REDIRECTION EFFECTIVENESS OF ROADSIDE CURBS

by

NADINE LAFOND

B. Eng. École Polytechnique de Montréal, 1995

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE
in
THE FACULTY OF GRADUATE STUDIES
Department of Civil Engineering

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
September 1997
© Nadine Lafond, 1997
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Civil Engineering

The University of British Columbia
Vancouver, Canada.

Date 12 September 97

DE-6 (2/88)
Abstract

Curbs are commonly used along urban streets, in channelised intersections, and along medians and ramps. One of its purposes is to protect pedestrians. The protection offered by a curb is measured by its ability to redirect errant vehicles. A curb redirection effectiveness depends upon the speed and the angle of impact of a vehicle, the height of the curb, the vehicle mass, and the tire radius. The effectiveness is also influenced by other factors such as the coefficient of friction between the tire and the curb, the tire pressure, and the geometric design of the curb.

The redirection ability of a 152 mm high curb of type C design from the AASHTO Manual was investigated during 28 full scale tests. Six vehicles, of a mass between 675 and 1750 kg, impacted the curb at a speed varying from 6 to 34 km/h, at angles of 5°, 10°, or 15°. Four tests were performed to evaluate scrubbing conditions and a 90° impact. Mass was added to some vehicles to measure the influence of the mass without modifying vehicle dimension and properties.

It was found that a type C curb does not provide an appropriate protection to pedestrians since it can easily be crossed when the component of the velocity normal to the curb exceeds 2 km/h. Redirection was not achieved in any of the tests performed at an impact angle of 15°. According to the tested data, the probability that a vehicle is not redirected by the curb starts at an impact speed of 10 km/h and reaches 100% at a speed of 40 km/h when approaching the curb at a 5° angle.

An equation relating redirection speed to the impact angle, the curb height, and the studied vehicle parameters, was validated. A safe curb height of 205 mm is suggested to substantially improve the curb’s ability to redirect an errant vehicle hitting a curb at a shallow angle, up to a normal speed of 4.7 km/h.
Table of Contents

Abstract ii
Table of Contents iii
List of Tables vi
List of Figures vii
Acknowledgment x

1. INTRODUCTION 1

1.1 Definitions 1
1.2 Nature of the Problem 3
1.3 Literature Review 4
1.4 Objectives 10
1.5 Organisation of the Thesis 11

2. THEORY - VARIABLES 12

2.1 Curbs Characteristics 12
  2.1.1 Height 12
  2.1.2 Geometric Design 14
  2.1.3 Coefficient of Friction 15
    2.1.3.1 Material 16
    2.1.3.2 Wet/Dry/Icy 17
2.2 Tire Parameters 18
  2.2.1 Construction 18
  2.2.2 Tire Radius 20
  2.2.3 Pressure 22
  2.2.4 Tread 23
2.3 Vehicle Mass 24
2.4 Impact 26
  2.4.1 Speed - Angle 26
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3.4 Vehicle Acceleration</td>
<td>69</td>
</tr>
<tr>
<td>4.4 Extreme Angle Impact</td>
<td>70</td>
</tr>
<tr>
<td>4.4.1 Scrubbing - Zero Degree Impact</td>
<td>70</td>
</tr>
<tr>
<td>4.4.2 Ninety Degrees Impact</td>
<td>72</td>
</tr>
<tr>
<td>4.5 Conclusion</td>
<td>74</td>
</tr>
</tbody>
</table>

5. CONCLUSION AND RECOMMENDATIONS 76

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Conclusion</td>
<td>76</td>
</tr>
<tr>
<td>5.2 Recommendations</td>
<td>80</td>
</tr>
</tbody>
</table>

6. BIBLIOGRAPHY 82

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A: Full Scale Tests Set-up</td>
<td>85</td>
</tr>
<tr>
<td>Appendix B: Video Pictures</td>
<td>86</td>
</tr>
<tr>
<td>Appendix C: Vehicle's Attitude Data</td>
<td>95</td>
</tr>
</tbody>
</table>
List of Tables

3-1: Description of the test vehicles 38
3-2: Measured vehicle characteristics 39
4-1: Summary of full-scale test results for a type C curb 47
4-2: Comparison of the predicted redirection speeds to the tested speeds and redirection behaviours 61
C-1: Measured steering wheel rotation, bumper rise, and vehicle roll 95
C-2: Maximal recorded longitudinal and lateral accelerations 96
# List of Figures

1-1: AASHTO curbs designs ........................................ 2
1-2: Curb designs for tests 1953 .................................. 5
1-3: Curb designs for tests 1955 .................................. 5
1-4: Curb designs in Dunlap’s study ............................... 8
2-1: Normal velocity required to climb a vertical face drop-off as a function of edge height .................. 13
2-2: Relationship between drop-off edge shape and safety ................................................................. 15
2-3: Influence of pavement edge friction ........................ 17
2-4: Effect of tire construction when mounting a pavement drop-off in a scrubbing condition with an intermediate vehicle at speeds of 56, 72, and 88 km/h ............................................ 19
2-5: Steer angles required to mount edges of different effective heights by a car and trucks .................. 21
2-6: The influence of curb height and radius of tire on redirection ...................................................... 22
2-7: Forces acting on a tire’s pavement contact patch ....... 23
2-8: Side force versus slip angle for various tread conditions, for a constant wheel load of 30 kN and a constant speed of 60 km/h ................................................................. 24
2-9: Vehicle size comparison for a non scrubbing condition at speeds of 56-72-88 km/h for various edge heights performed by a professional driver ........................................... 25
2-10: Redirection boundary curves ................................. 29
2-11: Comparison of 2 curves describing the redirection effectiveness of a type C curb ............................... 31
2-12: Positive vehicular sign convention .......................... 33
2-13: Curb’s redirection ability influence diagram ......... 36
3-1: Testing curb cross section ................................... 38
3-2: Camera positions .............................................. 41
3-3: Reference targets .............................................. 41
3-4: Testing vehicle approach angles ............................ 42
3-5: Tire radius and vehicle mass configuration ......... 44
4-1: Vehicle redirection capabilities of Type C curb, according to tested data

4-2: Probability of being redirected when striking a type C curb at an approaching angle of 5°

4-3: Influence of tire radius on redirection for a concrete curb of 152 mm high, impacted at an angle of 5°

4-4: Influence of the ratio of the curb height over the tire radius on redirection for a type C concrete curb, 152 mm high

4-5: Influence of the mass on redirection for a type C curb

4-6: Curb height to produce redirection as a function of the normal speed to the curb and the vehicle mass

4-7: Curb height to produce redirection as a function of the vehicle mass for various speeds normal to the curb

4-8: Bumper rise with respect to the top of the curb of a small vehicle (Sprint) impacting the curb at 5° and 19 km/h, with and without additional load

4-9: Bumper rise of two different size vehicles striking a curb at a 90° angle at a speed of 9 km/h

A-1: Front view

A-2: Overall view

B-1: Test No 15 - Redirection - Reliant with an additional mass impacting the curb at 11.3 km/h and at an angle of 5°

B-2: Test No 13a - Partial Redirection - Reliant impacting the curb at 17.6 km/h and at an angle of 5°

B-3: Test No 17 - No Redirection - Reliant with additional mass impacting the curb at 25.9 km/h and at an angle of 5°

B-4: Test No 25 - Civic climbing the curb from a scrubbing condition at approximately 30 km/h

B-5: Test No 26 - Cordoba climbing the curb from a scrubbing condition at approximately 30 km/h

B-6: Test No 27 - Cordoba impacting the curb at an angle of 90° at a speed of 8.4 km/h
B-7: Test No 28 - Civic impacting the curb at an angle of 90° at a speed of
9.1 km/h

C-1: Maximal measured longitudinal and lateral acceleration in function of the
speed normal to the curb

C-2: Maximal measured longitudinal acceleration experienced in each test in function
of the vehicle mass

C-3: Maximal measured lateral acceleration experienced in each test in function of the
vehicle mass
Acknowledgment

The completion of this study was very rewarding. It was made possible by the support and assistance of several individuals whose contributions should be recognised.

First, I would like to sincerely thank my supervisor, Dr. Frank Navin, for his guidance and support throughout the preparation of this thesis, and for his confidence in allowing me to work independently. I am also grateful to him for allowing me to participate in a student exchange program at the University of New South Wales in Australia. I would also like to acknowledge his wife, Marina Navin, for correcting my English.

A number of people also contributed directly to this project. I am especially thankful to Roy Klymchuk, for his help in the organisation of the experimental testing, for his judicious advice prior to and during the full scale tests, and for his exceptional performance as a professional driver. I would also like to express my gratitude to the following individuals: Robert Thomson and Emmanuel Felipe for their technical advice in the experimental set-up; Keith Mayhew from ICBC for his cooperation in supplying the vehicles; and Al Lund, director of PTEC, for providing a site to perform the full scale tests.

Finally, I would like to thank my peers in civil engineering for their help during the experimental testing: Dominique Poulin, Rafael Arce, Vincent Latendresse, Caroline Frénette, and Kim Nishimura.

This project would not have been possible without the financial participation of the Natural Science and Engineering Research Council of Canada (NSERC). I acknowledge their contribution to this project.
1. INTRODUCTION

Roadside accidents are a serious safety problem. A considerable amount of research has been devoted to developing roadside designs to maximise traffic safety. Roadside curbs are thought to provide some protection by redirecting errant vehicles. This research concentrates on measuring the ability of roadside curb to redirect an errant vehicle and developing equations to predict a curb's redirection capability.

1.1 Definitions

Curbs are used on all types of urban highways and streets, in channelised intersections, and along median and ramps. They serve one or more of the following purposes: (i) control drainage; (ii) discourage vehicles from leaving the road; (iii) provide protection to pedestrians; (iv) delineate the roadway edges; (v) give a more finished appearance, (vi) reduce maintenance; and (vii) aid orderly development of the roadside. To be considered a curb, some degree of vertical elevation above the roadway surface is required (AASHTO, 1994).

Curbs exist in two general classes: barrier and mountable. Barrier curbs are relatively high, ranging from 150 to 255 mm or more in height. The main function of barrier curbs is to prevent vehicles from leaving the roadway. Mountable curbs are designed so it is possible for a vehicle to cross them. The height of most mountable curbs does not exceed 150 mm and they have flat or round sloping faces. The American Association of State
Highway and Transportation Officials (AASHTO) defines one type of barrier curb and six types of mountable curbs as illustrated in Figure 1-1.

Figure 1-1: AASHTO curbs designs
Chapter 1: Introduction

Roadside barrier curbs are the subject of this study. However, research regarding the safety of pavement edge drop-offs will also be consulted since drop-off edges and curbs share similarities.

Pavement drop-offs are vertical discontinuities between adjacent road surfaces. They can occur at the joining of the following surfaces: (i) a paved road and an unpaved shoulder; (ii) a paved road and a paved shoulder; (iii) a paved shoulder and an unpaved adjacent area; and (iv) two travelled lanes. Drop-offs may be created during construction, or when new traffic lanes are added to existing one. Generally, they are created by the degradation of the shoulder material due to vehicle tire contacts, or erosion by wind, rain or other environmental conditions (Ivey et al., 1984).

1.2 Nature of the Problem

In 1985, 24,000 vehicles were involved in accidents related to impacts with roadside curbs in the United States, resulting in a cost of 1,078 million US$ (Viner, 1994). Roadside curbs are often used to redirect errant vehicles. When a vehicle unintentionally mounts a curb, it can cause injury to bystanders or collide with fixed objects located behind the curb. When curbs are used as dividers between opposing traffic lanes, vehicles crossing these curbs could become involved in accidents with oncoming traffic. Striking a curb can cause the driver to lose control of his vehicle. Curbs constitute a continuous roadside obstacle, since they are present on travelled lanes for appreciable length, and are consequently highly subject to be impacted by vehicles.
A vehicle’s level of safety upon hitting a curb is influenced by factors such as the height of the curb, its geometric design, the velocity of the vehicle, the angle of impact, the tire conditions, and the type of vehicle. If the angle of impact is very shallow, a phenomenon called scrubbing occurs. Scrubbing takes place when the wheels of a vehicle rub (scrub) along the vertical edge. Trying to mount a curb while scrubbing can result in loss of vehicle control and has been recognised as a significant safety problem (Ivey et al., 1988).

