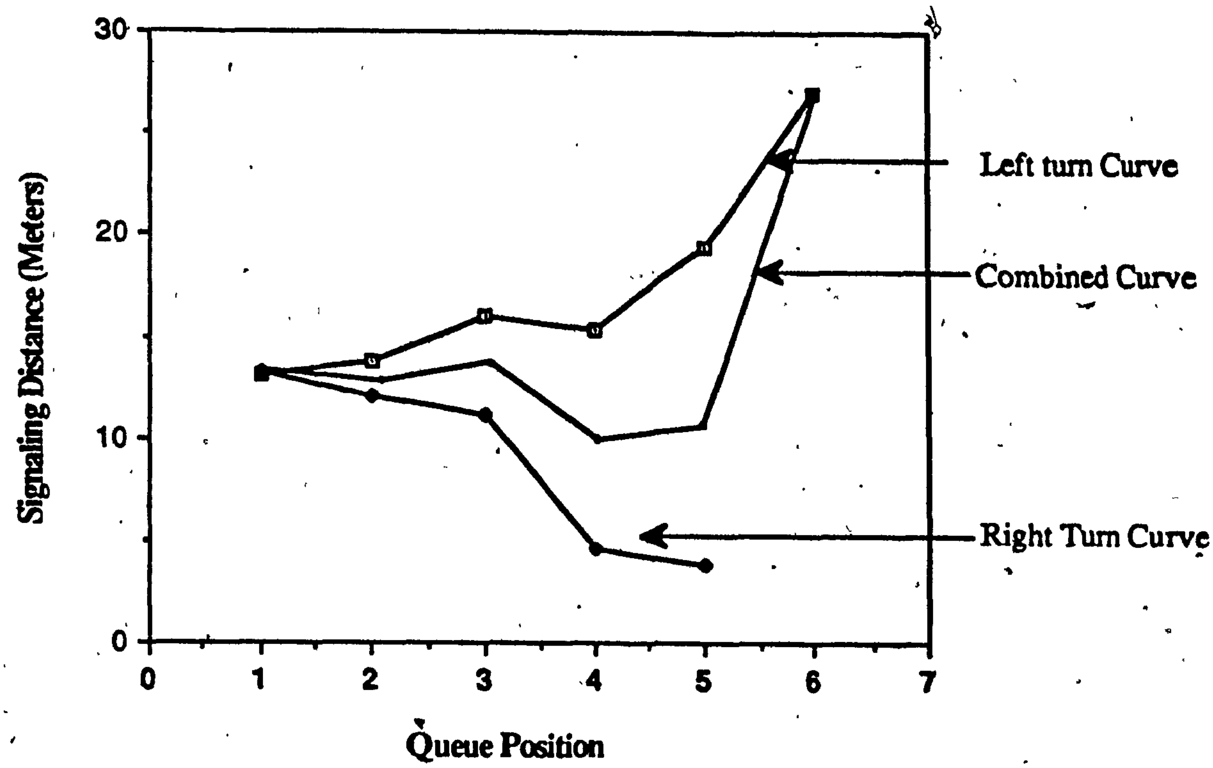


Figure 10 : Signaling Distance Vs Queue Position

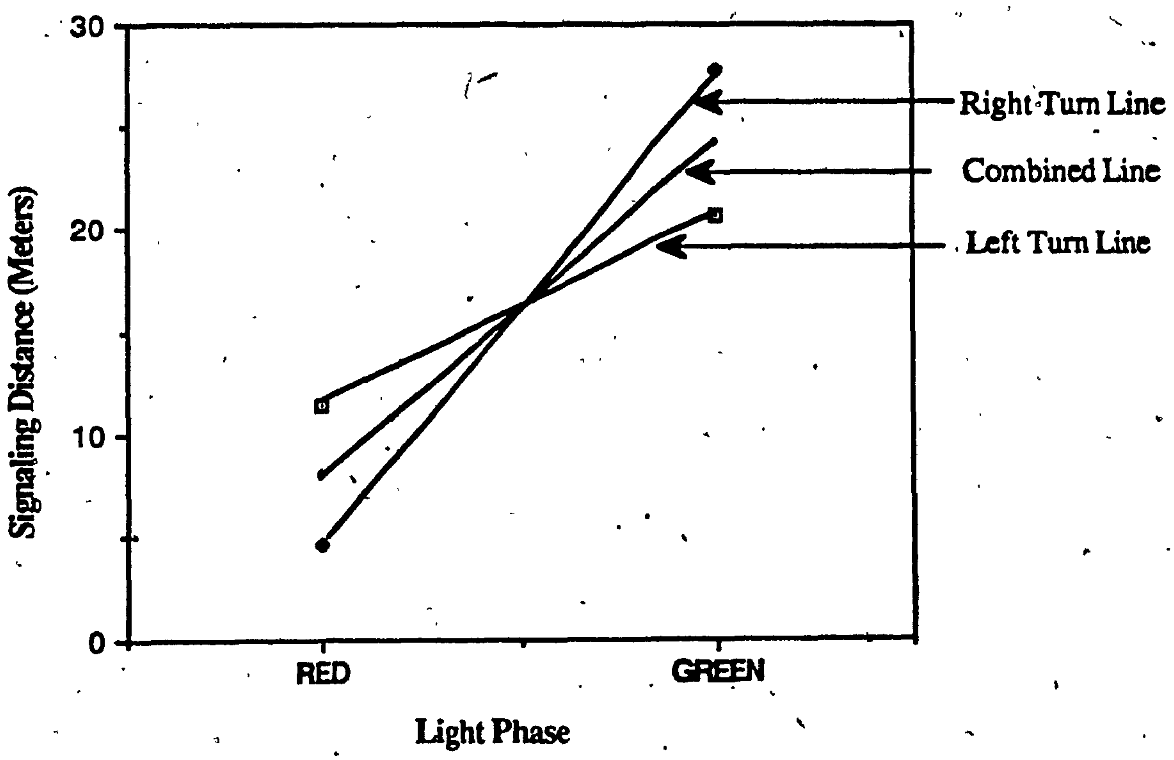


