PERFORMANCE OF DEFLECTING
CONCRETE HIGHWAY BARRIERS

By

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Abstract

Shaped concrete barriers are employed as roadside protection in many highway jurisdictions. Those found in British Columbia, Canada, are assemblages of 2.5 m precast concrete segments. Two types of barrier are currently employed: a 810 mm high barrier used for median protection and 690 mm tall roadside barriers installed on the shoulders of the roadway. The latter represents a unique roadside protection system to B.C. Both the median and roadside barriers are free standing structures that can deflect during a vehicle impact. The collision performance of these barrier was examined experimentally and through a mathematical model developed herein.

The experimental test program consisted of 26 vehicle crash tests of both barrier types. Principal findings of the testing were that the vehicle was redirected to the road for all test conditions and that the barriers could separate at their joints without allowing the vehicle to penetrate. Specialized tests on the joint structures were conducted to assist in developing a mathematical description of the barrier dynamics.

A mathematical model was developed to simulate a vehicle-barrier collision. This model was based on a planar representation of the collision event. The vehicle was modelled as a deformable body using structural deflection characteristics developed for accident reconstruction programs.

The dynamics of the barrier were modelled as a multibody system of rigid links. Connections between the barrier segments were defined with a five phase joint deflection
behaviour. These different phases represented (with increasing barrier deflections): 1) the slack between the segments, 2) joint rotations about the hook and eye, 3) initial binding contact of the concrete segment corners, 4) rotation about the point of binding, and 5) joint separation. Friction forces were calculated from a model of two planes in contact. Static and dynamic coefficients of friction were incorporated into this friction model.

The simulation used analytical descriptions of the impulsive or discontinuous events occurring during the collision event. These involved transitions between different joint or friction regimes. Numerical integration was suspended while an impulse analysis of the event was conducted. The post impulse parameters were used as the starting point for the resumption of numerical integration. This approach allowed the simulation to proceed efficiently without excessive iteration about these transition periods.

The resulting mathematical model was programmed into a personal computer program. This program allows arbitrary barrier and vehicle definitions to represent a vehicle-barrier impact. Results of a sensitivity analysis and comparison to test data were very encouraging. The vehicle model appears to reasonably represent a vehicle collision with a rigid vertical wall. Simulations with the deflecting barrier definition did not have as good agreement with test data, but showed a reasonable replication of the collision event.

The sensitivity analysis showed that the vehicle redirection variables describing the vehicle yaw and yaw rate at exit were the most sensitive to perturbations in the input parameters. The analysis suggests that the redirection is closely related to the impact of the rear axle and rear bumper with the barriers. Better representation of this event will improve the model's performance.
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This thesis is dedicated to the memory of my father, Alvin Thomson.
Chapter 1

Introduction and Objectives

1.1 Background

A wide variety of guardrail and barrier configurations are used in highway design to prevent vehicles from leaving their travel lane. In British Columbia, specially shaped concrete barriers are used to achieve this goal. These barriers consist of assemblages of 2.5 meter precast concrete sections which are linked with both steel hook-and-eye and concrete tongue-and-groove connection systems. There are two different sizes of barriers used in B.C. A 690 mm tall Concrete Roadside Barrier (CRB) is typically employed in roadside (or shoulder) applications. These barriers are used to prevent the vehicle from driving off the side of the roadway into natural or manmade hazards (rivers, ditches, rock bluffs, etc.). A taller 810 mm barrier is normally used to separate opposing traffic lanes. The function of this Concrete Median Barrier (CMB) is to prevent an errant vehicle from crossing the roadway centerline and moving into the path of oncoming traffic. Figure 1.1 shows the two barriers types installed on a roadway.

Many jurisdictions employ a concrete barrier for median protection. The typical height for these barriers is 810 mm, as is the case for the B.C. CMB. To implement a concrete barrier for roadside use, the B.C. Ministry of Transportation and Highways (MoTH) has scaled the CMB to produce the 690 mm high barrier. This provides vehicle passengers greater visibility over the barriers. Detailed drawings of both barriers are presented in Appendix A. Figure 1.2 illustrates the main features of the
Chapter 1. Introduction and Objectives

Figure 1.1: Concrete Barriers on British Columbia Roads

CMB. Weights of the individual barrier segments are approximately 1250 kg and 1650 kg for the CRB and CMB, respectively.

The concrete barrier design used in B.C. has a ‘Type F’ cross-sectional profile (Figure 1.2) which is a derivative of the New Jersey concrete barrier developed in the 1960’s [2]. Other concrete barriers developed for highway applications include the GM Barrier and a curved-face barrier (Figure 1.3) used in B.C. prior to the Type F CMB. The Type F barriers have proven to perform well under experimental and service conditions when fixed to the roadbed. The current barriers employed by the B.C. MoTH were adopted in 1982 and are used for all new construction and upgrades of older barrier installations.

Two features of concrete barriers and their applications distinguish B.C. from other jurisdictions. The first is that the barriers are free standing on asphalt portions of the roadbed. Secondly, B.C. uses a concrete barrier for shoulder protection which is uncommon elsewhere. Most highway authorities use post-and-beam guardrail to supply this protection. As shown in Figure 1.4, guardrail provides many design variations through post spacing, guardrail size, and height of rail. The guardrail is
Figure 1.2: B.C. Concrete Median Barrier

Figure 1.3: Cross-section of Typical Barriers (adapted from [5])
offset from the posts to reduce the potential snagging of a vehicle tire on a post during a collision.

There are a number of reasons why the B.C. MoTH chose to adopt the free standing barrier over the post-and-beam installations favored in the rest of North America. The main advantage is the reduction in maintenance costs provided by this barrier type. Little cosmetic maintenance is required and impact damage is easily repaired by realigning the barriers and replacing any damaged segments. An important maintenance consideration for highway terrain found in B.C. is the possibility of debris (dirt, rock, snow) falling behind the barrier. The ability of the barrier to be easily disassembled provides access for heavy equipment when clearing the debris.

In addition to the maintenance benefits, the capital cost to install the free standing B.C. barrier is lower than for fixed barriers systems. Connecting a concrete barrier to the roadbed requires cast-in-place equipment or a structural connection to the roadbed. The latter is achieved by grouting the barrier in place or bolting it to the substrate. For post and beam installations, adequate soil strength must be present and maintained to ensure the adequacy of the structure. All of these procedures are labour intensive and require special road preparation. The B.C. barrier is quickly assembled using general purpose lift equipment and requires no special preparation at the work site.

1.1.1 Barrier Collision Protection

Observations of vehicle-barrier crash tests suggest that the redirection process is influenced by the impact speed and impact angle. For low speed (≤ 50 km/h) and low
angle (< 15 degree) impacts, the front wheel contacts the barrier and rides up the lower face (batter curb) onto the vertical face. The rear wheel follows this behaviour but does not climb as high up the barrier. As the vehicle is directed upwards, it is also redirected towards the road center line. Body roll and suspension motion allows the vehicle redirection to be accomplished without involving the sheet metal structures of the vehicle, minimizing the damage to the vehicle. The vertical motion of the vehicle also serves to temporarily convert some of the vehicle's kinetic energy into potential energy. This reduces the lateral (vehicle referenced) impulsive loading on the vehicle.

The concrete barrier's low speed collision behaviour has an advantage over that for guardrail. Any vehicle contact with a guardrail will cause damage to the vehicle (and likely to the barrier). This means that every off-road excursion involving a guardrail will have some cost. However, minor contacts with concrete barriers typically result in little or no vehicle damage and no repair costs for the barrier.

Higher speed impacts are similar to low speed collisions but have some important differences. The wheel is no longer free to roll as it climbs onto the vertical face. Instead, it is quickly turned parallel to the barrier and scrapes along the face during contact. The higher vehicle-barrier contact forces cause deformation of the front bumper and fender and this loading combines with the wheel contact to rotate the vehicle towards the road. As the vehicle climbs the barrier, the loads applied to the vehicle usually cause all four wheels to come off the road. This eliminates the road/tire friction that would resist the redirection of the vehicle.

1.1.2 Barrier Warrant

Jurisdictions which employ a free standing concrete barrier have limited information for evaluating barrier performance. In the case of many jurisdictions, temporary use of these barriers in controlled traffic areas (such as construction zones), does not warrant significant research. However, authorities like B.C. MoTH have to ensure that all permanent highway infrastructure functions appropriately. MoTH must also ensure that these structures are appropriate as characteristics of the vehicle population change.
It is not practical, nor desirable, to totally contain a roadway with barriers or guardrails. The design engineer needs to determine locations that require roadside and/or median barriers and the length of barrier required to provide suitable protection. This can be achieved if the collision performance of a barrier can be documented and compared to other hazardous events to which a vehicle is exposed.