The question is whether the actual curb design is beneficial in redirecting an errant vehicle, or does it strictly constitutes an obstacle that aggravates the loss of control of the vehicle?

1.3 Literature Review

In 1953 and 1955, the Department of Public Works of California tested roadside bridge curbs of heights varying from 150 to 305 mm. Figure 1-2 illustrates the eleven different designs of roadway curbs that were tested in 1953. Ten of them were constructed from concrete, and one, Curb VI-M, had a metal face. In 1955, the four designs considered the most promising by the 1953 tests were studied and are shown in Figure 1-3. Two of them were made of concrete, and the two others were made of steel. The tests demonstrated that the effectiveness of a curb to redirect a vehicle varies directly with the curb height and inversely with the angle of collision. Also, the experiments disclosed that for reducing damage to the vehicle and to increase human safety, the three main factors to
consider in curb design were: (i) height of curb; (ii) material used in the construction; and (iii) geometric design.

![Curb designs for tests 1953](image)

**Figure 1-2: Curb designs for tests 1953**

![Curb designs for tests 1955](image)

**Figure 1-3: Curb designs for tests 1955**
In 1965, the Road Research Laboratory in the UK performed tests to determine the effectiveness of highway safety curbs. The Belgian Trief safety curb, illustrated in Figure 1-4 (b) stands about 305 mm above the road. It was tested at impact angles of 5° and 10° and at approach speed between 24 and 64 km/h. It was shown that the Belgian curb was an effective barrier for cars, provided that the component of the approach speed perpendicular to the curb was less than 4.9 km/h.

Marshall (1968) conducted sixty-eight full-scale tests on a precast traffic curb of type C (Figure 1-1) from the AASHTO manual. The approach angles varied from as flat as possible to 7.5°, and speeds from 15 to 90 km/h. The tests were performed on wet and dry pavement, for different tire pressures. Several simulated recovery actions by the driver were also studied. It was concluded that the AASHTO type C curb can be mounted with relative ease, and that the probability of damage to the vehicle’s undercarriage was high when the curb was crossed. It was recommended that one reduces the height of the mountable curbs in order to decrease the possibility of loss of control by a vehicle striking the curb at an angle and speed sufficient to go over it.

Dunlap et al. (1973) also studied the redirective effectiveness of curbs. They found that the efficiency of a curb as redirective device was defined by the percentage of the total errant vehicle population that could be expected to be redirected by a given curb. In mathematical terms, the desired percentage measure can be expressed by the following equation:
Chapter 1: Introduction

\[ P[V < V_p(\alpha)] = \int_0^{v_p(\alpha)} \int_0^{\pi/2} f(V, \alpha) dV d\alpha \quad (1-1) \]

where

\[ V \quad = \quad \text{impact velocity}; \]
\[ \alpha \quad = \quad \text{impact incidence angle}; \]
\[ V_p(\alpha) \quad = \quad \text{specific curb redirective performance limit expressed in terms of } \alpha; \]
\[ f(V, \alpha) \quad = \quad \text{joint frequency function of velocity and angle for ran-off-the-road vehicles}. \]

The redirective performance of a specific curb was found to conform to the following equation:

\[ V_p(\alpha) = \frac{K}{\sin \alpha} \quad (1-2) \]

where k is a constant. Two curb designs were studied under urban traffic conditions: the German Elsholz curb (Figure 1-4 (a)) and the Belgian Trief curb (Figure 1-4 (b)).
In 1974, Olson et al. analysed the effect of curb geometry and location on vehicle behavior. Some 18 tests were conducted by a professional driver and 36 were simulated. Three curb designs were analysed: type C, type E, and type H from the AASHTO curb designs shown in Figure 1-1. The tests led to the conclusion that curbs of 152 mm or less should be discontinued on high-speed highways because they offer no enhancement to safety at high-speed. The purpose of curbs as drainage and delineation can be achieved in other ways that do not produce roadway discontinuities.

Ross et al. (1989) looked at the roadside curbs safety design for small vehicles. Type C, type E, and type G from the AASHTO curb designs were tested. For a given curb design, the probability of a car to overturn when sliding into a curb increases as the vehicle size decreases. They found that to minimise the propensity of a minicar to overturn, the slope of the curb face should be as flat as possible, preferably 30° or less.
Very recently, Ogan et al. (1995) examined the acceleration levels and the motions of the occupant when a vehicle runs into and over a roadside curb of 152 mm. The mountable curbs were tested at impact angles between 30° and 90° and at relatively low impact speeds, ranging from 24 to 43 km/h, representative of the urban driving conditions. The measured peak acceleration levels were very low and the kinematic responses of the drivers and passengers were minimal. None of the occupants made physical contact with any of the interior components of the vehicles during the testing.

Finally, Navin and Thomson (1997) suggested analytical relationships to estimate the limiting approach speed at which a vehicle will be redirected when striking a curb as a function of the approaching angle, the height of the curb, the radius of the tire, the coefficient of friction of the edge surface, and the mass of the vehicle. Equation 1-3 expresses this relationship.

\[
V_r = \frac{50}{\sin \theta} \left( \frac{h}{r} \right)^{3.5} \left( \frac{\mu_{CD}}{\mu_N} \right) \left( \frac{m_T}{m_N} \right) \tag{1-3}
\]

where

\[
\begin{align*}
V_r & = \text{ redirection speed (km/h)} \\
\theta & = \text{ impact angle (degrees)} \\
h & = \text{ height of the curb (mm)} \\
r & = \text{ radius of the tire (mm)} \\
h/r & \leq 0.75
\end{align*}
\]
Chapter 1: Introduction

\[ \mu_{CD} = \text{coefficient of friction of smooth rubber on dry concrete} \]
\[ \mu_N = \text{coefficient of friction of smooth rubber on new surface} \]
\[ m_T = \text{average mass of test vehicles (kg)} \]
\[ m_N = \text{mass of actual vehicle (kg)} \]

### 1.4 Objectives

The purpose of this project is to study the redirection ability of a roadside curb of type C design from the AASHTO Manual, at speeds and angles of impact consistent where such curbs are used, for vehicles having a mass representative of the current vehicle market, and radial tires of varying radii.

The primary objectives are:

- to determine the relationship of the impact speed required to mount the curb as a function of the angle of impact, the vehicle mass, the tire radius, and the height of the curb in order to validate Equation 1-3;
- to determine a safe curb height that will produce vehicle redirection under given impact conditions.

Also, this study looks at the vehicle attitude following the curb impact. Also, to set lower and upper limits of impact angle, scrubbing and ninety degrees approaches were studied.
Chapter 1: Introduction

The application of the results from this project will contribute to a better understanding of vehicle behaviour when inadvertently striking a concrete roadside curb of type C. This knowledge should provide design engineers with a practical tool for curb design.

1.5 Organisation of the Thesis

In the next chapter, the theory related to roadside curbs and highway drop-offs, as well as the variables influencing the curb redirection effectiveness are explained. The experiment set-up is then described, followed by an analysis of the results obtained from full scale tests. Finally, conclusions of the study are presented and a number of recommendations are discussed.
2. THEORY - VARIABLES

This chapter describes the variables that influence the curb’s ability to redirect a vehicle. These variables are related to the curb itself, the vehicle, the tire, the impact speed normal to the curb, and the driver. Dynamic parameters that describe the vehicle’s attitude after the impact are also presented.

2.1 Curbs Characteristics

Curbs are characterised by their height, geometric design, and coefficient of friction of the curb-tire interface. This section looks at studies carried out on the safety of pavement edge drop-offs, since curbs and drop-offs share many similarities. However, it must be noticed that a driver behaves in an opposite way when interacting with one or the other: a driver will attempt mounting a drop-off, whereas they will avoid mounting a curb. For this reason, the level of safety associated with an edge drop-off interaction is determined in a different way to the one associated with a curb interaction. As the height of the edge increases, it becomes more hazardous to climb, therefore, as a curb it will be safer, but as an edge pavement drop-off it will be more risky.

2.1.1 Height

The curb height is a major factor influencing whether a vehicle will climb the edge or will be redirected.
Klein et al. (1979) stipulated that the edge height of a pavement drop-off and the normal velocity (velocity perpendicular to the edge) are the critical parameters that determine the climb or redirection, characteristics of a curb. Figure 2-1 shows that the normal velocity required to climb an edge increases as the shoulder height increases. It can be observed that when the pavement edge is higher than 100 mm, the normal speed required increases sharply, and consequently, so do the risk of loss of control. In the same way, the higher the edge of a curb, the higher the likelihood that a vehicle will be redirected.

Figure 2-1: Normal velocity required to climb a vertical face drop-off as a function of edge height
2.1.2 Geometric Design

It is obvious that an inclined edge is easier to climb than a vertical one. However it is more complex to determine the influence of the myriad of existing curb geometric designs, and experimental testing is therefore required. Figures 1-1 to 1-4 illustrate some of the possible curb designs. Tests conducted by the Department of Public Works of California (1955) demonstrated that an undercut curb produces higher deceleration of a deflected vehicle than a curb without an undercut.

Figure 2-2 shows how the shape of the edge of a drop-off influences the ability to climb it. Shape A is a vertical edge, shape B is a rounded drop-off with a 40 mm radius edge, and shape C is a 45° edge. Figure 2-2 shows how increasing the radius at the top of the edge eases the vehicle’s climb for a given vertical edge height. Providing a 45° angle (shape C) substantially increases the ease to mount a given vertical elevation. The qualifying terms of safety of Figure 2-2 are related to drop-off climbing, and must, therefore, be inverted to evaluate a curb redirection effectiveness.
2.1.3 Coefficient of Friction

The tire-edge friction partially controls whether the vehicle will climb or will be redirected when striking a curb. The coefficient of friction between a tire and an edge varies according to the material of the edge and whether the edge is dry, wet, or icy. It also depends upon the tread of the tire, and is discussed in the following sections.
2.1.3.1 Material

Concrete is the most universally used material for curbs. In the full scale tests conducted by the California Department of Transportation (1957) on the effects of vehicles climbing over curbs at various angles, two types of material were used: concrete and steel. The tests indicated that for curb heights ranging from 152 to 305 mm, steel surface curbs were more effective than concrete curbs in deflecting a vehicle at a high impact speed. Rubber tires tend to grip the concrete, making this type of curb more readily mountable than the steel curb. However, steel curbs accomplished very little deceleration of the vehicle after impact and are inclined to redirect a vehicle back into traffic at a relatively high angle. On the other hand, concrete curbs tend to slow down a vehicle at the same time they deflect it, because of their more pronounced friction that helps decelerate the vehicle.

The use of different materials results in a variation of coefficient of friction. The steer angle required to climb a pavement edge for various coefficients of friction was determined by Ivey and Sicking (1986), and the results are summarised in Figure 2-3. When the pavement height is smaller than 85 mm, the steering wheel angle required to climb increases very slightly as the pavement edge friction increases. When the pavement edge height is greater than 85 mm, the inverse situation happens: the smoother the surface, the higher the steering angle required to climb. Examination of Figure 2-3 shows that the influence of the coefficient of friction is negligible for edge height smaller than 100 mm. Over this height, a smooth surface will have a greater redirection effectiveness than a rough one.
2.1.3.2 Wet/Dry/Icy

A wet or icy edge has a lower coefficient of friction than its dry condition, and would generally be more difficult to mount.

Tests performed on the Belgian Trief Curb (Figure 1-4 (b)) by the UK’s Road Research Laboratory in 1965 confirmed the influence of tire-curb friction on mounting. When a vehicle hit a dry curb at an impact angle of 15°, the velocity needed to mount was 19 km/h. When the curb and the tires were wet, the mounting velocity increased to 32 km/h.

Marshall (1968) detected significant difference in vehicle reaction when the vehicles struck a curb in dry and wet conditions. There was a very noticeable amount of skidding.
whenever the vehicle crossed the wet curb and the rear wheels exhibited a propensity to slide along the curb for varying distances before crossing.

2.2 Tire Parameters

This study investigates the influence of tire construction and tire radius on a curb redirection effectiveness. However, other tire parameters such as the pressure and the tread may also affect the tire edge interaction. These tire parameters are not part of this study, but they are nevertheless described in the following section.