Figure 11 : Signaling Distance Vs Light Phase

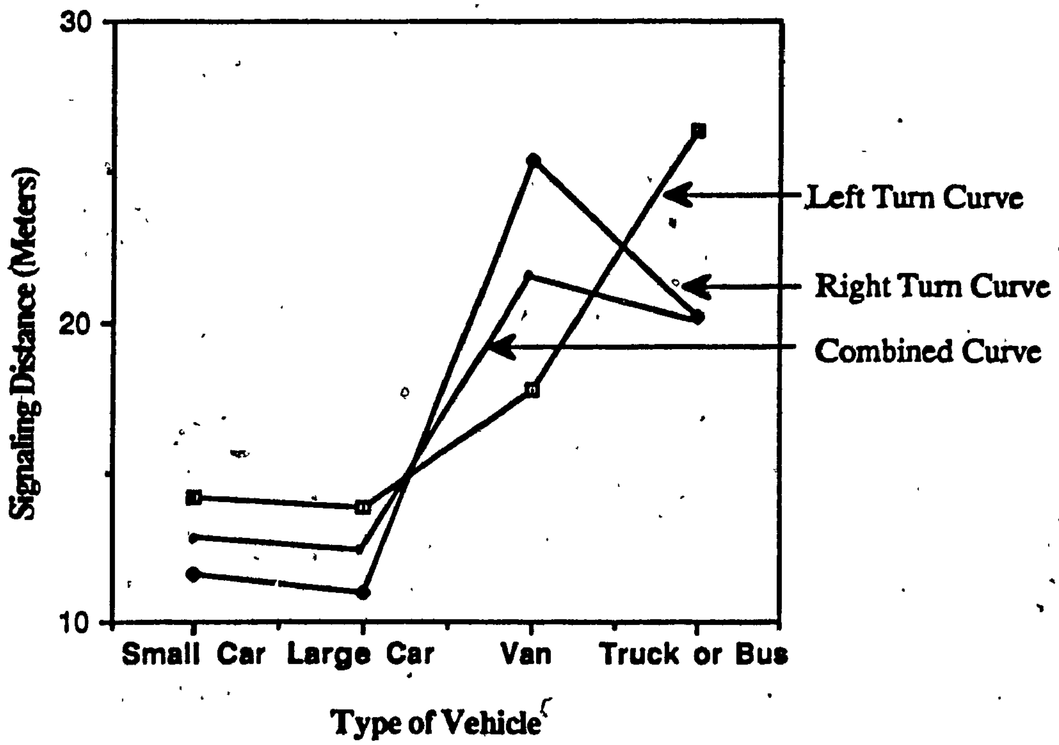


Figure 12 : Signaling Distance Vs Vehicle Type