The choice of a roadside environment is determined by guidelines developed by each jurisdiction. These guidelines and policies are referred to as a 'warrant'. Their purpose is to apply a consistent evaluation of a roadside environment design option. There are three potential roadside designs: 1) leave the site unmodified, 2) adjust the road's side slopes, or 3) install concrete barriers.

The warrant may be designed to provide the criteria for a new barrier installation and provide design details such as the required length of barrier to install. Other warrants may provide a rating that can be used to compare different remediation alternatives. Most warrants are set up as a nomograph using variables like curve radius, traffic volume, and shoulder width to evaluate a particular road section. Appendix A contains the Roadside Barrier Index Warrant for B.C.

A nomograph produces a numerical rating (Barrier Need Index-BNI) for a given roadside location. Barriers are warranted when the BNI exceeds the threshold value, a value determined by the highway jurisdiction. Although this number has no physical meaning, it does serve as a benchmark to compare different roadside conditions. The goal is to reduce this BNI for all new and existing locations in the highway system.

A detailed warrant for the B.C. CMB does not exist at this time. A simple, two parameter nomograph (median width and traffic volume) is available to provide some guidance, but no formal warrant has been developed.

The road safety engineers would like to develop a roadside barrier warrant which includes the economics of the three possible roadside design solutions. The cost for each of the design alternatives can be broken into capital costs, maintenance costs, and a safety expense. The first two costs are reasonably easy to estimate from previous construction and maintenance experience. However, the safety expense is more difficult to predict. This requires an estimate of the frequency of off-road excursions,
consequences of these events, and the associated event costs. The proposed warrant analysis incorporating a cost-benefit analysis is presented in Figure 1.5.

![Figure 1.5: Warrant Analysis](image)

Off-road excursions can be classified into three severity criteria: property damage only (PDO), personal injury (PI), or fatality accidents (FA). Actuarial data from the insurance industry can be used to determine a unit cost for each of these collision types. This information would be combined with frequency and severity of the off-road excursions to complete the cost-benefit analysis. Unfortunately, the latter information is difficult to obtain because of the random nature of collision events. The frequency of off-road excursions could be developed from previous accident data but the severity of these events is a function of many variables including the site characteristics, vehicle type, and the vehicle's trajectory leaving the road.

The B.C. MoTH currently uses the Roadside Hazards Simulation Model (RHSM) to evaluate the severity of an off-road excursion. This provides a simplified analysis of the
Chapter 1. Introduction and Objectives

vehicle leaving the roadway and is useful in predicting PDO and PI values for a given roadside environment. Unfortunately, it only contains a first-order approximation of a barrier impact. This may be useful in predicting low severity impacts with the barrier (PDO), but cannot provide a useful measure of the occupant risk for injury producing or fatality events. It cannot provide other information such as barrier deflection or potential joint failures arising during a collision.

1.2 Conclusions - Subjects for Study

Highway jurisdictions have to document the performance of their barriers so that they can be implemented appropriately. This information is necessary if adequate levels of safety are to be achieved in an economic fashion. This information can be obtained through service evaluation of the barrier, empirical data from crash testing, and/or analytical evaluation. This information should be developed so that a tool for highway engineers can be developed for conducting warrant analyses for roadside environments.

Service evaluation of barrier impacts can be difficult to implement. Presently, all accidents reported to police in B.C. are documented in the Motor Vehicle Department Form 104. This provides cursory data such as time of day, weather and road conditions, occupant casualties, and location. Unfortunately, this coded form provides limited information for barrier analysis and, as found by Sayed [1], can be unreliable in its accuracy.

It is difficult to reliably document barrier collisions in the field. The random timing and location of these events make it difficult for investigators to completely and accurately record the collision details. Repairs to the barrier and vehicle destroy evidence required for any thorough analysis. These difficulties were considerable enough to exclude an active service evaluation from the present study.

The study herein, focussed on the B.C. concrete highway barriers, investigated barrier performance through experimental testing and computer simulation. The following list of objectives were used to focus this study.
1. Literature Review
   Documentation on the performance of highway barriers is reviewed in Chapter 2. The objective of this review was to obtain information regarding the service conditions, experimental data, and analysis procedures available for highway barriers. Collision data and available test documentation were gathered in order to direct the testing and modelling program for the deflecting B.C. barriers.

2. Full Scale Crash Testing
   Collision performance information for the B.C. barriers was required to document their specific responses to vehicle impacts. These barriers have unique connection systems and implementations in B.C. that are not documented elsewhere. Using this experimental data, computer simulation models can be validated for analysis of barrier systems.

   The specific objectives of the experimental study were to:

   (a) Conduct vehicle impacts with the CRB and CMB for a range of impact conditions defined by vehicle mass, speed, or impact angle.
   (b) Determine the friction characteristics of the barriers sliding on the road surface.
   (c) Quantify the mechanical properties of the connection systems.
   (d) Conduct impacts for barrier configurations unique to B.C. such as curved barrier sections or large impact angles.
   (e) Analyze the results of the test data to observe the critical response features of the vehicle and barrier.

3. Development of an Analytical Model to Predict Barrier Performance
   Detailed analysis of roadside safety in B.C. would benefit from an effective model of the vehicle-barrier collision. The highway engineer needs to evaluate the collision performance for specific accident configurations for both accident investigations as well as evaluating new or existing barrier warrants. This process would benefit from a computer model that can estimate the barrier performance for a specific impact condition.

   The main objective of the analytical modelling was to develop a model of the vehicle-barrier collision. This broad goal is composed of the following specific objectives:
(a) Develop a model for the barrier kinematics. This model should be flexible to allow arbitrary barrier definitions in terms of number of segments and initial joint angles.

(b) Describe the joint behaviour between barrier segments. The joint definition should allow the barrier to be defined with different deflection behaviours represented by different connection systems.

(c) Model the friction forces that resist the barrier segments' sliding on the road. This model would predict the friction forces due to the translation and rotation of the segments on the road.

(d) Develop a vehicle model to interact with the deflecting barrier model. A vehicle model should provide representation of different vehicle types and utilize the available data for structural stiffness and inertial properties.

(e) Define the interaction between the vehicle and barrier model. The interface between the vehicle and barrier would determine how the two models interact. The contact forces will be determined by the geometry of the interface and the surface properties. Flexibility in the interface definition would be an advantage in studying barrier geometry and surface finish.

The developed model will require a review of its validity and sensitivity to input parameters. This will provide an indication of the effectiveness of the model and identify areas for improving the performance. Objectives for this procedure were to:

(a) Determine the effectiveness of the vehicle collision model independent of the deflecting barrier model. This will identify the abilities and limitations of the vehicle representation. Subsequent simulations with the barrier model can then be analyzed knowing how the two sub-models react independently. This process will also allow appropriate vehicle parameters to be identified for subsequent use. Experimental data will be used to determine the accuracy of the model while parameter variations are used to observe the sensitivity.

(b) Assess the validity and sensitivity of the vehicle-barrier model. The sensitivity of the barrier model will be analyzed through the variation of several
barrier parameters. Experimental data gathered in the experimental testing program will be used to analyze the accuracy of the model over a range of impact conditions.

The background of highway barrier performance has been presented in this section. Deflecting concrete roadside barriers are a unique safety device to B.C. These barriers offer many design and maintenance advantages for the highway department. However, the optimum use of these devices requires a thorough understanding of the performance of these barriers during a collision. Objectives of a research program to study these barriers have been presented and the following chapters describe the procedures used to achieve these goals.
Chapter 2

Review of Previous Research

Three sources of barrier performance information were reviewed for this study. Previous studies were located that described barrier service conditions, crash testing, and analytical methods. This information covered many different barrier and guardrail designs so a particular emphasis was placed on locating and reviewing studies of deflecting concrete barriers.

2.1 Observed Barrier Service History

Accident data for vehicle-barrier impacts have been collected by several investigators to characterize these collisions. Previous researchers made estimates of vehicle speeds and impact angles using the vehicle damage profiles and road surface markings. The results were compiled to determine trends in the pre-collision motion of the vehicles.

The most important observation for vehicle excursions from the road is that the angle at which a tracking vehicle leaves the roadway is inversely related to its speed. Cooper [2] compiled several studies which show this relationship, some of which are shown in Figure 2.1. The curve reported by Garrett and Tharp [3] indicates that the expected impact angle at the highway speeds (80-96 km/h) is below 5 degrees. However, theoretical impact angles of 20 degrees can be calculated from the roadway -
Chapter 2. Review of Previous Research

Figure 2.1: Relationship Between Impact Speed and Angle (adapted from Cooper [2])

shoulder width and the maximum steering ability for a vehicle travelling at 90 km/h. As reported by Deleys and McHenry [4], the theoretical impact angle takes the form:

\[
\psi = \cos^{-1} \left[ \frac{1 - gy(\mu + \phi)}{V^2} \right]
\]  

(2.1)

where: \( \psi \) = impact angle, \( y \) = lateral distance to the barrier [m], \( V \) = vehicle speed [m/s], \( g \) = gravitational acceleration (9.81 m/s\(^2\)), \( \mu \) = road surface friction, and \( \phi \) = road camber or superelevation.