2.2.1 Construction

Tires have two main types of construction: bias-ply and radial-ply, the latter dominates the current market. The older bias-ply design has been largely replaced by the more complex radial tire, to satisfy the increasing demand on operating capabilities of the tires used on today’s passenger and heavy vehicles.

Ivey and Zimmer (1982) evaluated the effect of the tire construction on their ability to mount a pavement drop-off during scrubbing. An intermediate and full size sedan were tested with both bias ply and radial tires. Figure 2-4 shows that radial tires can mount more easily than bias-ply tires for all edge heights and shapes.
Klein and Johnson (1979) demonstrated that the steering wheel rotation needed to climb an edge from a scrubbing condition was a function of tire characteristics. These experiments lead to the conclusion that radial tires required slightly less steering than bias belted tires to mount a vertical edge. However, the vehicles equipped with tires of different construction types were of various sizes and the tires had diverse diameters. The results might have been influenced by these two latter factors and are not considered conclusive.

Both studies concerning pavement edge drop-offs agree that radial tires are slightly more efficient to climb an edge than bias-ply tires. These results suggest that roadside curbs would be less efficient in redirecting a vehicle equipped with the radial tires than the older bias-ply design.

Figure 2-4: Effect of tire construction when mounting a pavement drop-off in a scrubbing condition with an intermediate vehicle at speeds of 56, 72, and 88 km/h
2.2.2 Tire Radius

Even though it seems obvious that the size of a tire affects its interaction with the edge of a curb, very few studies examined this aspect. In most of the experiments, the vehicles were equipped with tires of rim diameters between 330 and 380 mm.

It is expected that as the radius of the tire increases, the facility of a vehicle to climb an edge increases, and the ability of a curb to redirect a vehicle decreases. Klein et al. (1979) ran experiments with different tire radii climbing drop-off edges, but they were used on various vehicle sizes and/or the tires were of a different construction. For these reasons, no convincing conclusion could be drawn on the effect of tire radius on redirection from their studies.

Ivey et al. (1990) studied the loss of control of trucks caused by pavement drop-offs. Truck tires are 60 to 100% larger in diameter than those of automobiles. For a truck tire radius of 53.3 cm, the amount of steer angle needed to climb a series of different edge heights was determined. Figure 2-5 compares those results to the ones of an automobile previously investigated (Ivey & Sicking, 1986). Curve A represents an automobile front tire and Curve B, a truck front tire, which is twice as large as the car tire in this case. Even though the truck tire has an overall poorer cornering friction capacity than the automobile tire, it can mount a pavement edge at lower value of steer angle, because the tire size effect dominates the relationship.
[Ivey et al. 1990]

**Figure 2-5: Steer angles required to mount edges of different effective heights by a car and trucks**

Based on previous studies, Navin and Thomson (1997) plotted a graph of the impact speed versus the ratio of the curb height over the tire radius for two curb materials and for a pavement drop-off mounted in a scrubbing condition (Figure 2-6). The impact speed required to mount the edge was found to follow a power relationship with the ratio of the edge height over the tire radius, for a ratio smaller than 0.75.
Figure 2-6: The influence of curb height and radius of tire on redirection

2.2.3 Pressure

Tire pressure is another aspect that has been investigated fully. Ivey and Zimmer (1982) in their study on pavement edges and vehicle stability stipulate in their conclusion:

The influence of differential tire pressures, especially low pressures on one or more rear tires was not specifically investigated although it is anticipated that anything which enhances oversteering would be a more critical situation in a scrubbing edge manoeuvre.

Klein and Johnson (1979) in their measurements of vehicle responses as a function of tire parameters when climbing a pavement drop-off, experimented with three different tire pressures: 125 kPa (low), 165 kPa (normal), and 220 kPa (high). According to this study, for a pavement edge smaller than 100 mm and a tire pressure between 125 and 220 kPa, the steering wheel required to climb the edge is not affected by tire pressure. The same result was found when the edge height was greater than 100 mm and the tire
pressure was normal to high. But when the edge is higher than 100 mm, tires with low pressure are able to climb a pavement drop-off more easily than those with normal or higher pressure setting. The effect of tire pressure is still ambiguous and requires further investigation.

2.2.4 Tread

When the tire rotates at a slip angle ($\alpha$), side forces ($F_s$) are generated as illustrated in Figure 2-7. The side force is dependent on the slip angle, and increases as the tire rotates. For a constant load applied to the wheel ($F_r$), and at a constant speed ($v_o$), side-force/slip angle curves become steeper as the tread depth is reduced, and the side forces which can be transferred are increased as demonstrated in Figure 2-8. Because larger cornering forces are generated by a tire when it is worn, the experiments carried out by Klein and Johnson (1979) revealed that worn tires were able to climb a vertical elevation easier than new tires.

\[ \text{Figure 2-7: Forces acting on a tire's pavement contact patch} \]
Figure 2-8: Side force versus slip angle for various tread conditions, for a constant wheel load of 30 kN and a constant speed of 60 km/h

2.3 Vehicle Mass

The mass of a vehicle has an ambiguous effect on the redirection effectiveness of a curb and the ease with which it mounts a pavement drop-off. The reported data do not agree concerning the influence of a vehicle mass. Most of the previous studies did not make a clear distinction between vehicle mass and dimension. A heavier vehicle was inevitably of larger dimension, with bigger tires and different suspension type. The effect of the
mass by itself was therefore not measured directly and was difficult to derive from the reported data.

Most of the studies concerning pavement drop-off concluded that the ease with which it climbed a drop-off edge was independent of the vehicle size (Klein and Johnson, 1979; Norlin, 1979; Ivey and Zimmer, 1982).

Figure 2-9 also indicates little sensitivity of the vehicle size on the ease to climb a pavement edge drop-off. Pavement drop-off tests were performed by a professional driver in a non scrubbing condition at speeds between 56 and 88 km/h. For any edge height, the severity level is relatively similar for the four vehicle sizes.

Figure 2-9: Vehicle size comparison for a non scrubbing condition at speeds of 56-72-88 km/h for various edge heights performed by a professional driver.
However, more recent studies recognised differences in vehicle behaviour according to their size. In their 1986 experiments, Olson and Zimmer observed that small cars seemed to have greater difficulty in negotiating the edge drops than did the larger car. Also, Ross et al. (1989) studied the interaction of small cars with roadside features. Their results suggested that small cars do not climb as high as a larger car after crossing a curb, and that for nontracking impacts, a smaller car will overturn more easily than a larger car.

The influence of a vehicle mass on curb performance is indeterminate, and therefore, this research will look more closely at the consequences generated by the variation of vehicle mass when interacting with a curbs.

2.4 Impact

2.4.1 Speed - Angle

The speed of impact when hitting a curb or climbing a drop-off is reported to be one of the most important factors determining the safety of the manoeuvre. It is generally the normal or perpendicular speed to the edge that is considered in evaluating the safety of a vehicle-edge interaction. For this reason, the angle of impact plays an important role since it determines the speed component. Consequently, the angle of impact and the impact speed determine if redirection will or will not occur.
Olson et al. in 1974 investigated three types of the AASHTO mounting curbs: curbs of type C; type E; and type H (Figure 1-1). Full scale tests and simulation were executed to evaluate the redirection effectiveness at various impact angles and speeds. It was found that the mountable curbs do not achieve redirection when the impact speed is greater than 90 km/h, for an impact angle greater than 5°, as indicated in Figure 2-10. Nevertheless, at speeds lower than 50 km/h, which is representative of urban areas, a type C curb provides redirection for a large possibility of impact angles.

Several authors formulated relationships between the approach angle and velocity to describe the redirection effectiveness of a curb or a pavement drop-off.

Klein and Johnson (1979) stipulated that the necessary condition for climbing a shoulder edge drop-off up to 100 mm requires the vehicle velocity perpendicular to the shoulder to be proportional to the shoulder height. The required velocity is expressed as follows:

\[ V_p = 0.5h \]  \hspace{1cm} (2-1)

where

\[ V_p \] = perpendicular velocity necessary to climb the edge in ft/sec

\[ h \] = drop-off height in inches (smaller than 4 inches)

This equation can be rewritten in S. I. units and as a function of the impact angle.

\[ V = \frac{0.022h}{\sin \theta} \]  \hspace{1cm} (2-2)
where

\[ V = \text{redirection required speed in km/h} \]
\[ h = \text{height of drop-off in mm (smaller than 100 mm)} \]
\[ \theta = \text{impact angle in degrees} \]

This equation is represented in Figure 2-10 for an edge drop-off height of 100 mm. It can be observed that it provides less redirection than a type H curb of the same height with an inclined edge of 27°. It was demonstrated in a previous section that an inclined edge is easier to climb. These results are, therefore, in contradiction.

According to Equation 2-3, derived by Dunlap in 1973, whenever the component of vehicle velocity normal to a curb was larger than a fixed value, the vehicle would mount the curb. Below that value, redirection would occur.

\[ V \sin \alpha = \text{constant} = k \]  \hspace{1cm} (2-3)

where:

\[ V = \text{impact velocity in km/h} \]
\[ \alpha = \text{impact incidence angle in degree.} \]

The value of \( k \) was estimated at 4.9 km/h for the Belgian Trief curb and at 14.6 km/h for the German Elsholz curb (Figure 1-4). Their redirection boundary curves are represented in Figure 2-10. The various equations derived to estimate the redirection boundary as a function of the impact speed and angle, give incompatible results. It seems very unlikely
that a 305 mm high curb would provide redirection for the same impact conditions as a 100 mm high curb, even if their geometric design differs considerably.

\[ \text{German Elsholz curb (270 mm)} \]
\[ \text{Type C curb (150 mm)} \]
\[ \text{Types E (150 mm) & H (100 mm) curb} \]
\[ \text{Belgian Trip curb (305 mm)} \]
\[ \text{Drop-off (100 mm)} \]

[Olson et al. 1974; Dunlap, 1973; Klein et al., 1979]

Figure 2-10: Redirection boundary curves

If Equation 2-3 is applied to the Olson's curve describing the redirection effectiveness of a type C curb, the value of \( k \) is about 10 km/h. That means that if the velocity perpendicular to the curb in any approach exceeds 10 km/h, the curb will be climbed.

Based on previous studies, Navin and Thomson (1997) derived an equation delimiting redirection for a given impact speed and a given impact angle, and as a function of the
height of the edge. This relationship (Equation 2-4) is applicable for curb as well as drop-off, for edge heights between 100 and 500 mm, and for shallow angles.

\[ V = \frac{0.01h}{\sin \theta} \]  \hspace{1cm} (2-4)

where

\[ V = \text{redirection required speed in km/h} \]
\[ h = \text{height of the edge in mm (between 100 and 500 mm)} \]
\[ \theta = \text{small impact angle in degrees} \]

This latter equation does not fit the suggested curves of Olson et al. (1974) for a type C curb. As indicated in Figure 2-11, Navin’s equation underestimates the capacity of redirection in comparison to Olson (1974) results. It can be observed from the data points used to plot Olson’s redirection curve, that only one redirection point came from a full scale test. The remaining six redirection data arose from simulated tests.

The two redirection equations characterising a type C curb as a function of speed and angle of impact show an important inconsistency between Olson curve and the one by Navin. This project should resolve this inconsistency.
Figure 2-11: Comparison of 2 curves describing the redirection effectiveness of a type C curb

2.4.2 Scrubbing

For very shallow angles of impact, a phenomenon called scrubbing can occur when a vehicle interacts with a vertical edge. The term scrubbing describes the near-parallel traversal of the tire along a vertical edge. It occurs when the wheel that contacts the curb or pavement edge has insufficient normal velocity to overcome the retarding force produced by the tire and edge contact. It happens at edge height levels as low as 25 mm, even though it is not related to safety at such low height. Scrubbing has been recognised as a safety problem, since it can result in vehicle loss of control once the vehicle mounts the edge. Because it is such a serious problem the present research uses it as one of the boundary conditions.
2.5 Driver

Driver skill is obviously a large factor in the accident rate, but it is also a very complex variable. It is difficult to evaluate the effect of surprise experienced by the driver as he/she strays from the road surface onto the shoulder or hits a roadside curb.