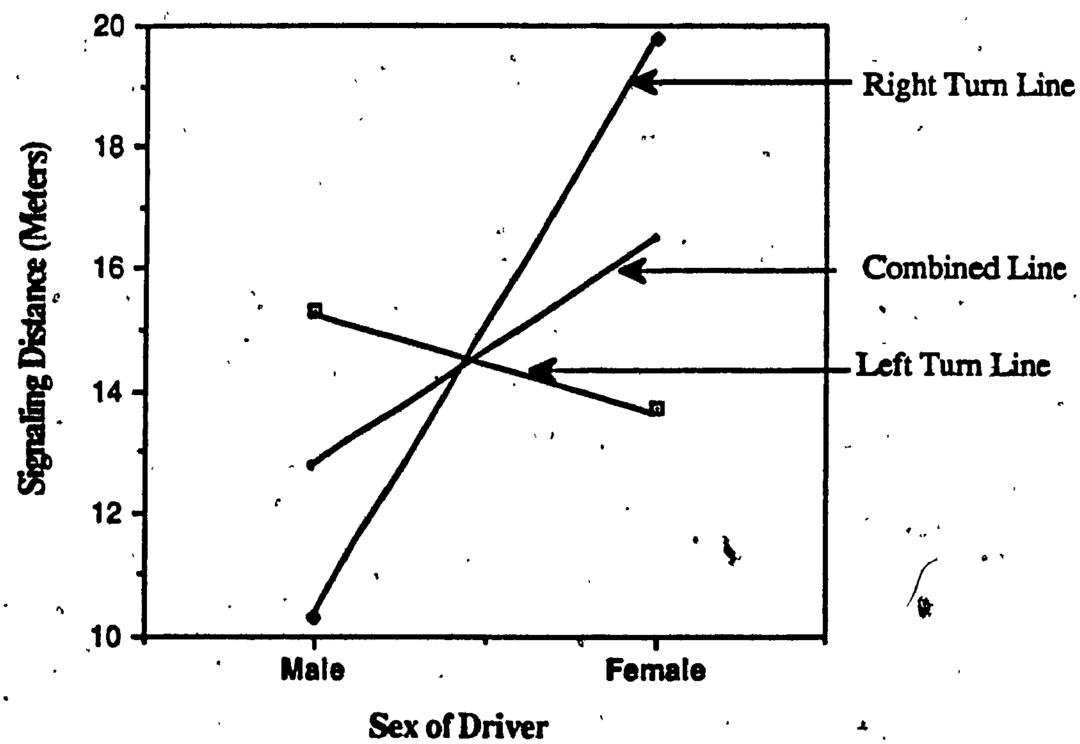


Figure 13 : Signaling Distance Vs Sex of Driver

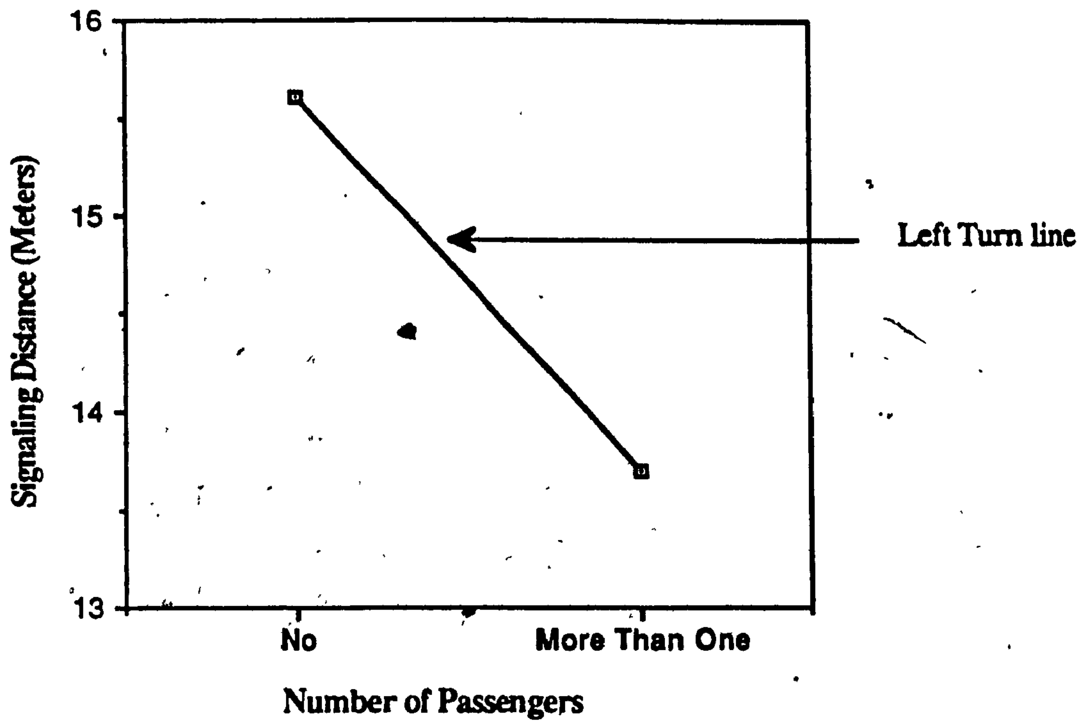