Cooper [2] found that the combined accident data indicated that 85% of all impact angles are below 25 degrees and 85% of impacts speeds are below 80 km/h. These figures provide a benchmark for crash test requirements. Impact conditions greater than 25 degrees and 80 km/h should be more severe than the expected service condition and provide a conservative assessment of a barrier's performance.

The study by Lisle and Hargroves [5] was the only one encountered which investigated the service performance of deflecting concrete barriers. They studied a construction zone with unanchored New Jersey barriers as median protection. The barrier segments were 3.7 m long, 810 mm high and were linked by tongue and groove connection
systems. Their study barrier experienced an average of 49 minor, unreported vehicle-barrier impacts were experienced (indicated by tire scuff marks) for every reported accident. Barrier deflections from the reported impacts were less than 0.3 m except for a severe impact with a van (88 km/h - 45 degrees) which resulted in a 2.44 m deflection. The unanchored barriers appeared to adequately contain the vehicles to the roadside of the barrier. However, some of the exit conditions reported suggest that there was the possibility of errant vehicles encroaching on vehicles in the adjacent traffic lanes after redirection.

The literature review by Cooper [2] found that accident statistics for highway barriers have not been analyzed in the context of highway alignment. This is an important consideration for B.C. barriers because of the significant length of curved sections in the highway system. Crash tests were conducted on a rigid concrete barrier mounted on a curved highway off-ramp [6]. However, the focus of these crash tests was to try different vertical orientations of the barrier relative to the super-elevation of the road. No other information has been observed to relate highway barrier performance with road geometry.

2.2 Previous Experimental Testing

2.2.1 Test Protocols

A protocol for impact testing roadside barriers was initially discussed in NCHRP 153 [7] and then further developed by Michie in NCHRP 230 [8]. This has been recently updated in NCHRP 350 [9] which is accepted as the standard for testing roadside hardware in the United States. The goal of this procedure was to maintain consistent data reporting between test agencies and set some ‘reasonable’ design objectives. The test conditions recommended by NCHRP 230 are listed in Table 2.1¹ for passenger vehicles. There are similar tests listed for heavy trucks. However, there are slightly different performance requirements for truck tests which are not considered in the present study.

¹NCHRP 350 had not been released until late into the program described herein. Therefore, NCHRP 230 was used as the testing guideline throughout this research. Appendix D lists the major differences between the two reports.
Table 2.1: Test Matrix for NCHRP Highway Barrier Testing

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<td>Redirection/Structural Adequacy</td>
<td>Impact at Joint</td>
</tr>
<tr>
<td><strong>Transition Between Barrier Systems</strong></td>
<td>2050</td>
<td>96</td>
<td>25</td>
<td>Redirection/Structural Adequacy Impact 4.5 m upstream of transition</td>
</tr>
<tr>
<td><strong>Barrier Terminal Section Requirements</strong></td>
<td>2045</td>
<td>96</td>
<td>25</td>
<td>Redirection/Structural Adequacy Impact at transition of terminal section</td>
</tr>
<tr>
<td>2045</td>
<td>96</td>
<td>0</td>
<td>Occupant Safety/Redirection</td>
<td>Impact at end structure of terminus</td>
</tr>
<tr>
<td>1023</td>
<td>96</td>
<td>15</td>
<td>Structural Adequacy</td>
<td>Impact mid way between terminus and barrier</td>
</tr>
<tr>
<td>1023</td>
<td>96</td>
<td>0</td>
<td>Occupant Safety/Redirection</td>
<td>Impact at end structure of terminus</td>
</tr>
<tr>
<td>820</td>
<td>96</td>
<td>15</td>
<td>Occupant Safety/Redirection</td>
<td>Impact mid way between terminus and barrier</td>
</tr>
<tr>
<td>820</td>
<td>96</td>
<td>0</td>
<td>Occupant Safety/Redirection</td>
<td>Impact at end structure of terminus</td>
</tr>
</tbody>
</table>

Table Notes:
1) Redirection:
- exit angle < 60% of impact angle
- vehicle speed change < 24 km/h
- when warranted, the structure should stop the vehicle in a controlled manner

2) Occupant Safety
- occupant impact speeds on car interior < 15 m/s longitudinally < 12 m/s laterally
- occupant acceleration exposures < 15 g
- passenger compartment not compromised
- no vehicle rollover

3) Structural Adequacy
- barrier debris and deformations should not endanger other traffic
- barrier components should not pose a threat to the passenger compartment
- vehicle does not penetrate barrier
The first three test conditions listed in Table 2.1 evaluate how well a barrier redirects a colliding vehicle. The subsequent tests listed are ancillary tests that ensure that end sections and transitions between barrier types provide consistent protection throughout a barrier installation. The evaluation criteria used for all NCHRP 230 testing are the vehicle redirection, structural adequacy of the barrier, and occupant safety risk during an impact. All three factors are observed during the tests but each test has a specific focus that the impact conditions were designed to address.

Structurally adequate barriers are those capable of containing or redirecting a striking vehicle. The test designed to ensure this ability is a 2045 kg vehicle striking the barrier at 25 degrees and 96 km/h. Poor performance is indicated by the vehicle vaulting or penetrating the barrier. Performance is also unacceptable if the final position of the barrier obstructs normal traffic flow. Compared to the collision data discussed previously, this impact condition is extreme and provides conservatism to the design.

The redirectional capabilities of the barrier are tested by an 820 kg vehicle striking at 96 km/h and 15 degrees. The barrier should not allow the vehicle to rebound into the travel lanes in such a manner that it presents a risk to surrounding traffic. Therefore, the exit angle must be lower than 60% of the impact angle and the speed change of the vehicle must not exceed 24 km/h during its contact with the barrier. Vertical climb of the vehicle should not exceed the height of the barrier and lead to vaulting of the barrier.

The last major test evaluates the occupant's safety risk. The 820 kg vehicle impacts the barrier at 25 degrees and 96 km/h. The trajectory of the vehicle must not result in high risk vehicle motions such as rollovers or vaulting of the barrier. In addition, human tolerance data have been used to provide limits on the dynamics that an occupant experiences during the collision.

Occupant safety is evaluated using a simple dynamic model for a vehicle occupant. An occupant is assumed to behave as a lumped mass at their seating position. This mass will move relative to the vehicle during impact until it reaches a boundary representing the dashboard or side door structures. The area within this boundary is the 'flail space'. The occupant is assumed to strike this boundary with some impact velocity and then stay in contact with this surface through the rest of the collision.
Chapter 2. Review of Previous Research

The risk is assessed by the magnitude of the occupant’s impact speed and the maximum acceleration experienced while in contact with the flail space boundary. Impact velocities below 12 m/s laterally and 15 m/s longitudinally and accelerations below 15 g's (averaged over a 10 ms window) are deemed as survivable for these collision types. Unfortunately, the variability of occupant parameters (age, sex, weight, etc.) make specific injury analysis difficult. Therefore, conservative thresholds are set to separate satisfactory and unsatisfactory performance.

There have been suggestions to improve the flail space contact dynamics by considering more complete vehicle motions. These techniques are presently listed as optional procedures under with NCHRP 350. Ray et al [10] have reviewed the injury rating and concluded that the current procedure is incomplete. They found that the flail space concept appears reasonable but the amount of occupant motion and the thresholds for injury may be overly conservative. Another important observation of their work was that vehicle impacts with longitudinal barriers appear to be lower risk events compared with potential of subsequent impacts into other obstacles. These secondary collision events were suggested to be a greater risk to vehicle occupants.

2.2.2 Review of Experimental Research

There is considerable crash test information available for rigid concrete barriers. The rigid implementation of the New Jersey barrier and its Type F derivative have been shown to be suitable for redirecting vehicles including large freight trucks. An excellent source of barrier test results is provided in a video [11] demonstrating various vehicle-barrier collisions.