Results of studies carried out with only professional drivers gave more favourable results than ones performed with a large sample of naive subjects regarding drop-off negotiations. On the other hand, most curb studies made use of a professional driver, since most of the tests were conducted in a hands off steering wheel mode, and professional skills are needed to maintain the assigned speed and course prior to impact, in order to control the vehicle after crossing the curb. For these reasons, the driven experiments in our test will use a professional driver.

2.6 Dynamic Parameters

Vehicle behaviour, and the severity of a recovery manoeuvre during and after impact with an edge, is often evaluated with the help of the following dynamic parameters:

- roll angle;
- pitch angle;
- yaw angle;
- acceleration.

The measurements of these parameters provide additional insight into forces acting on the vehicle and how the driver must respond to maintain vehicle stability.
2.6.1 Roll, Pitch, and Yaw Angles

The first three parameters are rotation of the vehicle around the x, y and z axis, as illustrated in Figure 2-12.

According to Nordlin et al. (1979), the vehicle roll angle was not a very relevant indicator of the severity level encountered by the driver when mounting a pavement edge of less than 114 mm high. The vehicle roll angle was not correlated to the height of the drop-off, and the maximum roll angle recorded was 10°, which is far from an impending rollover condition.

Similar conclusions were drawn concerning the yaw angle (Olson & Zimmer, 1986). Regardless of the pavement edge height or the speed of the vehicle, the yaw rate averaged between 20 and 30 degrees/sec.
However, the combination of vehicle roll and pitch angles provides an indication of the safety level of a curb impact, based on the Olson et al. study. The maximum bumper rise, which is dependent on the combination of vehicle roll and pitch, determines the risk of a secondary collision with an obstacle located behind the curb. The maximum bumper rise increases with speed for a given impact angle. However, neither the maximum roll nor pitch angle has a clear relationship with the impact speed.

2.6.2 Acceleration

Vehicle acceleration can be measured in the three axis's directions: longitudinal (x), lateral (y), and vertical (z).

Based on the Kemmer and Meyer study (1967), the average driver considers any lateral acceleration above 0.30g to be excessive. This could lead to a situation where the average driver will hesitate to develop lateral acceleration over 0.30g and thus, cause a vehicle to lose control.

From the Olson and Zimmer study (1986), the lateral acceleration was not correlated to the drop-off edge height or other input conditions. Regardless of the condition being tested, lateral acceleration peaks averaged close to 0.5g for a scrubbing condition, for a 115 mm edge height or less.
There have been studies relating curb's impact and vertical acceleration. Impact tests on curbs of 150 mm high or less, revealed that most of the time, vehicle vertical acceleration appears to be negligible because the time duration is short, and peak acceleration is small (Olson et al, 1974). Ogan et al. (1995) tested the vertical acceleration levels of a vehicle hitting a curb and also concluded that the acceleration levels experienced during curb impacts are minimal. The largest peak acceleration levels were measured when the vehicle did not mount the curb. Then, as the speed increases, the peak acceleration experienced decreases. In this project, longitudinal and lateral accelerations will be analysed.

2.7 Conclusion

This chapter presented the factors that influence a curb's redirection ability and how they will be treated in the present research. These factors are summarised in Figure 2-13. The center of the influence diagram represents the heart of this research, the redirection ability of roadside curbs. It is linked to the parameters that influence the curb's redirection ability, which are divided in subcategories representing the factors investigated through this research.
Chapter 2: Theory - Variables

Figure 2-13: Curb’s redirection ability influence diagram
3. EXPERIMENTS

Twenty-eight full-scale tests were conducted of vehicle impacts on an AASHTO type C curb (Figure 1-1) at various approaching speeds and angles, and with various vehicle sizes. The vehicle in each test was driven by a professional driver in a “hands-off” steering mode.

3.1 Curb Configuration

The type C curb was selected for full-scale testing because it represents the most widely used cross-sections. Moreover, most safety studies of roadside curbs investigated a type C curb. Consequently, a larger amount of data concerning this type of curb is available and facilitates the comparison of the current results.

Contrary to the geometry illustrated in the AASHTO manual for a type C curb (Figure 1-1), the cross section used for the full-scale tests did not include the gutter section. Only the extruded part was cast with a 152 mm (6 in) high. A width of 610 mm (2 ft) was chosen in order to dowel the curb to the concrete surface as shown in Figure 3-1. The curb was made up of six sections of 3.35 m (11 ft) each, for a total length of 20 m (66 ft).
3.2 Vehicles

Six vehicles were used; five passenger cars classified in three categories regarding their mass (small, medium, and large) and one van, as described in Table 3-1.

Table 3-1: Description of the test vehicles

<table>
<thead>
<tr>
<th>Category</th>
<th>Vehicle make and model</th>
<th>Year</th>
<th>Tire type</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>small</td>
<td>Chevrolet Sprint</td>
<td>84</td>
<td>P145/80R12</td>
<td>675 kg</td>
</tr>
<tr>
<td>small</td>
<td>Honda Civic</td>
<td>81</td>
<td>P155/R12</td>
<td>823 kg</td>
</tr>
<tr>
<td>medium</td>
<td>Plymouth Reliant</td>
<td>86</td>
<td>P175/80R13</td>
<td>1128 kg</td>
</tr>
<tr>
<td>medium</td>
<td>Dodge Aries</td>
<td>87</td>
<td>P185/70R14</td>
<td>1128 kg</td>
</tr>
<tr>
<td>large</td>
<td>Chrysler Cordoba</td>
<td>81</td>
<td>P205/65R15</td>
<td>1542 kg</td>
</tr>
<tr>
<td>van</td>
<td>Dodge Van E 150</td>
<td>84</td>
<td>225/75R15</td>
<td>1750 kg</td>
</tr>
</tbody>
</table>

Figure 3-1: Testing curb cross section
Chapter 3: Experiments

The tire diameter of each vehicle was measured, as well as the wheelbase, and the tire pressure. The results are reported in Table 3-2.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Tire Radius</th>
<th>Wheelbase</th>
<th>Tire Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
<td>psi</td>
</tr>
<tr>
<td>Sprint 85</td>
<td>270</td>
<td>225</td>
<td>28</td>
</tr>
<tr>
<td>Civic 81</td>
<td>278</td>
<td>225</td>
<td>28</td>
</tr>
<tr>
<td>Reliant 86</td>
<td>302,5</td>
<td>255</td>
<td>35</td>
</tr>
<tr>
<td>Aries 87</td>
<td>305</td>
<td>256</td>
<td>-</td>
</tr>
<tr>
<td>Cordoba 81</td>
<td>345</td>
<td>286</td>
<td>29</td>
</tr>
<tr>
<td>Dodge Van 84</td>
<td>360</td>
<td>323</td>
<td>32</td>
</tr>
</tbody>
</table>

3.3 Instrumentation

For most of the tests, three video cameras and one high speed camera were used. The high speed camera was focused on the tire-curb interaction. It was located approximately 2 m from the impact point. White stripes were painted on the tires in order to measure the tire deformation when sticking the curb. One video camera was installed inside the vehicle on a support drilled to the roof of the vehicle in order to record the driver’s perspective as well as the steering wheel rotation. Stripes of white tape were placed every 45° to measure the steering wheel rotation. A second video camera was located at a height of 3.3 m for a general film coverage. Finally, a camera was positioned in a straight line with
the vehicle trajectory, around 15 m in front of the impact point, in order to film the vehicle’s attitude following the impact. Camera positions are shown in Figure 3-2.

Although it was expected that acceleration would be small during the impact, a g-analyst was used to measure the longitudinal and lateral accelerations. The accelerometer was installed as close as possible to the center of gravity of each vehicle, on the floor, usually under the passenger seat.

Three targets were mounted on each side of each vehicle; two were located over the fender at the wheel center, and the other one was positioned at the longitudinal center of gravity, as illustrated in Figure 3-3. These targets served as reference points by which means vehicle motion was determined from the film analysis.

Photographs of overall view of the experimental set-up are shown in Appendix A.

3.4 Test procedures

All tests were conducted in a “hands-off” steering mode to minimise the influence of the driver’s behaviour on the vehicle trajectory after the impact. Once the driver had accelerated to the desired speed, he removed his hands from the steering wheel immediately prior to impacting the curb. Manual steering control was not regained until the vehicle had stabilised after impact. Consequently, the vehicle path, was dependent only on the wheel forces induced by the curb and terrain.
3.4.1 Impact Angle

In the first six tests, the curb was set at an angle of 15 degrees. The vehicle approached the curb in a straight line delineated by a joint in the concrete pavement. One test was performed at an angle of 10°. For this case, the curb was still positioned at an angle of 15° with respect to the concrete joints, and a path was delineated with paint on the
concrete surface. For the next seventeen tests, the curb repositioned at an angle of $5^\circ$ with respect to the concrete joint. Finally, two tests were conducted in a scrubbing condition, and the last two tests were performed at a $90^\circ$ impact angle. For these four tests, the curb was removed and positioned parallel to the concrete joints. Figure 3-4 illustrates the various vehicle approach positions. The driver experienced no difficulty in achieving the scheduled approach angle or impacting the curb at the desired point.

![Figure 3-4: Testing vehicle approach angles](image-url)
3.4.2 Impact Speed

The vehicle's scheduled approach speed varied from 5 to 40 km/h. The driver was asked to accelerate to the desired speed using the speedometer and to maintain a constant speed until the vehicle impacted the curb. The actual speeds were determined using the video analysis. The video tapes were played in slow motion, at a speed of 30 frames per second. The distance between the targets being known, the time taken for the targets to cross a given point was calculated to determine the actual speed. The speed of each run was also measured using the time required to achieve one wheel revolution. This gave three estimates of the impact speed.

3.4.3 Acceleration

Longitudinal and lateral accelerations were measured for most of the tests. The researcher unfamiliarity with the g-analyst instrumentation, and the small acceleration values produced some erroneous data. Consequently, the resulting data should be interpreted with caution.

3.4.4 Tire Radius

The testing vehicles were equipped with tire rim diameters that measured 305, 330, 355, or 406 mm (12, 13, 14, or 15 inches). However, the primary point of interest of this study was the tire radius that includes the rim radius and the sidewall (see Figure 3-3). The
tested tire radii were classified in three categories: small (270-280 mm), medium (300-305 mm) and large (345 mm and more).

### 3.4.5 Vehicle Mass

The vehicle mass indicated in Table 3-1, is also classified in three categories: small (825 kg and less), medium (1120-1130 kg), and large (1500 kg and more). In order to test the various tire radii at a given mass, mass was added into the vehicles to obtain the desired mass as illustrated in the following diagram. For example, mass was added to the vehicle $M_1$ with a S (small) tire radius so that it had a mass equivalent to vehicle $M_2$.

![Diagram: Tire radius and vehicle mass configuration](image)

**Figure 3-5: Tire radius and vehicle mass configuration**

### 3.4.6 Coefficient of Friction

The experiments took place on an old airport runway that has a flat concrete surface. The pavement was dry for most of the tests. Three tests were performed under rainy
conditions. The pavement and the tires being wet, the coefficient of friction was, therefore, lower.

3.4.7 Driver

A professional driver ran the 28 tests. No additional safety equipment was used because the seat-belt restraint was enough to prevent any injury. The driver subjectively evaluated the test runs.

3.5 Conclusion

A type C curb, which configuration is described in this chapter, was used in the 28 full scale tests. The physical characteristics of the six vehicles used for the crashes are given. The camera set-up is illustrated, and the test procedures are explained. Impact angles of 5°, 10°, and 15° were tested at scheduled speeds between 5 and 40 km/h. The resulting vehicle behaviour for each test is given in the following chapter and an analysis of the results is presented.
4. RESULT ANALYSIS

A summary of the 28 full scale test results is shown in Table 4-1. The redirection ability was divided in three scenarios. Complete redirection occurred when none of the wheels mounted the curb, but after striking the curb, the vehicle yawed and scrubbed along the curb. Partial redirection was obtained when the front passenger wheel or the two passenger wheels mounted the curb, but the vehicle was slightly redirected, and, therefore, did not cross the 610 mm wide curb, but kept rolling on it. Finally, no redirection occurred when one or more wheels crossed the curb entirely. Photographs, taken from the film recorded with the vehicle front view camera, representing the three scenarios, are shown in Appendix B. The three examples chosen to illustrate redirection, partial redirection, and no redirection, are the tests No 15, 13a, and 17, respectively. These three tests were performed with the Reliant, impacting the curb at an angle of 5° and at various impact speeds.