Figure 14 : Signaling Distance Vs Number of Passenger in the Car

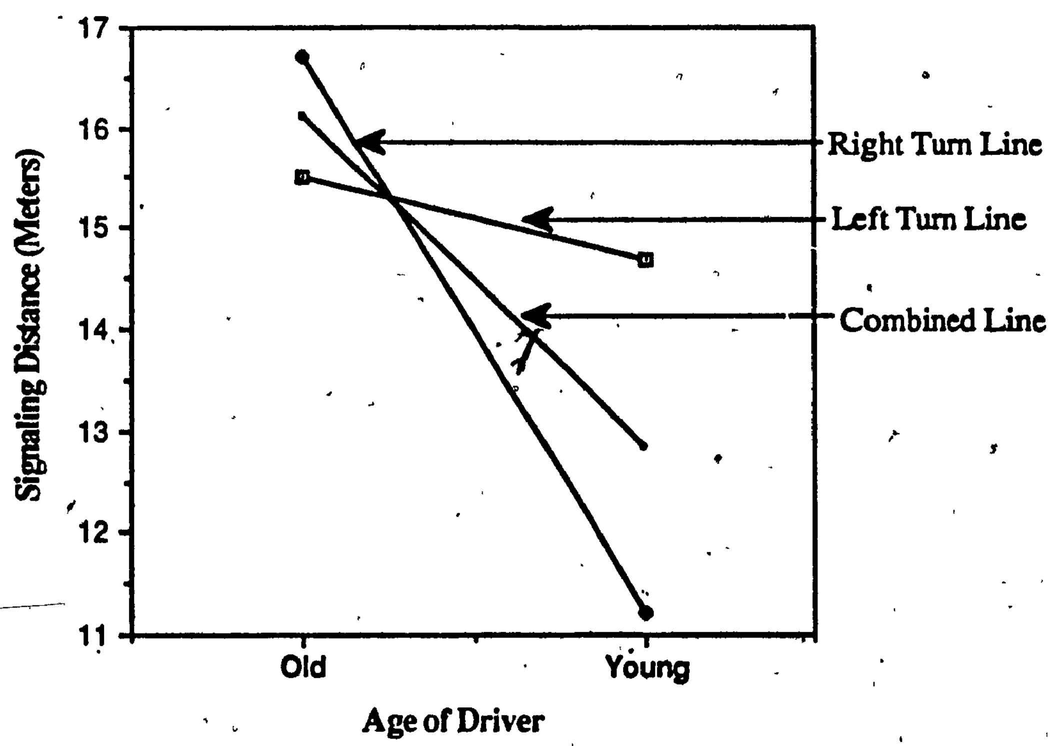


Figure 15 : Signaling Distance