Empirical data for deflecting concrete barriers is not as prevalent as for rigid barriers. Crash test results for deflecting concrete barriers with shaped profiles (New Jersey, Type F, etc.) were listed by Beason and Ivey [12, 13] (Table 2.2). It is significant that the barrier segment length in all but those tested by New York in tests 44-46 were at least 3.7 m long, larger barriers than those used in B.C. (2.5 m). The small barrier deflections recorded are likely due to the large segment sizes and, as in the case for the New York barrier, a strong joint design that limits joint rotations.
It is important to note that Tests 44 and 45 conducted by New York resulted in vehicle rollover. This performance may be attributed to the New Jersey barrier profile (Figure 1.3) and the surface finish of the concrete. Fortuniewicz et al [14] found that the rough surface of the barriers in Tests 44-46 caused excessive vehicle climb and poor redirection performance when compared to Test 47 with a smoother finish. It was also found through experiments by Jehu & Pearson[15] that the Type F barrier (used in B.C.) has better rollover prevention than the New Jersey shape barrier.

The tests reported in Table 2.2 involve barrier segment designs that differ from the B.C. barrier. In particular, they exhibit significantly different joint designs (tending to be more rigid) and longer segment lengths. Barriers with these characteristics are likely to exhibit ‘stiffer’ deflection characteristics than the B.C. barriers. There are several connection systems used to connect portable concrete barriers and some are shown in Figure 2.2. A barrier which is likely more flexible than the B.C. barrier was tested by Glauz [16]. This barrier consisted of 1 m precast concrete segments connected by 2 pin connections at each joint. It was designed for counterflow traffic situations where lane dividers are moved twice a day. Four crash tests were conducted at speeds above 90 km/h, the most severe being a 1982 kg vehicle striking at 95 km/h and 24 degrees. This impact produced 1.14 m of lateral deflection. The joints had sufficient strength to maintain barrier integrity even for these large deflections. Occupant accelerations in all tests were within the NCHRP 230 guidelines and there were no rollovers encountered. However, all four tests exceeded the exit angle criteria recommended in NCHRP 230.

An important characteristic of barrier performance is that the vehicle must not climb over or vault the barrier. Tested barriers that were approximately 810 mm high (rigid or free standing implementation) appeared to adequately contain the vehicle. The B.C. CMB is 810 mm and should thus provide sufficient vaulting protection, however, the CRB is only 690 mm tall. Limited tests of 660 mm high segmented barriers by Hahn and Bryden [17] showed that impacting vehicles could rise higher than the barrier. Their test program produced one rollover which indicated unacceptable barrier performance. The implication of these test results for the CRB is not known without more test data.
### Table 2.2: Previous Test Results of Portable Concrete Barriers [12][13]

<table>
<thead>
<tr>
<th>Testing Agency</th>
<th>Test Number</th>
<th>Test Conditions [km/h][deg]/[kg]</th>
<th>Segment Length [m]</th>
<th>Static Deflection [m]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTI</td>
<td>TX-1</td>
<td>97.4/17.8/2045</td>
<td>4.6</td>
<td>0.27</td>
<td>Smooth redirection, negligible barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>TX-2</td>
<td>89.4/26/2045</td>
<td>4.6</td>
<td>0.40</td>
<td>Smooth redirection, negligible barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>3825-7</td>
<td>94.7/25/2050</td>
<td>3.7</td>
<td>0.55</td>
<td>Smooth redirection, slight barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>3625-6</td>
<td>96.2/24/2045</td>
<td>3.7</td>
<td>0.55</td>
<td>Vehicle redirected but rolled after recontact with pavement subsequent to primary collision, slight barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>3825-5</td>
<td>97.1/25/2050</td>
<td>3.7</td>
<td>0.49</td>
<td>Smooth redirection, slight barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>3825-9</td>
<td>101.4/25/2045</td>
<td>3.7</td>
<td>1.98</td>
<td>Smooth redirection, side plates failed, slight barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>3825-8</td>
<td>92.3/15/9090</td>
<td>6.1</td>
<td>4.57</td>
<td>Bus redirected but rolled 90 degrees onto side after collision, slight barrier damage.</td>
</tr>
<tr>
<td>TTI</td>
<td>CMB-2</td>
<td>96.0/25/2020</td>
<td>9.1</td>
<td>0.34</td>
<td>Smooth redirection, negligible barrier damage.</td>
</tr>
<tr>
<td>CALTRANS</td>
<td>291</td>
<td>104/7/2070</td>
<td>3.8</td>
<td>0.15</td>
<td>Smooth redirection, slight barrier damage.</td>
</tr>
<tr>
<td>CALTRANS</td>
<td>292</td>
<td>109/23/2160</td>
<td>3.8</td>
<td>0.58</td>
<td>Vehicle redirected but penetrated over top of barrier and slid sideways along top. Segment fractured, major barrier damage.</td>
</tr>
<tr>
<td>CALTRANS</td>
<td>293</td>
<td>106/40/2160</td>
<td>6.1</td>
<td>N/A</td>
<td>Vehicle penetrated and rolled. Segment tipped over, major barrier damage.</td>
</tr>
<tr>
<td>CALTRANS</td>
<td>294</td>
<td>62/25/2090</td>
<td>6.1</td>
<td>0.15</td>
<td>Smooth redirection, Steel vertical connection rods were severely bent., significant barrier damage.</td>
</tr>
<tr>
<td>SWRI</td>
<td>CMB-18</td>
<td>99/25/2000</td>
<td>6.1</td>
<td>N/A</td>
<td>Vehicle redirected, flexural failure in the segments, major barrier damage.</td>
</tr>
<tr>
<td>NEW YORK</td>
<td>NY-17</td>
<td>85/25/1890</td>
<td>6.1</td>
<td>0.40</td>
<td>Smooth redirection, slight barrier damage.</td>
</tr>
<tr>
<td>NEW YORK</td>
<td>NY-18</td>
<td>93/25/1880</td>
<td>6.1</td>
<td>0.9</td>
<td>Vehicle redirected but rolled after recontact with pavement subsequent to primary collision, slight barrier damage.</td>
</tr>
<tr>
<td>NEW YORK</td>
<td>NY-44</td>
<td>104/25/1880</td>
<td>2.4</td>
<td>0.43</td>
<td>Vehicle redirected but subsequently rolled, slight barrier damage.</td>
</tr>
<tr>
<td>NEW YORK</td>
<td>NY-45</td>
<td>106/15/970</td>
<td>2.4</td>
<td>0.09</td>
<td>Vehicle redirected but could have rolled, slight barrier damage.</td>
</tr>
<tr>
<td>NEW YORK</td>
<td>NY-46</td>
<td>98/25/1930</td>
<td>2.4</td>
<td>0.18</td>
<td>Vehicle redirected, slight barrier damage.</td>
</tr>
</tbody>
</table>
Chapter 2. Review of Previous Research

Figure 2.2: Barrier Connection Systems
2.3 Review of Analytical Barrier Evaluation Methods

A vehicle collision with a highway barrier is a very complex dynamic event that deals with highly variable components - vehicle properties, road geometry, and occupant characteristics. The methods reviewed for this study range from simple static analysis for estimating structural adequacy to complex computer programs used for dynamic simulation.

Analysis of portable barrier connection details, such as those depicted in Figure 2.2 has been conducted by Loumiet et al [18], Beason and Ivey [12, 13], and Ivey et al [19]. The first two references suggest that the joint strength of the barrier can be used to determine an acceptable service level (highest expected impact energy) for segmented barriers. This approach has merit, however it does not consider the dynamic performance of the barrier. This method only rates the barrier's ability to stay intact and does not account for its redirective ability nor its occupant safety risk. Ivey et al [19] developed an energy based model to predict lateral deflections of segmented barriers. They balanced the energy of vehicle crush, barrier sliding, and joint resistance with the impact energy directed at the barrier. The results of this analysis did compare well with the six experimental observations used for verification (correlation coefficient $R^2 = 0.78$). Limitations of the Ivey et al [19] approach for application to B.C. barriers stem from the simplifications used in its formulation. The most significant restriction is this model only considers two moving barrier segments and would require significant modification if more segments move during a collision.

A more advanced dynamic model of deflecting barriers was presented by Walker and Ross [20]. They derived the equations of motion from Lagrange's equation for the barriers. This provided a method of observing sliding barriers but required a known impact load history. This does not allow the coupling between the vehicle and barrier motions to be easily evaluated. This requirement limits the model's application for design evaluations where this coupling is the parameter of interest.

The major sophisticated barrier simulation models currently available (HVOSM [21], BARRIER VII [22], GUARD [23]) provide good representations of vehicles striking rigid barriers. In particular, HVOSM has been used extensively to evaluate rigid concrete barriers during vehicle impact conditions. The modifications of HVOSM by
Chapter 2. Review of Previous Research

Perera [24] provide very good agreement between simulated and experimental collisions for various vehicle sizes. Although good agreement was achieved for vehicle yaw motions, the roll and climb predictions were not as accurate. The author attributed this to the difficulty in modelling vertical tire forces on the barrier. This observation was also noted for the GUARD program by Welch [23] and is important to consider in future simulation work.