Most of the actual speeds, measured prior to the impact using video analysis, were smaller than the scheduled speeds. Presumably the driver was focusing on driving the vehicle at the appropriate impact point and was less concerned about the speed just before impacting the curb. Also, the speedometers might not have been well calibrated. Some of the tests were performed twice when the instrumentation (cameras or g-analyst) did not work properly. These repeated tests are identified with the letter “b”.

46
Chapter 4: Result Analysis

Table 4-1: Summary of full-scale test results for a type C curb

<table>
<thead>
<tr>
<th>Test No</th>
<th>Vehicle</th>
<th>Mass (kg)</th>
<th>Scheduled Speed (km/h)</th>
<th>Actual Speed (km/h)</th>
<th>Angle (degree)</th>
<th>Redirection Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aries</td>
<td>1128</td>
<td>20</td>
<td>22.1</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 wheels crossed, front suspension deformed, camber pushed inward</td>
</tr>
<tr>
<td>2</td>
<td>Aries</td>
<td>1128</td>
<td>10</td>
<td>11.1</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 wheels crossed, idem as #1</td>
</tr>
<tr>
<td>3</td>
<td>Aries</td>
<td>1128</td>
<td>30</td>
<td>33.0</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 wheels crossed, front right tire blew, vehicle is out of service</td>
</tr>
<tr>
<td>4</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>19.1</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 wheels crossed</td>
</tr>
<tr>
<td>5a</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>15.9</td>
<td>10</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 wheels crossed</td>
</tr>
<tr>
<td>5b</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>20.9</td>
<td>10</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>wheels crossed the curb only at its end</td>
</tr>
<tr>
<td>6a</td>
<td>Reliant</td>
<td>1128</td>
<td>20</td>
<td>14.5</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 wheels crossed, vehicle came to a stop restrained by the curb mounting bolts</td>
</tr>
<tr>
<td>6b</td>
<td>Reliant</td>
<td>1128</td>
<td>20</td>
<td>13.3</td>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 wheels crossed, idem as #6a</td>
</tr>
<tr>
<td>7</td>
<td>Reliant</td>
<td>1128</td>
<td>10</td>
<td>6.5</td>
<td>15</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>only front right wheel climbed, not enough momentum to cross it</td>
</tr>
<tr>
<td>8a</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>18.3</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>completely redirected, skid marks left along the curb face of 960 cm long</td>
</tr>
<tr>
<td>8b</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>17.2</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>completely redirected</td>
</tr>
<tr>
<td>9</td>
<td>Civic</td>
<td>823</td>
<td>20</td>
<td>16.7</td>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 wheels crossed, vehicle was strongly yawed, driver steered</td>
</tr>
<tr>
<td>10</td>
<td>Civic</td>
<td>1123</td>
<td>20</td>
<td>16.2</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>completely redirected, scrubbed along the curb</td>
</tr>
<tr>
<td>11</td>
<td>Civic</td>
<td>1123</td>
<td>30</td>
<td>26.9</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>vehicle started to be redirected, but 2 wheels climbed</td>
</tr>
<tr>
<td>12</td>
<td>Civic</td>
<td>1123</td>
<td>40</td>
<td>33.3</td>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 wheels crossed, vehicle continued on a straight path over the curb</td>
</tr>
<tr>
<td>13a</td>
<td>Reliant</td>
<td>1128</td>
<td>20</td>
<td>17.6</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels climbed and rolled on the curb</td>
</tr>
<tr>
<td>13b</td>
<td>Reliant</td>
<td>1128</td>
<td>20</td>
<td>18.1</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels climbed and rolled on the curb</td>
</tr>
<tr>
<td>14</td>
<td>Reliant</td>
<td>1128</td>
<td>30</td>
<td>27.2</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels climbed and rolled on the curb</td>
</tr>
<tr>
<td>15</td>
<td>Reliant</td>
<td>1508</td>
<td>15</td>
<td>11.3</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>completely redirected, tires skidded along the curb from contact point to the end of the curb</td>
</tr>
<tr>
<td>16</td>
<td>Reliant</td>
<td>1508</td>
<td>20</td>
<td>15.6</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels climbed, vehicle skidded at the beginning</td>
</tr>
<tr>
<td>17</td>
<td>Reliant</td>
<td>1508</td>
<td>30</td>
<td>25.9</td>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels crossed, vehicle straddle the curb</td>
</tr>
<tr>
<td>18</td>
<td>Cordoba</td>
<td>1542</td>
<td>10</td>
<td>14.8</td>
<td>5</td>
<td>partly</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 passenger wheels climbed and rolled on the curb</td>
</tr>
</tbody>
</table>
The redirection capability of the type C curb was less effective than expected. According to the Olson et al. (1974) studies, a vehicle hitting a curb at an angle of 15° should be redirected at a speed of 43 km/h or less. Contrary to Olson’s results, the vehicles in this study were not redirected at a speed as low as 11 km/h when approaching the curb at 15°. For any of the vehicle mass and tire radius tested, the four wheels of the vehicle entirely crossed the curb even at an approaching angle of 10°. The vehicles were slightly yawed after it crossed the curb, in the opposite direction of the curb.
Since it was made evident that redirection would not occur at an approaching angle of 15° or even 10°, the remaining tests were conducted at an impact angle of 5°. The resulting tested data are plotted in Figure 4-1 (white shapes). The results reveal that type C curb design does not offer satisfactory redirection when the vehicle speed exceeds 15 km/h and the impact angle exceeds 5°. Examination of Figure 4-1 shows that redirection can be expected for very restricted conditions: a considerable low speed and a shallow angle. The results do not agree with Olson suggested redirection curve (1974), which overestimated the curb’s redirection capability. The nine situations where the vehicle was not redirected are all attributed to coordinates of speed and angle that are located on the “redirection” side of Olson boundary curve. Navin’s redirection curve is much more representative of the current data. All the data representing a non redirection behaviour are located on the appropriate side of the boundary redirection curve. This latter curve is drawn from Equation 4-1 and does not take into account vehicle mass, tire radius, and coefficient of friction.

\[
V = \frac{0.01h}{\sin \theta} \tag{4-1}
\]

where

\[
\begin{align*}
V &= \text{impact speed (km/h)} \\
h &= \text{curb height (mm)} \\
\theta &= \text{impact angle (degrees)}
\end{align*}
\]
As mentioned previously, only one redirection data from Olson’s study came from full scale tests. The remaining redirection data were simulated using the Highway Vehicle Object Simulation Model (HVOSM). The simulated data are shown in Figure 2-11, and only the tested data are shown in Figure 4-1 (black shapes). It seems that the simulated data, used to plot the redirection curve, did not adequately represent the reality. This would explain the major difference between Navin and Olson’s curves. Olson’s simulations were performed in 1974, an update version of the computer model would possibly give more compatible results.

Also, Olson’s tested speeds were between 48 and 120 km/h, whereas the tested speeds in this research were all below 34 km/h. Therefore, this research completed Olson’s study, since it covered a range of data that has not been investigated in his research.

The only one redirection data obtained from full scale tests by Olson does not conform neither with Navin’s redirection curve nor with this research tested data. Vehicle redirection was achieved at a speed of 54.7 km/h and at an impact angle of 5°, according to Olson’s tests, whereas redirection was achieved at a maximum speed of 18.3 km/h for a same impact angle in this research. However, partial redirection occurred at a speed of 27 km/h, at an impact angle of 5°, and could possibly occur at a higher speed. The considerably higher speed at which redirection was achieved in Olson’s full scale tests could be explained by the use of bias-ply tire against radial tire, which is discussed further.
At an encroachment angle of 5°, the three redirection alternatives occurred. Out of fifteen tests performed at an impact angle of 5°, three had the vehicle redirected, eight had it partly redirected, and four had it not redirected. The probability of each redirection behaviour happening at an approaching angle of 5° is shown in Figure 4-2. The columns represent the frequency in percentage of vehicles that responded in each of the three alternatives, at a given speed range. For example, six vehicles were tested at speeds included between 15 and 20 km/h. Out of these six tests, one was redirected (17%), four were partially redirected (67%), and one was not redirected (17%). Probability curves of the outcomes were then plotted according to their respective frequency.
Chapter 4: Result Analysis

To be very likely redirected (with a probability $\geq 90\%$), a vehicle approaching the curb at an angle of $5^\circ$ requires a speed under 8 km/h, which is remarkably slow. At a speed of 14 km/h, the chances to be redirected or partially redirected are equal. From 14 to 26 km/h, a vehicle approaching the curb at $5^\circ$ is more likely to be partially redirected. Over 26 km/h, the probability of not being redirected increases sharply.

The practically non existent capability of a curb of 152 mm high to redirect a vehicle operating at speed higher than 26 km/h indicates that, curbs of this height placed with the intent of vehicle redirection are creating an additional hazard rather than mitigating a potential vehicle impact with an obstacle located behind the curb.

![Figure 4-2: Probability of being redirected when striking a type C curb at an approaching angle of $5^\circ$](image)

Figure 4-2: Probability of being redirected when striking a type C curb at an approaching angle of $5^\circ$
4.1 Influence of Vehicle Characteristics on Redirection

Up to this point, a curb's redirection capability was examined independently of the vehicle characteristics. This section will determine the influence of tire construction, tire size and vehicle mass on curb redirection.

4.1.1 Tire Construction

Olson's (1974) full scale tests were performed in the early 70's, when bias-ply tires were commonly. Bias-ply tires are more rigid than radial tires, and a vehicle equipped with that type of tire would, therefore, have a greater propensity to be redirected. To verify the influence of tire construction on redirection, a bias-ply tire was installed on the front right wheel (impact wheel) of an intermediate size vehicle.

In the three tests performed with a bias-ply tire, more energy was dissipated through the impact compared to radial tires. At an approaching angle of 15° and speed of 14 km/h, only two wheels of the vehicle equipped with a bias-ply tire crossed the curb, whereas the same type of vehicle, but entirely equipped with radial tires, crossed the curb completely with its 4 wheels at a lower speed of 11 km/h. The vehicle equipped with a bias-ply tire did not have enough momentum to cross the curb, it came to a stop straddling the curb.

It is important to notice that the tests performed using a bias-ply tire were executed under rainy conditions, the lower coefficient of friction available might also have influenced the results. However, the greater rigidity of bias-ply tire is presumably the explanation to the
greater curb effectiveness to redirect a vehicle in previous investigation than in the present one. This result goes in the same direction than the conclusion drawn from the influence of tire construction on the easiness to climb a pavement drop-off discussed in section 2.2.1.

4.1.2 Tire Radius

It was expected that as the tire radius increases, a curb’s ability to redirect a vehicle is diminished, for a constant curb height. The vehicles tested were equipped with tires of radius between 270 to 360 mm, a variation of 33%. The curb had a constant height of 152 mm. The tests performed at an impact angle of 5° are reported in Figure 4-3. The curves suggest that as the tire radius increases for a constant curb height, the curb ability to redirect a vehicle decreases for a given speed. The lower boundary curve suggests that a vehicle equipped with tires of a radius between 200 and 400 mm, hitting a curb at a speed located below the boundary curve and at an angle of 5°, will be redirected. For a situation where the coordinates of tire radius and impact speed are located above the lower boundary curve, but below the upper boundary curve, the vehicle is either partially redirected or not redirected. When the tire radius and impact speed are such that their coordinates are located above the upper boundary curve, the vehicle will in all likelihood traverse the curb, or not be redirected.
Figure 4-3: Influence of tire radius on redirection for a concrete curb of 152 mm high, impacted at an angle of 5°.