Vs Age of the Driver

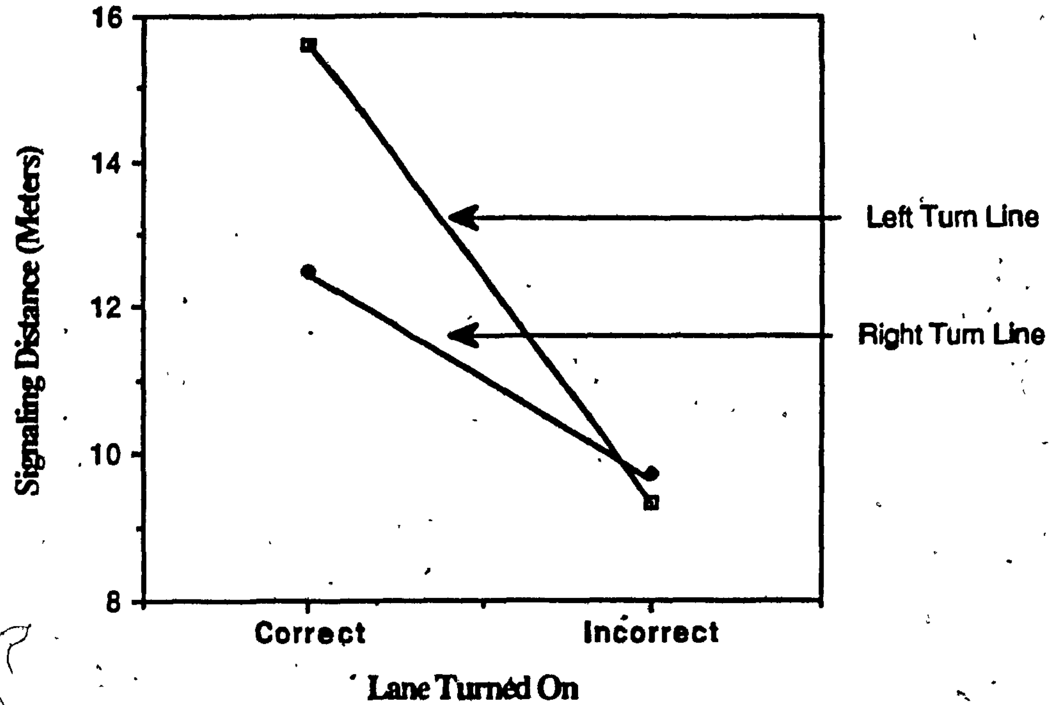


Figure 16 : Signaling Distance Vs Type of Lane Turned On