A noticeable omission in the reviewed literature is any references using a model like HVOSM to simulate deflecting concrete barriers. It appears that these programs do not have the facility to simulate the motion of barrier segments over a road surface.

Bronstad et al [25] developed a model of vehicle-barrier impacts for concrete barriers. This model was designed to investigate different barrier fixations to the road. The goal of this exercise was to determine acceptable barrier segment designs (length, mass, etc) for each given fixation method. They developed a model that used a rigid body representation of the barrier and springs to represent constraint forces from adjacent barriers and resistive loads from the road. Figure 2.3 shows the model schematic. Known load history data from a crash test was used to drive the simulation. Bronstad et al [25] were able to conduct some comparative studies for the different barrier designs, but like the work of Walker & Ross [20], the model cannot replicate the interaction of the vehicle and barrier during the impact. The large deflections possible and resulting friction forces experienced by the B.C. barrier could not be suitably modeled using the spring arrangement shown in Figure 2.3.

The current model used by the B.C. MoTH for predicting the consequences of a vehicle leaving the roadway is the ‘Roadside Hazard Simulation Model’ (RHSM). This model uses first order approximations of vehicle excursions to estimate the safety risk in terms of property damage, injuries and fatalities. Unfortunately, the assumptions used in this model oversimplify the physics of the event. The vehicle is described as a point mass and collisions with roadside objects are represented through a power dissipation model. As a result, RHSM can only be used to observe trends in the accident outcomes. The values predicted for specific vehicle performance cannot be accurately correlated with an actual vehicle excursion. Work by the Highway Safety Branch at MoTH [26] has updated the program to refine the results of a vehicle striking a barrier. However, its current applications do not extend beyond evaluating vehicle rollover on side slopes.
Chapter 2. Review of Previous Research

2.4 Discussion

The reviewed material describing performance of deflecting concrete barriers did not yield any information that can be directly applied to the B.C. barrier. It appears that the main focus of previous research has been on rigidly mounted barriers for straight road alignments. Only a cursory review of barrier curvature was uncovered for any barrier type. Testing or evaluation of deflecting concrete barriers by other jurisdictions has not been a priority because of its limited exposure as a temporary protection device.

There are a number of parameters that influence a vehicle-barrier collision outcome. These parameters may or may not be independent of the deflecting nature of the barrier. Cross-section profile, barrier height, surface finish, as well as all the vehicle impact variables (speed, angle, weight) are common to rigid and deflecting barriers. Segment length, segment mass, joint deflection details, and road-barrier friction are specific to deflecting barriers.

Crash data available for deflecting barriers are insufficient to identify the influence of individual collision variables. There are at least ten variables identified above, but
As a result, there have been no studies that use existing crash data to predict barrier performance of a new deflecting barrier design.

There have been a number of analysis techniques explored for highway barriers. There are first order models that use structural strength or energy methods to assess deflecting barriers. However, these approaches do not provide more than ‘back of the envelope’ calculation quality.

Sophisticated vehicle highway barrier models exist and have been shown to provide excellent results for rigid concrete barriers. The application of these models to deflecting barriers has not yet been uncovered and the modification to do so is not trivial. They are unsuitable for modelling the B.C. concrete barriers without significant modification.

The only other model that has promise for use with the B.C. barrier was that of Walker and Ross [20]. Unfortunately the requirement of a-priori barrier-vehicle contact forces restricts its effectiveness.

A complete study of the B.C. deflecting concrete barrier is not possible with the available information. Previous empirical data must be supplemented with crash test specific to the B.C. barrier. Any modelling of the barrier performance will require upgrading existing computer models or developing a new one to incorporate the features unique to deflecting concrete barriers. The study herein addresses the two deficiencies mentioned above and implements them to provide a tool of use to highway engineers.
Chapter 3

Experimental Barrier Evaluation Program

The objectives of the experimental component of this study were to observe and record the performance of the B.C. concrete barriers. The majority of this testing consisted of full scale vehicle impacts with the barriers. The test matrix was selected to quantify the barrier performance with progressively increasing impact severities. In addition to the vehicle crash testing, quasi-static testing of the connection systems was conducted to record the joint deflection characteristics.

3.1 Crash Test Program

The experimental program described herein was designed to develop a database describing the impact performance of the B.C. MoTH CRB and CMB. The starting point for the test program design was the test protocol described in NCHRP 230 [8] (Table 2.1). Using this existing protocol as a basis, additional test conditions were determined using the B.C. highway experience of MoTH personnel. The test data reviewed in Chapter 2 did not fully address the conditions identified for study in this project so a crash testing program had to be initiated.

Testing was conducted during three summer test periods from 1990 to 1992 and comprised twenty-six individual tests. The first test period consisted of thirteen discovery tests. These tests were divided between ten tests with the CMB and three tests with the CRB. Data were collected on the performance of the barrier under increasing impact conditions. The second test session involved six tests of the CRB
and focused on its structural abilities. The last test session of seven tests was used to observe the CRB under particular B.C. service conditions. The influence of joint construction was also observed in this test period. Specifically, comparisons between the standard and a modified (stronger) connection hook were conducted through crash testing and local joint deflection testing.

### 3.2 Test Conditions

NCHRP 230 testing protocol was used to build up a test program for the B.C. barriers. Test procedures and equipment were adopted for the testing conducted herein, but the impact conditions specified by NCHRP 230 were modified. NCHRP 230 guidelines were originally designed as a 'proof of concept' exercise and were not designed for comprehensive barrier performance research. Thus, the test conditions were varied to encompass a greater range of impact severities and address unique features of the B.C. barrier and its service implementation.

Three passenger vehicle sizes were suggested by NCHRP 230 as listed in Table 2.1: small (820 kg), compact (1023 kg) and large (2045 kg). At the time of testing, Transportation Research Board (TRB) Committee A2A04(2) was deliberating over the use of a van or pick-up truck as a 2045 kg vehicle and dropping the compact vehicle size 1. However, the vehicle size predictions of Navin et al [35] suggest that the downward trends in motor vehicle weights will lead to an average vehicle weight of 900 kg with a large automobile weighing approximately 1300 kg.

Two test vehicle sizes were selected for the crash test program in order to investigate small and midsize vehicles impacting the B.C. barriers. The large vehicle (2045 kg) was dropped from this test program for the reasons described above and the additional testing resources required of this vehicle size. The small car size (820 kg) was adopted from NCHRP 230 and a heavier compact car (1140 kg) was introduced. This creates a greater difference between the vehicle sizes. The heavier compact vehicle represents more vehicles (on a percentile basis of weight) than the compact size in NCHRP 230. The 820 kg vehicle class includes cars like the Volkswagen Rabbit and Honda

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1 NCHRP 350 now recommends a sub compact (700 kg), compact (820 kg) and '3/4 ton' (2000 kg) pickup truck for roadside hardware testing.
Civic, vehicles commonly reported in previous research and used herein. The 1140 kg compact car was represented by vehicles in the GM X-body line (Chevrolet Citation, Pontiac Phoenix, etc) and the Chrysler K-Car series (Dodge Aries, Plymouth Reliant, etc.) in this test program.

The first test series consisted of thirteen discovery tests to observe the barrier response to increasing severity impacts. Impact angles of 15, 20, and 25 degrees were adopted from the NCHRP 230 protocol and impact speeds starting at 60 km/h and increasing to 94 km/h were utilized. Both the median and roadside barriers were tested with an increased emphasis on the median barrier.

The last two test series dealt only with the CRB performance. This barrier appeared to be more sensitive to vehicle impacts in the first test series. An important performance feature that arose in the first test series was the potential for the joints to separate. Impact conditions were focused to determine the conditions which cause joint separation and to observe the resulting influence on vehicle redirection and occupant safety. A number of tests at a single impact condition (80 km/h - 20 degrees) provided an indication of the repeatability of the barrier response. Table 3.1 lists the test conditions studied and identifies the specific focus of each test.

Performance of the terminal sections used for the roadside barrier was studied in the final test series. Two factors introduced by the terminal section employed in B.C. are an increase of the encroachment angle and a reduction of upstream barrier mass. As shown in Figure 3.1, the terminal structure is constructed using a flare of approximately 4 degrees (with respect to the lane edge) and an end fitting. The flare moves the ‘bull nose’ (end fitting) away from traffic to reduce the probability of an end-on impact. Impacts near the bull nose have fewer upstream barrier segments that can affect the barrier deflection. The bull nose components taper the CRB height down to ground level and are smaller than a standard segment. There is no rigid link between the bull nose and the road.

The flare of the barrier ends will increase all encroachment angles by about 4 degrees along its length. This larger angle was included in the last series of tests by adding 5 degrees to the maximum impact angle (25 degrees) specified by NCHRP 230. The importance of these higher impact angles is reinforced by the studies of Olson et al.
Chapter 3. Experimental Barrier Evaluation Program

[31] and Ross & Nixon [32] which theorize that the impact response of vehicles against barriers is more sensitive to impact angle than speed.