To describe the influence of tire radius on redirection, Navin (1997) used experimental field data and developed the following relationship by curve fitting:

$$V_r = \frac{50}{\sin \theta} \left( \frac{h}{r} \right)^{3.5} \left( \frac{\mu_{cp}}{\mu_N} \right)$$

(4-2)

where:

- $V$ = impact speed (km/h)
- $\theta$ = impact angle (degrees)
- $h$ = curb height (mm)
- $r$ = radius of tire (mm)
- $h/r \leq 0.75$
Chapter 4: Result Analysis

\[ \mu_{CD} = \text{coefficient of friction, smooth rubber on dry concrete} \]

\[ \mu_N = \text{coefficient of smooth rubber on new surface} \]

Since the present experiments were performed on dry concrete, the ratio of coefficient of friction is equal to one and Equation 4-2 can be simplified as:

\[
V_r = \frac{50}{\sin \theta} \left( \frac{h}{r} \right)^{3.5} \tag{4-3}
\]

If the speed perpendicular to the curb \((V \sin \theta)\) is plotted versus the ratio of the curb height over the tire radius, Equation 4-3 does not accurately fit the resulting data. Figure 4-4 shows that Navin's equation overestimates the curb capability to redirect a vehicle. Out of nine results which were not redirected, seven are located in the redirection side of the boundary curve. Equation 4-3 can be modified to fit more correctly the given data. A modified curve has been plotted assuming that a vehicle partially redirected is in fact redirected. The modified curve was obtained simply by diminishing the constant in Equation 4-3 from 50 to 22.

The diameter of the tire compared to the height of the curb has a less notable influence on redirection than expected. In Figures 4-3 and 4-4, it can be observed that the speed, or more precisely, the speed normal to the curb has a much greater influence. Also, the limited variation in tire radii generates ambiguity in the determination of its influence over a wider range. It can be observed from Figure 4-4, that the tested \(h/r\) ratios are
limited from 0.42 to 0.56. However, the vehicles that were redirected all possessed a tire radius smaller than 303 mm, and it seems that it would be difficult to achieve redirection with vehicles tires with a radius larger than 335 mm, when striking a 152 mm high curb (i.e. a ratio curb height/tire radius smaller than 0.45).

Figure 4-4: Influence of the ratio of the curb height over the tire radius on redirection for a type C concrete curb, 152 mm high

When the edge height (h) exceeds the tire radius (r), the tire-edge interaction is changed, and the previous equation is no longer applicable. Navin’s study (1997) estimated the boundary ratio at 0.75. No tire radius generating that ratio was tested, therefore, this value of the upper boundary was not confirmed.
4.1.3 Vehicle Mass

The mass of the vehicle has a complex influence on redirection. Adding mass to a vehicle had in some circumstances an opposite effect than what was expected. It was anticipated that a heavier vehicle would be more inclined to cross the curb, since it possesses a higher kinetic energy ($\frac{1}{2}mv^2$). However, when the various masses tested were plotted against the speed normal to the curb, no distinctive relationship was found between the mass and the redirection capability of the curb. Figure 4-5 demonstrates that a relationship could be divided in two parts. In the first part, the redirection capability increases considerably as the vehicle mass increases up to a certain point, around 1110 kg in this case, and subsequent to this critical point, the tendency is reversed. As the vehicle mass increases, the propensity of the vehicle to be redirected decreases slightly.

These results suggest that for light vehicles, the redirection would be governed by the potential energy ($mgh$), whereas heavy vehicle redirection would be governed by kinetic energy ($\frac{1}{2}mv^2$). A very light vehicle would be very easy to lift up, and would therefore encounter little difficulty to climb over the curb. For example, a very big balloon tire would require a small force to make it cross a 152 mm high curb. As the mass increases, the force necessary to lift up the vehicle increases, so at a given speed and angle of impact, a heavier vehicle would have a lower tendency to cross the curb than a lighter vehicle of the same dimension. This relationship is applicable up to a given mass of approximately 1100 kg. After this critical point, the kinetic energy seems to take over,
and an increase in mass provides a surplus of energy that propels the vehicle over the curb.

![Figure 4-5: Influence of the mass on redirection for a type C curb](image)

To investigate the influence of the vehicle mass, without modifying the vehicle dimensions, around 35% of the vehicle mass was added into some vehicles. So 300 kg was added to the Honda Civic, a small size vehicle, to equal the mass of the Aries and the Reliant, intermediate size vehicles, and 230 kg were added to the Sprint. Similarly, 380 kg was added to the Reliant to attain a mass similar to that of the Cordoba, a large vehicle. Salt bags were placed on the back seat of the vehicles which produced the side effect of lowering the center of gravity and slightly moving it backward.

It was found that in the two cases conducted with a small vehicle, the heavier vehicle had a greater tendency to be redirected. For example, the two passenger wheels of the
unloaded vehicle mounted the curb and crossed it when striking the curb at 5° and 19.5 km/h. With an extra load of 230 kg, and the same impact conditions, the two passenger wheels mounted the curb, but the vehicle was partially redirected, and therefore kept rolling on the curb.

In the case of the intermediate size vehicle, the addition of mass had an opposite effect. When a mass of 380 kg was added, the vehicle crossed the curb at a speed of 26 km/h, whereas the unloaded vehicle was partially redirected in similar impact conditions. Therefore, adding mass in that case decreases the probability of being redirected. These results agree with the two slopes redirection boundary curve of Figure 4-5.

### 4.2 Redirection equation

If the influence of the vehicle mass, the tire radius, the curb height, the speed and the angle of impact are simultaneously taken into account, the boundary redirection equation has the following form:

\[
V_r = \frac{8}{\sin \theta} \left( \frac{h}{r} \right)^{35} \left( \frac{m}{440} \right)
\]

The constant value has been diminished again, from 22 to 8, when the effect of mass was incorporated.

60
Table 4-2 shows the redirection normal speed \( (V_r \sin \theta) \) calculated using Equation 4-4 in m/s. That is the maximum speed perpendicular to the curb at which a vehicle of a given mass and a given tire radius would be redirected or partly redirected when striking a 152 mm high curb. Over this speed, the vehicle would cross the curb. The tested speeds perpendicular to the curb are also listed with their respective redirection behaviour.

Table 4-2: Comparison of the predicted redirection speeds to the tested speeds and redirection behaviours

<table>
<thead>
<tr>
<th>Test No</th>
<th>Tire radius (mm)</th>
<th>Vehicle mass (kg)</th>
<th>Redirection normal speed from Equation 4-4 ( V_r \sin \theta ) (m/s)</th>
<th>Tested normal speed ( V \sin \theta ) (m/s)</th>
<th>Redirection?</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>270</td>
<td>675</td>
<td>5.91</td>
<td>6.12</td>
<td>no</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td>4.42</td>
<td>yes</td>
</tr>
<tr>
<td>23</td>
<td>270</td>
<td>905</td>
<td>7.93</td>
<td>6.02</td>
<td>partly</td>
</tr>
<tr>
<td>4</td>
<td>278</td>
<td>823</td>
<td>6.51</td>
<td>17.80</td>
<td>no</td>
</tr>
<tr>
<td>5a</td>
<td>278</td>
<td></td>
<td></td>
<td>9.94</td>
<td>no</td>
</tr>
<tr>
<td>10</td>
<td>278</td>
<td>1123</td>
<td>8.88</td>
<td>5.08</td>
<td>yes</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td>8.44</td>
<td>partly</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td>10.45</td>
<td>no</td>
</tr>
<tr>
<td>13a</td>
<td>303</td>
<td>1128</td>
<td>6.60</td>
<td>5.52</td>
<td>partly</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td>8.53</td>
<td>partly</td>
</tr>
<tr>
<td>1</td>
<td>305</td>
<td>1128</td>
<td>6.45</td>
<td>20.59</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>10.34</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>30.75</td>
<td>no</td>
</tr>
<tr>
<td>15</td>
<td>303</td>
<td>1508</td>
<td>8.83</td>
<td>3.55</td>
<td>yes</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>4.89</td>
<td>partly</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td>8.13</td>
<td>no</td>
</tr>
<tr>
<td>18</td>
<td>345</td>
<td>1542</td>
<td>5.73</td>
<td>4.64</td>
<td>partly</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td>5.71</td>
<td>partly</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td>8.60</td>
<td>no</td>
</tr>
<tr>
<td>24</td>
<td>360</td>
<td>1750</td>
<td>5.60</td>
<td>6.59</td>
<td>partly</td>
</tr>
</tbody>
</table>
In only one case did Equation 4-4 slightly overestimate the curb capability. For a heavy vehicle (1508 kg) and medium tire radius (303 mm), the predicted boundary speed was 8.83 m/s (under this speed a vehicle should be redirected or partly redirected), but the vehicle crossed the curb at a normal speed of 8.13 m/s. Also, in two cases, the vehicle was partly redirected at a normal speed higher than the predicted redirection speed. Overall, Equation 4-4 accurately represents the actual data, especially for light vehicles.

The relationship to estimate the safe redirection height needed by a curb so that a vehicle is redirected or partly redirected may be estimated as:

\[
h = r \left[ \frac{V \sin \theta \left( \frac{440}{m} \right)}{8} \right]^{\frac{1}{35}}
\]  

This relationship counts five variables, but vehicle mass and tire radius were found to be dependent variables. For most of the vehicles, there exists a relationship between the tire radius and the vehicle mass; heavy passenger vehicles, have necessarily larger dimensions and consequently, larger tire radius than lighter ones. If the mass of the tested vehicles is plotted against their corresponding tire radius, a linear relationship is found, with an R-squared value of 0.995. This relationship has the following form:

\[
r = 0.087m + 208.3
\]
Therefore, the value of the tire radius can be estimated for a given vehicle mass. Figures 4-6 and 4-7 are drawn from Equations 4-5 and 4-6. Figure 4-6 is a tridimensional representation of the safe curb height required for redirection as a function of the speed perpendicular to the curb (Vsinθ) and the vehicle mass from 600 to 2000 kg. Figure 4-7 shows the safe curb height as a function of the vehicle mass, for five different normal speeds. As an indication, a perpendicular speed of 1 km/h represents a speed of 11 km/h at an angle of 5°, or a speed of 4 km/h at 15°; and a normal speed of 10 km/h is equivalent to a speed of 115 km/h at an angle of 5° and 39 km/h at 15°.

It can be observed from Figure 4-6 and more obviously from Figure 4-7, that a curb height of 152 mm offers no satisfactory redirection for a normal speed over 2 km/h for any vehicle mass tested. Since the tire radius increases proportionally to the vehicle mass, but that they have an inverse effect on the safe curb height, the overall effect of the vehicle mass is almost negligible. The curb height required to produce redirection decreases slightly as the vehicle mass increases from 600 to around 960 kg, and then starts to increase slightly for a given normal speed.

According to Figures 4-7, a curb height of 205 mm will achieve redirection in many representative urban conditions: at a normal speed lower than 4.7 km/h (50 km/h at 5.4°), and for a vehicle mass between 600 and 1500 kg (small, intermediate or large passenger vehicle). Adding 50 mm to the actual type C curb height, would generate redirection capabilities to a much wider range of impact conditions.
Figure 4-6: Curb height to produce redirection as a function of the normal speed to the curb and the vehicle mass

According to the equation derived from tests performed with a 152 mm high curb, a curb height of 205 mm would provide redirection or partial redirection in most of urban impact conditions, and would still be mountable. It would provide a redirection capability similar to that of the Belgian Trief curb of 305 mm high.
Figure 4-7: Curb height to produce redirection as a function of the vehicle mass for various speeds normal to the curb

4.3 Vehicle's Attitude

Vehicle's attitude is defined in terms of the bumper rise, the rotation of the steering wheel, the vehicle roll angle, and the acceleration. Vehicle attitude after impact determines the level of safety of the manoeuvre and influences the severity of a secondary collision with an obstacle located behind the curb.
4.3.1 Rotation of Steering Wheel

The rotation angle that the steering wheel undergoes during the impact is related to the severity of the impact. As the steering wheel rotation increases, so does the difficulty to control the vehicle. The experiments demonstrated that small vehicles which were not redirected, underwent very high steering wheel rotation, from 90° to 270°. On the other hand, the steering wheel of medium and large size vehicles, as well as redirected vehicles underwent a rotation less than 45°. This considerable difference in steering wheel rotation is partly explained by the difference in steering wheel system. The two small vehicles were equipped with manual steering wheel system, whereas the other vehicles were equipped with power-assisted steering system.

In conclusion, a small vehicle that hits a curb with sufficient speed to cross it, would represent the most hazardous situation. The steering wheel rotation experienced in some tests are listed in Table C-1.