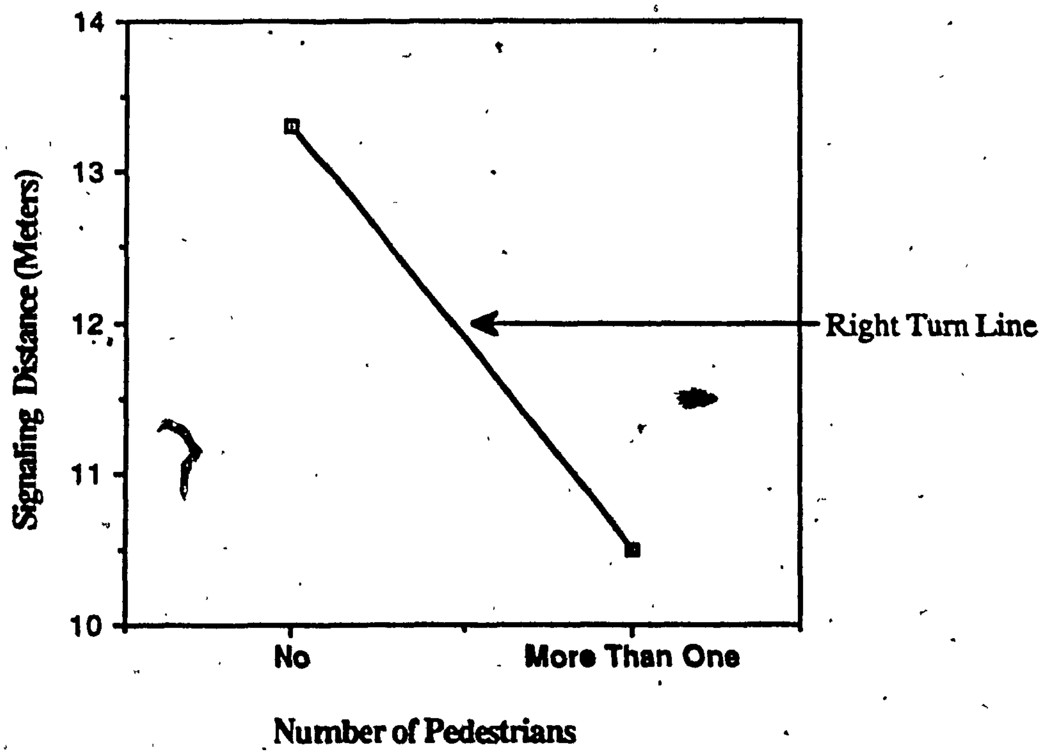


Figure 17 : Signaling Distance Vs Number of Pedestrians

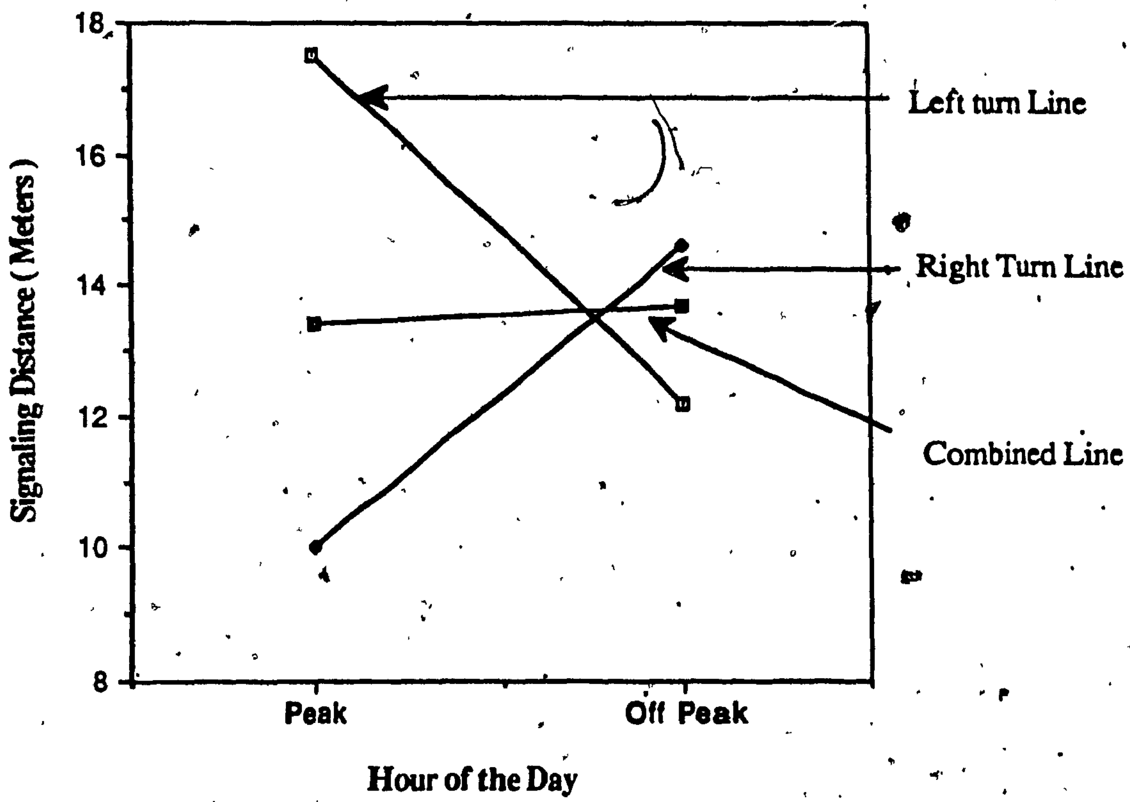