Table 3.1: Test Matrix for UBC Highway Barrier Testing

<table>
<thead>
<tr>
<th>Test</th>
<th>Barrier Type</th>
<th>Vehicle (kg)</th>
<th>Speed (km/h)</th>
<th>Angle (deg.)</th>
<th>Focus of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CMB</td>
<td>820</td>
<td>60</td>
<td>15</td>
<td>Redirection</td>
</tr>
<tr>
<td>2</td>
<td>CMB</td>
<td>820</td>
<td>63</td>
<td>25</td>
<td>Occupant Safety</td>
</tr>
<tr>
<td>3</td>
<td>CMB</td>
<td>1140</td>
<td>60</td>
<td>25</td>
<td>Structural Adequacy</td>
</tr>
<tr>
<td>4</td>
<td>CMB</td>
<td>1140</td>
<td>80</td>
<td>25</td>
<td>Structural Adequacy</td>
</tr>
<tr>
<td>5</td>
<td>CMB</td>
<td>1140</td>
<td>80</td>
<td>15</td>
<td>Structural Adequacy</td>
</tr>
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<td>6</td>
<td>CMB</td>
<td>820</td>
<td>78</td>
<td>20</td>
<td>Redirection</td>
</tr>
<tr>
<td>7</td>
<td>CRB</td>
<td>820</td>
<td>80</td>
<td>15</td>
<td>Redirection</td>
</tr>
<tr>
<td>8</td>
<td>CRB</td>
<td>820</td>
<td>78</td>
<td>20</td>
<td>Redirection/Vehicle Climb</td>
</tr>
<tr>
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<td>CRB</td>
<td>1140</td>
<td>75</td>
<td>25</td>
<td>Structural Adequacy</td>
</tr>
<tr>
<td>10</td>
<td>CMB</td>
<td>820</td>
<td>94</td>
<td>15</td>
<td>Vehicle Redirection</td>
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<td>CMB</td>
<td>1140</td>
<td>90</td>
<td>15</td>
<td>Vehicle Redirection</td>
</tr>
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<td>12</td>
<td>CMB</td>
<td>820</td>
<td>93</td>
<td>25</td>
<td>Occupant Safety</td>
</tr>
<tr>
<td>13</td>
<td>CMB</td>
<td>1140</td>
<td>89</td>
<td>25</td>
<td>Structural Adequacy</td>
</tr>
<tr>
<td>14</td>
<td>CRB</td>
<td>820</td>
<td>85</td>
<td>25</td>
<td>Occupant Safety</td>
</tr>
<tr>
<td>15</td>
<td>CRB</td>
<td>1140</td>
<td>60</td>
<td>25</td>
<td>Barrier Separation</td>
</tr>
<tr>
<td>16</td>
<td>CRB</td>
<td>1140</td>
<td>83</td>
<td>20</td>
<td>Barrier Separation</td>
</tr>
<tr>
<td>16a</td>
<td>CRB</td>
<td>1140</td>
<td>82</td>
<td>20</td>
<td>Barrier Separation</td>
</tr>
<tr>
<td>17</td>
<td>CRB</td>
<td>1140</td>
<td>82</td>
<td>20</td>
<td>Barrier Separation</td>
</tr>
<tr>
<td>18</td>
<td>CRB</td>
<td>820</td>
<td>83</td>
<td>25</td>
<td>Occupant Safety</td>
</tr>
<tr>
<td>20</td>
<td>CRB</td>
<td>820</td>
<td>73</td>
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</tr>
<tr>
<td>21</td>
<td>CRB</td>
<td>1140</td>
<td>63</td>
<td>30</td>
<td>Structural Adequacy</td>
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<tr>
<td>22</td>
<td>CRB</td>
<td>1140</td>
<td>73</td>
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<td>Curved Barrier Geometry</td>
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<tr>
<td>23</td>
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<td>820</td>
<td>79</td>
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<td>End Conditions</td>
</tr>
<tr>
<td>24</td>
<td>CRB</td>
<td>1140</td>
<td>78</td>
<td>20</td>
<td>Connection Strength</td>
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<tr>
<td>25</td>
<td>CRB</td>
<td>820</td>
<td>76</td>
<td>20</td>
<td>End Conditions</td>
</tr>
<tr>
<td>26</td>
<td>CRB</td>
<td>1140</td>
<td>78</td>
<td>20</td>
<td>Connection Strength</td>
</tr>
</tbody>
</table>

The CRB is a standard roadside barrier in B.C. and must accommodate different highway geometries including highway access ramps. NCHRP 230 tests only require a straight barrier section and only one reference [6] describes impacts on a curved
Chapter 3. Experimental Barrier Evaluation Program

barrier. To test the barrier's sensitivity to road alignment, the barrier was installed on a 250 m radius horizontal curve. This represents the minimum design curve radius for highway design on secondary highways. An impact angle of 12 degrees was chosen, as this would be the impact angle for a vehicle driving from a straight road tangent into this curve without any steering corrections.

The characterization of the barrier joints was another objective of the experimental component of the study. A comparative study of two joint types was undertaken in the crash testing. The two joints studied were the standard steel hook of 25 mm diameter and a thicker, 32 mm diameter hook. Both hook designs were tested under identical test conditions with extra instrumentation. Strain gauges were applied to the hooks of one male barrier segment for the collision. This segment was placed such that it was the first segment the vehicle struck in the barrier test section. Barrier joint characteristics were also studied through quasi-static testing of the joint in addition to the crash testing. Details of these test arrangements are discussed in the following sections.

3.3 Test Facility

The full scale crash testing of an automobile into a roadside barrier requires a large testing facility. There must be sufficient space to install a minimum 30 m length of test barrier as well as accelerate an automobile to the 96 km/h speeds required in the NCHRP protocol. The Pacific Traffic Education Centre (PTEC), located on an inactive runway of the Boundary Bay International Airport, provided a suitable site for the B.C. MoTH barrier tests. The facility for crash testing concrete roadside barriers shown in Figure 3.2 was designed and refined over the three test periods from 1990 to 1992.

The main component of the test facility was a section of steel I-beam (up to 200 m long) which was bolted to the concrete surface to form a guiderail. A fixture was centered on the underside of the car and mounted slightly rearward of the front wheels (Figure 3.3). This fixture guided the test vehicle along the rail to the point of impact on the barrier.
Figure 3.1: End Treatment for Roadside Barriers

LAYOUT PLAN OF FLARES

Flare length and setback are set by the travel speed of the road

DETAILS OF STANDARD TERMINAL
The test vehicle was towed towards the barrier by another vehicle. The 300 m tow cable was routed along the guide rail and through a channel in the road surface beneath the barrier test section. The tow vehicle was positioned on the opposite side of the barrier from the test vehicle and aligned to achieve a straight pull along the guide rail. The tow cable was disconnected from the test vehicle approximately four metres prior to impact.

An important feature of the test apparatus was a remote control braking system installed on the test vehicle. This system was used to abort a test in the event of an emergency and to also limit the vehicle runout after impact. This system used remotely activated pneumatic cylinders which depressed the brake pedal of the test vehicle. Prior to testing, the test vehicle was drained of fuel and had its battery removed to avoid fire and chemical hazards.

An overhead camera tower was constructed to position one high speed video imager 13 m above the surface as illustrated in Figure 3.2. This provided a field of view of approximately 3 vehicle lengths and allowed the critical barrier and vehicle deflection during a collision to be recorded.

The surface of the test facility was tested to document its surface characteristics. The test site is a concrete runway which is harder than asphalt, the common road surface material. The coefficient of friction was measured at PTEC and was found to be approximately 0.75-0.85 for the concrete-concrete interface of the barrier on the runway as shown in Figure 3.4. Tests on an asphalt patch at the test site indicated that concrete-asphalt friction values were similar.