4.3.2 Bumper Rise

The height to which the bumper rises when impacting the curb influences the subsequent trajectory of the vehicle. As the bumper rise increases, the severity of a secondary collision increases, as well as the discomfort experienced by the driver, and, consequently, the level of safety of the manoeuvre decreases. The right corner of the bumper was selected as the reference point to determine vertical rise with respect to the
top surface of the curb. It was measured using photographs of the vehicles front view recorded by the video camera, and the results are given in Table C-1.

Figure 4-8 shows the bumper rise with respect to the top of the curb of a small vehicle (Sprint) with and without mass added, impacting the curb at an angle of 5° and at a speed of 19 km/h. The unloaded vehicle was not redirected whereas the loaded vehicle was partially redirected. The data were collected from the moment when the first wheel made contact with the curb, and then at various instants, approximately every 0.15 second, until the two passenger wheels have climbed the curb. It represents a distance of approximately 5 m and a duration of roughly 1 second. The first rise of the bumper occurs when the front passenger wheel climbs the curb, and the second one when the rear passenger wheel mounts it. It can be observed that the lighter vehicle encountered a higher bumper rise than the heavier vehicle at the first curb contact, confirming the results of section 4.1.3. This suggests that a lighter vehicle is easier to lift up, that enables it to climb the curb more easily. However, contrary to previous studies, no correlation was observed between the maximum bumper rise and the speed of impact.

It must be noted that the measurements of the bumper height is quite rough and its approximation might have altered the results. Even though various measurements seem to confirm that lighter vehicles encountered greater bumper rise, further research is necessary to clearly identify the relationship between bumper rise and vehicle mass.
Figure 4-8: Bumper rise with respect to the top of the curb of a small vehicle (Sprint) impacting the curb at 5° and 19 km/h, with and without additional load

4.3.3 Vehicle Roll

The vehicle roll was measured at the same point for each test, when the passenger wheel had just mounted the curb, where it appeared very likely that the highest roll angle encountered by the vehicle was achieved. The results are listed in Table C-1.

None of the roll angles experienced by the various vehicles were significant. The maximum roll angle was 10° when impacting the curb at 15°. The roll angles were slightly smaller for an impact angle of 5°. The vehicles approaching the curb at an angle of 5° did not experience a roll angle greater than 6°.
Chapter 4: Result Analysis

The roll angle was found to be independent of the vehicle mass. It increases slightly as the speed normal to the curb increases, the angle of impact having a greater influence than the speed.

4.3.4 Vehicle Acceleration

The longitudinal and lateral accelerations were measured using a g-analyst. The lateral accelerations were insignificant, most of the values being as low as 0.01 g, with a maximum value of 0.15 g. The longitudinal accelerations were slightly greater, but not considered significant. The average of the maximum values of each test was 0.2 g. The maximal recorded longitudinal and lateral accelerations are provided in Table C-2.

No strong relationship was established between the lateral or longitudinal accelerations and the speed normal to the curb. Figure C-1 shows the recorded maximal lateral and longitudinal accelerations in function of the speed normal to the curb.

Regarding the acceleration against the vehicle mass, according to the collected data, the longitudinal acceleration tended to increase as the mass of the vehicle increases and no correlation was found between lateral acceleration and mass (Figures C-2 and C-3). However, according to the professional driver, the shock felt when the vehicle impacted the curb was much higher for a small vehicle than for a large one, implying that the acceleration is mitigated when vehicle mass increases. The shock experienced was described as “unsettling” when driving a small vehicle, “uncomfortable” for an
intermediate size vehicle, “almost insignificant” for a large size vehicle and a “non-event” when striking the curb with a van. In the professional driver’s opinion, the comfort experienced when striking the curb decreases logarithmically as the vehicle dimension increases.

Since a type C curb is relatively easy to climb for a wide range of speed, angle, and vehicle characteristics, it is important to establish the vehicle attitude following the curb crossing. The results reveal that small vehicles are much more hazardous than large, more stable vehicles. The smaller vehicles experienced larger steering wheel rotation, higher bumper rise, and more noticeable shock impact when impacting a curb. These may provoke more discomfort and a significant effect of surprise to the driver which could cause difficulties in the control of the vehicle. Moreover, the higher bumper rise increases the chance of a collision with an obstacle located behind the curb. The situation of lack of control, together with a higher probability of a secondary collision, generate a greater risk of collision when a small vehicle inadvertently climbs a roadside curb.

4.4 Extreme Angle Impact

4.4.1 Scrubbing - Zero Degree Impact

Two tests were performed in a scrubbing condition, one with a small vehicle (Civic) and one with a large vehicle (Cordoba) at a speed of approximately 30 km/h. Contrary to previous results, it was not described as hazardous to mount the curb of 152 mm high,
following a scrubbing condition. Less than 45° rotation of the steering wheel was required to mount the curb. Photographs of each vehicle climbing the curb from a scrubbing condition are shown in Figures B-4 and B-5.

According to the professional driver, climbing the curb following a scrubbing condition was not described as a significant event when driving a large vehicle. The vagueness of the steering wheel and the large dimensions of this automobile generates control difficulty in the position of the tires with respect to the curb edge, and therefore, it was difficult to scrub along the curb for a long distance.

On the other hand, it required considerably more effort to climb the curb from a scrubbing condition when driving a small vehicle. The characteristics of a small vehicle produce a greater control accuracy and make it easier to scrub, but the stiffer suspension causes discomfort to the driver as the vehicle climbs the curb.

In both cases, the driver did not lose control of the vehicle after climbing the curb. These results might modify the conclusions drawn concerning the maximum height of drop-offs found in other studies. Olson and Zimmer (1986) in their investigation evaluating the performance of naive drivers negotiating pavement drop-offs in a scrubbing condition, concluded that a vertical edge drop of 114 mm high could not be negotiated safely at a speed of 48 km/h or higher. A vertical edge of only 76 mm high was also declared unsafe when negotiated with a small car over a speed of 48 km/h. Considering the fact that the
tested curb was twice the height of the latter drop-off edge, it would be expected that a higher drop-off edge could possibly be tolerated. This particular question requires additional study.

4.4.2 Ninety Degrees Impact

Two tests were performed at an impact angle of 90°, one with a large vehicle (Cordoba) and the other with a small one (Civic). The tests were executed at very low speed, around 9 km/h, sufficient to cross the curb. The bumper height relative to the ground was measured for each test at various moments. Photographs of vehicle hitting the curb at an angle of 90° are shown in Figure B-6 and B-7.

Figure 4-9 illustrates the resulting bumper rise curve for each vehicle. The distance from the curb is taken from the center of the front wheel to the first contact edge of the curb. The first data represents when the front wheel makes contact with the curb, the bumper being at its regular height. The first bumper rise is caused by the front wheel climbing the curb. It can be observed that the bumper of the Cordoba rose considerably higher than the bumper of the Civic. The rise of the large car bumper relative to its normal height is 31.5 cm, compared to 18 cm for the small car, which is 75% higher in the case of the large vehicle. The second rise occurred before the rear axle crossed the curb and resulted in an oscillation response. The second trough occurred when the rear tires climbed the curb.
Chapter 4: Result Analysis

The larger amplitude of the bumper height encountered by the large vehicle compared to the small one can be explained by its type of suspension. Driving comfort is largely determined by the degree of vehicle oscillation. The large vehicle experienced higher amplitude, but the smoother suspension mitigates the driving discomfort. On the other hand, the smaller vehicle has a lower body amplitude, but because of its stiffer suspension, the driving is less comfortable. The type of suspension takes over the effect of the mass determined in section 4.3.2, where it was stipulated that lighter vehicles have a higher bumper rise. The fact that a large car climbs higher than a smaller car after crossing a curb agrees with the conclusion drawn by Roll et al. (1989).

![Graph](image_url)

**Figure 4-9: Bumper rise of two different size vehicles striking a curb at a 90° angle at a speed of 9 km/h**
Angle Boundary

From Equation 4-4, the speed required to mount the curb at 90° is 1.8 km/h for the Civic, and 1.6 km/h for the Cordoba, which is not realistic. Although a velocity less than the tested 9 km/h would probably be sufficient to cross the curb, it seems reasonable to affirm that a speed greater than 2 km/h would be necessary.

Also, applying the redirection equation to Ogan et al. (1995) testing data showed that a 1454 kg vehicle equipped with tires of 311 mm radius, impacting the curb at an angle of 60°, would require a speed of 2.5 km/h to cross the curb. The results show however, that the vehicle was redirected at a speed of 6.9 km/h. These results show that Equation 4-4 is valid for a restricted range of angle of impact, the upper bound being presumably less than 60°. Moreover, the redirection equation is not applicable in a scrubbing condition, which implies a very shallow angle close to 0°, and therefore, a division by 0.

4.5 Conclusion

In this chapter, the 28 experimental results were presented. The influence of the tire construction, tire radius, curb height, vehicle mass on curb’s redirection ability at a given speed and impact angle were discussed. Minor modifications were made to Navin’s redirection equation and it was validated for the tested impact conditions.

The results obtained from the full scale tests demonstrated that Olson’s redirection curve (1974) overestimated curb’s redirection ability, especially at speeds lower than 50 km/h.
Olson’s redirection curve was plotted from experimental and simulated data, in which speeds were between 48 and 120 km/h and impact angles between 5° and 20°. The different range of vehicle normal speeds used in Olson’s study in comparison to this study, explained partially the inconsistency in the redirection curves. The use of simulated data, which tended to overestimate the curb’s redirection ability is also part of the explanation. Finally, the use of stiff bias ply tires in the full scales tests slightly helped the achievement of vehicle redirection.

It was concluded that a 152 mm high type C curb does not offer satisfactory redirection for a wide range of impact conditions, where the speed normal to the curb exceeds 2 km/h. A safe curb height of 205 mm was suggested to increase redirection effectiveness and pedestrian safety. The analysis of vehicle attitude following the curb crossing demonstrated that small cars represent a more hazardous situation in vehicle control.
5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The purpose of this project was to evaluate the redirection effectiveness of a type C design roadside curb of 152 mm, for various speeds and angles of impact, different vehicle mass and different tire radii. A total of 28 full scale tests were completed. The tests were filmed by three normal cameras and a high speed camera. A g-analyst was used to collect acceleration data. The vehicles were driven by a professional driver and the impacts were in the “hands off” mode.

It was concluded that type C curb does not provide vehicle redirection capability for a wide range of impact speeds and angles. No redirection or partial redirection was achieved during testing for an approaching angle of 10° or 15°. The curb may easily be traversed when the vehicle speed normal to the curb exceeds 2 km/h, for all the vehicles tested.

Navin’s (1997) general equation (Equation 4-1), which considers curb height, vehicle velocity and angle of impact, accurately describes the test data. It is much more representative of the current tested results than Olson’s redirection curve (1974). This latter curve overestimated type C curb’s redirection ability, especially at low speeds, presumably because of the higher tested speeds, the uncertainty concerning simulated data, and the use of stiff bias-ply tires.
Since the three redirection scenarios (redirected, partly redirected, and not redirected) occurred for an encroachment angle of 5°, the vehicle redirection behaviour was better described by a probability of occurrence. The chance of being redirected by a 152 mm curb was nil at a speed over 25 km/h. The probability of not being redirected started at 10 km/h, and reached 100% at a speed of 40 km/h, when the vehicle stroke the curb at an angle of 5°.

**Redirection Equation**

A primary objective of this project was to validate Navin’s equation of the relationship between the redirection impact speed, encroachment angle, vehicle mass, tire radius, and the height of the curb. This study did not consider the effect of the coefficient of friction, which is also included in Navin’s equation. Only minor modifications of Navin’s equation were necessary to accurately fit the tested data. The resulting redirection equation has the following form:

\[ V_r = \frac{8}{\sin \theta} \left( \frac{h}{r} \right)^{3.5} \left( \frac{m}{440} \right) \]  \hspace{1cm} (5-1)

The redirection equation shows that the curb’s redirection ability decreases if:

- the speed of impact increases;
- the angle of impact increases;
- the tire radius increases;
- the height of the curb decreases;
the vehicle mass increases.

The variation of the vehicle mass actually has a somewhat mixed effect. A more detailed review of the tested data showed that the curb’s redirection ability decreases if:

- the vehicle mass decreases for light vehicles (mass under 956 kg);
- the vehicle mass increases for intermediate and heavy vehicles (mass over 956 kg).