Figure 18 : Signaling Distance Vs Hour of the Day

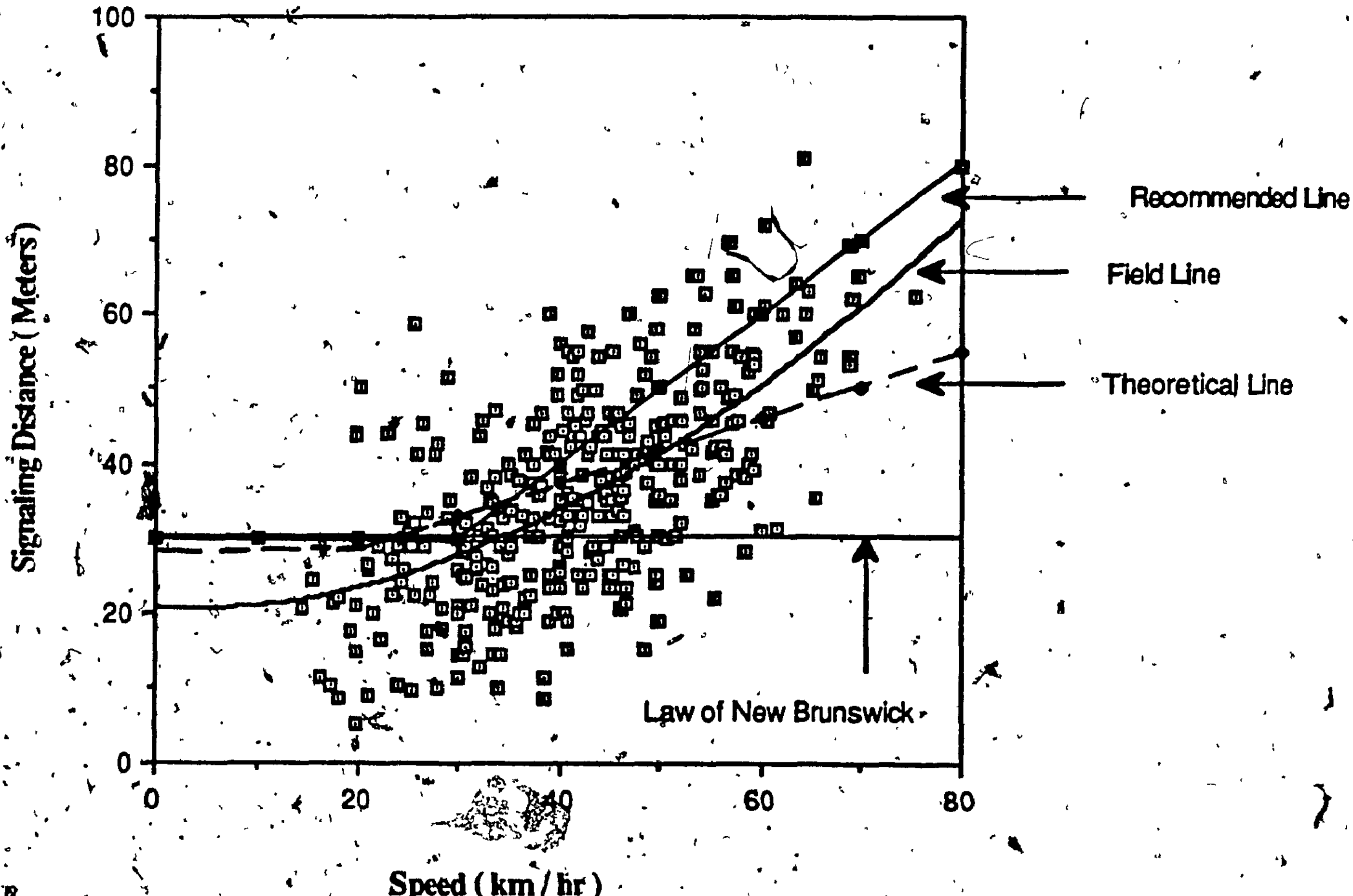


Figure 19 : Signaling Distance Vs Speed of the Vehicle