3.3.1 Instrumentation

Measurements of the vehicle and barrier motions were necessary to document the performance of the barriers. The parameters monitored in NCHRP 230 testing include: barrier deflections, vehicle impact velocity, vehicle exit velocity and vehicle accelerations. Physical characteristics of the test vehicle (size and weight) were also recorded. A comparison of the instrumentation recommended by NCHRP 230 and that used during the crash tests described herein are listed in Table 3.2.
Figure 3.2: Roadside Barrier Testing Facility
A high speed video system (Kodak Ekta-Pro 1000) was used to record the collision from overhead and road level views. This system originally recorded one image at 1000 frames/second with a smaller image from the second camera overlaid on the screen. This was upgraded in the last test series to record two separate images at a sampling rate of 500 frames per second per image and allowed three dimensional vehicle motion information to be derived. The location of video reference marks were

![Vehicle Guidance Fixtures](image)

**Figure 3.3: Vehicle Guidance Fixtures**

![Coefficient of Friction for a B.C. CMB on Concrete Surface](image)

**Figure 3.4: Coefficient of Friction for a B.C. CMB on Concrete Surface**
Table 3.2: Crash Test Instrumentation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NCHRP 230</th>
<th>UBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit trajectory</td>
<td>high speed film (200 fps).</td>
<td>high speed video (500-1000 fps).</td>
</tr>
<tr>
<td>Barrier Deflection</td>
<td>high speed film (200 fps). displacement potentiometers.</td>
<td>high speed video (500-1000 fps). total station surveying system.</td>
</tr>
<tr>
<td>Vehicle Rotation Rates</td>
<td>rate gyros.</td>
<td>3-D video analysis.</td>
</tr>
<tr>
<td>Vehicle Acceleration</td>
<td>accelerometers.</td>
<td>accelerometers.</td>
</tr>
</tbody>
</table>

surveyed on the site such that photogrammetric techniques could be applied to the high speed video images. This analysis provided all the vehicle trajectory information.

Accelerometers were used to record the vehicle dynamics during the collision. These instruments were arranged in an array of nine accelerometers shown in Figure 3.6 and mounted close to the vehicle’s center of mass. The specific accelerometer array was designed to provide the angular motion of the vehicle. Previous researchers ([29], [30]), have been able to use accelerometer arrays to obtain angular motion by employing Euler’s equations of motion for a rigid body. This approach was attempted in this project, however, the noise in the accelerometer’s signal caused a cumulative integration error and corrupted the processed data. Attempts were made to filter out the high frequency components of the accelerometer signal. These components correspond to the structural vibration of the vehicle which are superimposed on the rigid body motions of the vehicle recorded by the accelerometers. The collision event was sufficiently long (at least 0.5 s) that any drift of the processed signal would mask the vehicle motions and suggests this measurement scheme may have been inappropriate for this application.

In tests 1-18, the accelerometers were connected to a personal computer based data
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Figure 3.5: Instrumentation Locations

Figure 3.6: Accelerometer Array Employed in Testing
acquisition system through a 250 m umbilical cord. Unfortunately, mechanical dam-
age to the cable resulted in poor system reliability. An onboard data recorder was
used in the remaining tests with some success. At least 10 seconds of test data were
collected at sample rates exceeding 2 kHz per channel for both systems. The data
systems were triggered when the vehicle approached the end of the guide rail.

Vehicle scales and load cells were used to weigh both the vehicles and the barrier
segments, as well as measure the coefficient of friction for the surface. In two tests, the
steel hooks connecting the barriers were instrumented with strain gauges to measure
hook deflections for the segments in the impact zone. Video cameras (30 frames per
second) were positioned around the road surface (as shown in Figure 3.5) to capture
qualitative information from the impact and completed the photo-documentation of
the tests. The vehicles were assessed using SAE J224 [28] recommended practice,
allowing the Collision Deformation Classification (CDC) to be determined. A police
radar handset was used to measure the impact speed of the vehicle. This equipment
was placed at the end of the rail to allow a direct reading of vehicle speed along the
rail.

3.4 Test Results

The major findings of the barrier crash testing were that the vehicle was redirected
for all impact conditions investigated and that barrier separation could occur without
allowing the vehicle to penetrate. The test results are summarized in Table 3.3. The
general response of the vehicle was found to be similar to that described by previous
researchers, as described in Chapter 1. For low severity impacts, the body roll and
suspension motions allowed the vehicle to be redirected without involving the side
metal structures of the vehicle. However, as the impact conditions became more
severe, the vehicle damage increased. The majority of the damage was restricted to
the front corner of the vehicle contacting the barrier. Interestingly, barrier contact
marks were not observed on the vehicle between the firewall and the rear tire area.
The rear tire and bumper would contact the barrier as a second impact after the
initial impact had rotated the vehicle towards the road. This second impact is an
important component of the vehicle redirection process and is discussed in more detail
below. Data sheets and photographs of vehicle damage from one of these tests are
Table 3.3 Results of B.C. Barrier Crash Testing

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions (Size)/km/hr)(deg) (S-900kg/M-1200kg)</th>
<th>Barrier</th>
<th>Exit Angle [deg]</th>
<th>Joint Separation</th>
<th>Vehicle Climb [m]</th>
<th>Barrier Deflection [m]</th>
<th>Comments</th>
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<td>No</td>
<td>0.3</td>
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</tr>
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<td>0.33</td>
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<tr>
<td>5</td>
<td>(M/80/15)</td>
<td>CMB</td>
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<tr>
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<td>0.31</td>
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<tr>
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<td>CRB</td>
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<tr>
<td>12</td>
<td>(S/93/25)</td>
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<td>11.5</td>
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<td>11.5</td>
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<td>14</td>
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<td>12.5</td>
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<td>0.58</td>
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<td>16</td>
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<tr>
<td>16a</td>
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<td>No</td>
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<tr>
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<td>CRB</td>
<td>15</td>
<td>Yes (1)</td>
<td>&gt;0.69</td>
<td>0.61</td>
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<td>CRB</td>
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<td>No</td>
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<td>25</td>
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<td>CRB</td>
<td>7</td>
<td>No</td>
<td>0.50</td>
<td>0.53</td>
<td>Vehicle Smoothly Redirected</td>
</tr>
</tbody>
</table>
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provided in Appendix B.

3.4.1 Vehicle Redirection

Figure 3.7 shows typical vehicle and barrier impact response as observed in the crash testing component of this project. The series of video images was recorded from the overhead (camera 1, Figure (3.5)) and barrier level (camera 3) cameras. For most impact angles, the geometry of the barrier permits the right front tire and bumper to contact the barrier nearly simultaneously. Except for light impact severities, a preliminary phase of vehicle crush with little change in vehicle momentum occurs (t < 25 ms). As the contact forces rise, the vehicle begins to rotate until it is parallel to the barrier. The rear section of the vehicle then swings into the barrier and this second impact is evident in the vehicle acceleration results (t < 250 ms) presented later. The barrier has begun to move by this time and the redirection of the vehicle will depend on the position of the barrier during the second impact and the magnitude of this impact. The barrier orientation provides a ramp along which the vehicle is directed.

The second impact may be influenced by the height of vehicle climb. If the bumper is above the barrier, only the tire forces provide a contact force, but if the bumper can contact the barrier, a larger force may be produced. This second impact is important as it serves to arrest the vehicle yaw and set up the exit conditions for the vehicle. If the impact is too light, the vehicle continues to rotate after exiting the barrier and may produce undesirable motions downstream of the impact.

The vehicle motions which characterize a barrier impact are shown in three figures. Figure 3.8 shows the vehicle rotations and Figure 3.9 is a plot of the trajectory of the center of mass. The triaxial accelerations experienced by the vehicle are displayed in Figure 3.10. All of these plots are of the same test and are representative of the general vehicle response observed in the test program.

From Figure 3.8 we see that the largest vehicle rotations are those about the yaw axis. The exit angle requirement for yaw (the only rotation parameter specified in NCHRP 230) is that the vehicle must exit the barrier at an angle less than 60% of the impact angle. Thus, for the 20 degree impact displayed, the vehicle can rotate through a
Figure 3.7: Vehicle Motion During Impact
Overhead View of Impact

a) View Parallel to Barrier
maximum of 32 degrees and still meet the performance requirements. In Test 23, the yaw does not continue to increase after the vehicle has left the barrier and is an example of a stable exit condition. The yaw rate of the vehicle leaving the barrier may not be sufficiently reduced if the second impact of the vehicle's rear components against the barrier is not large enough. In this case, the vehicle may continue to rotate into traffic after leaving the barrier. An example of continued rotation is shown in Figure 3.11. Tests conducted with the roadside barrier exhibited this behaviour more frequently than tests with the CMB. The rear bumper was observed to exceed the height of the CRB during some collisions. This reduced the amount of the vehicle's second contact with the barrier which reduced the arresting moment applied to the vehicle.

The vehicle trajectory shown in Figure 3.9 shows how the vehicle and barrier motions appear when transformed to the plane of the road. It shows the original position of the barrier, and the position of the vehicle's center of mass during the collision. It can be seen that the vehicle's center of mass moves to a position above the original edge of the barrier. The original barrier edge shown on the figure refers to half of the base width. This lateral deflection is the combination of the barrier's deflection, the vertical climb on the barrier (due to the vertical barrier taper), and any vehicle roll present at that point. The vehicle's center of gravity does not deflect beyond the
original centerline of the barrier and indicates there is no potential for the vehicle to vault or roll over the barrier in this test.