Equation 5-1 estimated, with a reasonable level of precision, the redirection test speeds of this project. The equation could be used in accident reconstruction to estimate a vehicle’s minimum speed to mount a curb for impact conditions similar to those tested.

**Boundary of the Redirection Equation**

Equation 5-1 is valid when the tire radius is smaller than the edge height. When the ratio of the curb height over the tire radius reaches a value slightly less than one, the tire-edge interaction is modified, and the redirection equation is no longer applicable. Further research is necessary to evaluate the upper bound value of the h/r ratio.

Experiments performed at an angle of 90° showed that the equation is probably not applicable when striking the curb perpendicularly, but again, further research is required to determine the angle of impact boundary.
Safe Curb Height

From Equation 5-1, a safe curb height can be established for given impact conditions. Since a relation was found between the vehicle mass and the tire radius, a chart was plotted representing the curb height necessary to achieve redirection as a function of the vehicle mass and the speed normal to the curb. The safe curb height is highly dependent of the speed and the angle of impact, but varies very little for different vehicle masses. For shallow approaching angles (less than 5.4°), a curb height of 205 mm is required to redirect a vehicle driven at a speed less than 50 km/h, and a vehicle mass ranging from 600 to 1500 kg.

Vehicle Behaviour

A secondary objective of the research was to evaluate the vehicle’s attitude following the curb impact, especially when the vehicle mounted the curb, where collision with an obstacle located behind the curb is possible. It was shown that small and light vehicles experienced a greater steering wheel rotation, a higher bumper rise, and a much more marked shock impact than large and heavy vehicles. Consequently, these vehicles have a higher probability of loss of control and of a secondary collision when inadvertently crossing a roadside curb.

Scrubbing

The ease with which the vehicle climbed the 152 mm high curb in a scrubbing condition (0° impact angle) brings into question the previous studies regarding the maximum height
tolerated for highway pavement edge drop-offs. A maximum drop-off height of 76 mm was suggested by Olson and Zimmer (1986) at a speed of 40 km/h. This research found that a curb (acting as a drop-off) of 152 mm was easily and safely mounted at a speed of 30 km/h by both a small and a large size vehicle.

5.2 Recommendations

At locations where vehicle redirection is a major concern, a curb height of 205 mm is suggested. This 50 mm addition in height would still make the curb mountable, but would increase considerably the curb’s redirection effectiveness and the safety of bystanders. This curb height would achieve redirection with a normal speed of 4.7 km/h, and for most of the passenger cars in the current fleet. However, this was found from the equation derived from the tests performed with a 152 mm high curb and for this reason, it is necessary to have further testing to confirm the recommended height.

This study agrees with previous findings that a 152 mm high curb offers no safety benefit on high speed highways and that their omission along highways will enhance safety (Olson, 1974). Moreover, this project indicates that 152 mm high type C curb should not be used when the main purpose is to redirect errant vehicles or to protect pedestrians, along any type of road.

The AASHTO manual suggests six types of mountable curbs, of height varying from 100 to 150 mm, for median edges to outline channelising island in intersection areas.
Chapter 5: Conclusion and Recommendations

Considering the gravity of vehicle accidents crossing these mountable curbs and becoming involved with oncoming traffic, a 205 mm high curb is also recommended for median edges. A curb height smaller than 150 mm, especially with an inclined edge, is very easy to climb and the lack of vehicle redirection may cause the vehicle to crash with the oncoming traffic. Even if the intent of the curb is not to provide a physical barrier between the traffic lanes, but rather to discourage the driver from leaving the road, an increase in the curb redirection effectiveness should mitigate the risk of head-on collisions.

This research focused on the AASHTO type C curb design, which is the usual curb for urban roads. Further research is required to investigate the redirection capability of other curb designs.

The resulting data of this research could be used to validate the computer simulation code HVOSM, for the case of a vehicle impacting a 152 mm high curb at speeds below 34 km/h, and at impact angles of 5°, 10°, and 15°.
6. BIBLIOGRAPHY

American Association of State and Transportation Highway Officials (AASTHO). A

of California, Department of Public Works, Division of Highways, 1957.

Dunlap, D. F. “Barrier-Curb Redirection Effectiveness.” Highway Research Record 460,

Glennon, John C. “Effect of Pavement/Shoulder Drop-offs on Highway Safety.”

and Failures: The Hidden Trigger to Accidents” Proceedings of the XVI th
International Congress of the International Federation of the Societies of
Automotive Engineers, 1976.

Characteristics on Vehicle Handling and Stability.” Transportation Research
Record 1084 (1986).

Maintenance Guidelines.” Texas Transportation Institute, Research Report 328-1,
Texas, 1982.

Trucks Caused by Pavement Edge and Shoulder Conditions.” Surface
Chapter 6: Bibliography


Chapter 6: Bibliography


Appendix A: Full Scale Tests Set-up

Figure A-1: Front view

Figure A-2: Overall view
Appendix B: Video Pictures

Figure B-1: Test No 15 - Redirection - Reliant with additional mass impacting the curb at 11.3 km/h at an angle of 5°
Figure B-2: Test No 13a - Partial redirection - Reliant impacting the curb at 17.6 km/h at an angle of 5°


Figure B-2: (continued)
Figure B-3: Test No 17 - No Redirection - Reliant with additional mass impacting the curb at 25.9 km/h at an angle of 5°
Figure B-3: (continued)
Figure B-4: Test No 25 - Civic climbing the curb from a scrubbing condition at approximately 30 km/h
Figure B-5: Test No 26 - Cordoba climbing the curb from a scrubbing condition at approximately 30 km/h
Figure B-6: Test No 27 - Cordoba impacting the curb at an angle of 90°, at a speed of 8.4 km/h
Figure B-7: Test No 28 - Civic impacting the curb at an angle of 90° at 9.1 km/h
### Appendix C: Vehicle’s Attitude Data

Table C-1: Measured steering wheel rotation, bumper rise, and vehicle roll

<table>
<thead>
<tr>
<th>Test No</th>
<th>Vehicle</th>
<th>Mass (kg)</th>
<th>Actual Speed (km/h)</th>
<th>Angle (degree)</th>
<th>Redirection</th>
<th>Steering wheel rotation (degree)</th>
<th>Bumper rise (mm)</th>
<th>Vehicle Roll (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aries</td>
<td>1128</td>
<td>22.1</td>
<td>15</td>
<td>no</td>
<td>42</td>
<td>340</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Aries</td>
<td>1128</td>
<td>11.1</td>
<td>15</td>
<td>no</td>
<td>-</td>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Aries</td>
<td>1128</td>
<td>33.0</td>
<td>15</td>
<td>no</td>
<td>45</td>
<td>58</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Civic</td>
<td>823</td>
<td>19.1</td>
<td>15</td>
<td>no</td>
<td>200</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Civic</td>
<td>823</td>
<td>15.9</td>
<td>10</td>
<td>no</td>
<td>270</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Reliant</td>
<td>1128</td>
<td>14.5</td>
<td>15</td>
<td>no</td>
<td>-</td>
<td>104</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Reliant</td>
<td>1128</td>
<td>6.5</td>
<td>15</td>
<td>partly</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Civic</td>
<td>823</td>
<td>18.3</td>
<td>5</td>
<td>yes</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Civic</td>
<td>823</td>
<td>16.7</td>
<td>5</td>
<td>no</td>
<td>360</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Civic</td>
<td>1123</td>
<td>16.2</td>
<td>5</td>
<td>yes</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Civic</td>
<td>1123</td>
<td>26.9</td>
<td>5</td>
<td>partly</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Civic</td>
<td>1123</td>
<td>33.3</td>
<td>5</td>
<td>no</td>
<td>-</td>
<td>56</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>Reliant</td>
<td>1128</td>
<td>17.6</td>
<td>5</td>
<td>partly</td>
<td>40</td>
<td>72</td>
<td>3.5</td>
</tr>
<tr>
<td>14</td>
<td>Reliant</td>
<td>1128</td>
<td>27.2</td>
<td>5</td>
<td>partly</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Reliant</td>
<td>1508</td>
<td>11.3</td>
<td>5</td>
<td>yes</td>
<td>45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>Reliant</td>
<td>1508</td>
<td>15.6</td>
<td>5</td>
<td>partly</td>
<td>60</td>
<td>92</td>
<td>5.5</td>
</tr>
<tr>
<td>17</td>
<td>Reliant</td>
<td>1508</td>
<td>25.9</td>
<td>5</td>
<td>no</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>Cordoba</td>
<td>1542</td>
<td>14.8</td>
<td>5</td>
<td>partly</td>
<td>45</td>
<td>170</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>Cordoba</td>
<td>1542</td>
<td>18.2</td>
<td>5</td>
<td>partly</td>
<td>35</td>
<td>183</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>Cordoba</td>
<td>1542</td>
<td>27.4</td>
<td>5</td>
<td>no</td>
<td>30</td>
<td>51</td>
<td>3.5</td>
</tr>
<tr>
<td>21</td>
<td>Sprint</td>
<td>675</td>
<td>19.5</td>
<td>5</td>
<td>no</td>
<td>130</td>
<td>47</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>Sprint</td>
<td>675</td>
<td>14.1</td>
<td>5</td>
<td>yes</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Sprint</td>
<td>905</td>
<td>19.2</td>
<td>5</td>
<td>partly</td>
<td>100</td>
<td>52</td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>Dodge Van</td>
<td>1750</td>
<td>21.0</td>
<td>5</td>
<td>partly</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>
### Appendix C: Vehicle’s Attitude Data

#### Table C-2: Maximal recorded longitudinal and lateral accelerations

<table>
<thead>
<tr>
<th>Test No</th>
<th>Vehicle</th>
<th>Speed (km/h)</th>
<th>Angle (degree)</th>
<th>Maximal longitudinal acceleration (g)</th>
<th>Maximal lateral acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Aries</td>
<td>33.0</td>
<td>15</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>Civic</td>
<td>19.1</td>
<td>15</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>Reliant</td>
<td>13.2</td>
<td>15</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>Civic</td>
<td>16.0</td>
<td>5</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>11</td>
<td>Civic</td>
<td>26.5</td>
<td>5</td>
<td>0.23</td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td>Civic</td>
<td>33.2</td>
<td>5</td>
<td>0.28</td>
<td>0.03</td>
</tr>
<tr>
<td>13</td>
<td>Reliant</td>
<td>17.6</td>
<td>5</td>
<td>0.20</td>
<td>-0.05</td>
</tr>
<tr>
<td>15</td>
<td>Reliant</td>
<td>11.3</td>
<td>5</td>
<td>0.24</td>
<td>-0.12</td>
</tr>
<tr>
<td>16</td>
<td>Reliant</td>
<td>15.6</td>
<td>5</td>
<td>0.18</td>
<td>-0.15</td>
</tr>
<tr>
<td>17</td>
<td>Reliant</td>
<td>25.9</td>
<td>5</td>
<td>0.26</td>
<td>-0.13</td>
</tr>
<tr>
<td>18</td>
<td>Cordoba</td>
<td>14.8</td>
<td>5</td>
<td>0.14</td>
<td>-0.02</td>
</tr>
<tr>
<td>19</td>
<td>Cordoba</td>
<td>18.2</td>
<td>5</td>
<td>0.25</td>
<td>-0.02</td>
</tr>
<tr>
<td>20</td>
<td>Cordoba</td>
<td>27.4</td>
<td>5</td>
<td>0.40</td>
<td>-0.02</td>
</tr>
<tr>
<td>21</td>
<td>Sprint</td>
<td>19.5</td>
<td>5</td>
<td>0.19</td>
<td>-0.02</td>
</tr>
<tr>
<td>22</td>
<td>Sprint</td>
<td>14.1</td>
<td>5</td>
<td>0.14</td>
<td>-0.02</td>
</tr>
<tr>
<td>23</td>
<td>Sprint</td>
<td>19.2</td>
<td>5</td>
<td>0.22</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Figure C-1: Maximal measured longitudinal and lateral acceleration in function of the speed normal to the curb

Figure C-2: Maximal measured longitudinal acceleration experienced in each test in function of the vehicle mass
Figure C-3: Maximal measured lateral acceleration experienced in each test in function of the vehicle mass