NCHRP 230 does not specify maximum rotations for the vehicle’s pitch and roll axes. However, the evaluation criteria requires the pitch and yaw motion to not be so severe as to cause vehicle rollover. Vehicle rollover is a dynamic event that cannot be predicted without all the inertial and kinematic descriptions of the vehicle. The static rollover conditions for most cars can be calculated from the position of the center of gravity and the overall dimensions. This produces static rollover angles of approximately 60 degrees and 75 degrees for roll and pitch respectively. As seen in Figure 3.8, the roll and pitch angles were sufficiently low to exclude the possibility of vehicle rollover. No rollovers were encountered in any of the tests.

The barrier motions were essentially planar in the crash tests conducted. Figure 3.12 is a photo showing the final barrier positions, the original positions are identified by the line on the road. A maximum barrier deflection of 37 cm was produced by the impact of a small vehicle travelling at 76 km/h and 20 degrees relative to the undeformed barrier. The point of impact was near the terminal section which provides a limited amount of barrier mass compared to an impact further along the barrier.
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The inertia of the barriers and the sliding resistance on the road causes a lag between initial vehicle contact and the time for the barriers to begin moving. Barrier inertia caused their continued motion after the vehicle had exited the barrier section. This inertial effect was the cause of most barrier separations. In some cases the vehicle was still in contact with adjacent sections when the joint separated and the increasing barrier motions contributed to the larger exit angles. These conditions were often associated with the continued yaw of the vehicle after leaving the barrier (Figure 3.11). An exception to this behaviour was observed in Test 9. One joint separated
while the vehicle was still in contact with the segment. The continued loading on the segment in this situation produced an over-turning moment that caused the segment to rotate along its longitudinal axis. The resulting barrier motion directed the vehicle upward and caused the abrupt redirection noted in Table 3.3. The structural integrity of the barrier was not breached since the vehicle did not penetrate the test section. However, the upper limit of vehicle impact conditions that can be accommodated by the roadside barrier would not be much higher than the impact conditions of this test situation.

Occupant safety is only evaluated in NCHRP 230 as a pass/fail rating using the flail space model of occupant dynamics. The calculation assumes the collision is planar and uses the vehicle's lateral and longitudinal accelerations. The values calculated from the available acceleration data are provided in Table 3.4 and examples of vehicle accelerations are shown in Figure 3.10. Some subjective assessments of occupant safety using minor, moderate and severe as the three levels of risk exposure are also presented. These assessments were based on the accelerations, vehicle rotations and extent of vehicle crush into the occupant compartment. The minor and moderate
ratings suggest that the impact is survivable, although injuries to the occupants are to be expected. A severe rating would be associated with a potential fatality and would be a result of excessive accelerations, vehicle rollover, or penetration of the barrier. As shown in Table 3.4, no severe ratings were assessed in this test program. These subjective assessments were designed to assist in the barrier warrant program used by the B.C. MoTH where property damage only, personal injury, or fatality are the categories used to estimate the financial cost of a collision.

The accelerations shown in Figure 3.10 highlight the important impact dynamics of the event. The reader should note that these are accelerations in the vehicle frame of reference and thus do not correspond to the inertial coordinate system. The accelerometers were placed as close as possible to the vehicle's center of mass.

The initial impact of the front wheel and right fender into the barrier is witnessed in the increasing vehicle accelerations over the first 50 ms in Figure 3.10. The accelerations drop off as the vehicle begins to rotate parallel to the barrier. This decrease in the acceleration is due to rotation of the vehicle away from the barrier. The instantaneous velocity of the contact points on the vehicle relative to the barrier may be lower or have changed direction when compared to the velocity of the vehicle center of gravity. This ebb in the accelerations continues until the rear of the vehicle contacts the barrier. The yaw rate of the vehicle is large enough to cause the rear of the vehicle to slide laterally into the barrier. The smaller vehicles could have their rear wheels lifted off the ground as the vehicle's rear swung into the barrier.

After the rear of the vehicle contacts the barrier and retards the vehicle yawing, the vehicle begins to move away from the barrier and we see the reduction in vehicle accelerations once again. As the vehicle departs the barrier, it is usually airborne. The vehicle climb on the barrier results in the vehicle pitching downward upon leaving the barrier and causes the vehicle front wheels to impact the road surface first. This is seen in the video footage displayed in Figure 3.7.
Table 3.4: Calculated Occupant Safety Risk

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Impact Speed</th>
<th>Acceleration</th>
<th>Subjective Assessment</th>
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</thead>
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<td>Long. [m/s]</td>
<td>Lateral [g]</td>
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<td>N/A</td>
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3.4.2 Specialized Barrier Tests

The special tests conducted beyond the redirective tests already discussed involved the terminal section, a curved barrier section, and joint characteristics. These tests were used to explore components of the B.C. barriers' performance that were unique to their design or implementation. The first two test types address the physical
placement on B.C. roadways while the last tests address the particular joint design for the CMB and CRB.

The terminal section tests covered both the influence of reduced upstream mass and large impact angles. Four different tests conditions were used to investigate this area:

1. small vehicle impacting at 70 km/h and 30 degrees
2. medium vehicle impacting at 60 km/h and 30 degrees
3. small vehicle (80 km/h and 20 degrees) striking one segment downstream from the bull nose - barrier transition point
4. small vehicle (80 km/h and 20 degrees) striking at the bull nose - barrier transition point

The first test produced no undesirable motion of the vehicle or barrier during redirection. However, the second test resulted in the vehicle climbing onto the top of the barrier. The vehicle undercarriage slid along the top of the barrier for about 5 m. The test vehicle fell back to the ground on the traffic side of the barrier, remaining upright during the entire collision event.

The impacts near the end of the barrier showed no serious degradation in the barrier performance. The barrier deflections were not excessively high, even when there was only one effective barrier segment upstream of the point of impact.

The test condition used to observe the influence of curvature was conducted on the barrier section laid out on a 250 m radius. The measured impact speed was 70 km/h and the impact angle was 12 degrees. The impact severity was small enough that the vehicle was easily redirected without significant damage to the body panels. The barrier curvature appeared to have little influence on the vehicle redirection and barrier deflections when compared to similar test conditions with a straight barrier section.

Crash tests were also conducted to observe the effect of a thicker steel hook used in the joints. Two different barrier sections were impacted under identical impact conditions. One was fitted with large diameter (32 mm) hooks and the other with
standard diameter (25 mm) hooks. The larger hooks exhibited less deflection than the regular hooks as illustrated in Figure 3.13. The reduced joint deflection resulted in a 10% decrease in maximum lateral barrier deflection and a 22% increase in the total occupant acceleration (see Table 3.4). Barrier hook deflections are discussed further in the following section.

**Connection Hook Strain Measurement**

Characterization of the barrier's joint characteristics was investigated by special crash tests and static testing of the joint. In all of these tests, the steel hooks of a male barrier were instrumented with strain gauges as shown in Figure 3.14. The bridge configurations were bending and torsion as noted in Figure 3.14.

Two different quasi-static tests were developed to measure the joint characteristics. One was an in-situ test of an instrumented steel hook connecting two segments. The free ends of the barrier were constrained by cables to prevent the lateral deflection of the assembly. A hydraulic jack was placed near the joint and was used to create a relative rotation of the segment. A load cell and displacement transducer were used to
record the load deflection history while the strain gauges measured hook deformation. The test arrangement is displayed in Figure 3.15.

The second static test method used to measure the barrier's joint parameters was the tensile testing of steel hook specimens. The hooks were instrumented in the same fashion as the crash testing and in-situ tests. A load fixture (Figure 3.16), for a Tinuis-Olsen tension machine, was designed to duplicate the mating eye position on the hook and create the bending load on the hook. The applied load, hook displacement, and the strain gauge output were recorded during the test. Both the 25 and 32 mm diameter hooks were tested to measure the differences in their deflection characteristics.

The hook strain data from the bending gauges collected during a crash test is displayed in Figure 3.17. Torsion and bending gauge output in Figure 3.18 shows the relative influence of the longitudinal and lateral loads placed on the joint. The torsion data has been corrected to provide the same load-gauge output constant as the bending gauge and provide a relative comparison between the two.

It is evident that the majority of the load is developed longitudinally and causes the hook to bend away from the end of the barrier. As the relative angle between
Figure 3.15: In-Situ Barrier Test Arrangement

Figure 3.16: Tension Testing of Steel Hooks
the segments increase, there is a larger lateral component acting on the hook which appears as a torque on this particular instrumentation arrangement. The torsion gauge output indicated that the lateral loads can reverse during the impact. Thus, some barriers rotate in both directions during the impact. Unfortunately, the torsion gauges consistently stopped recording early in the collision. This was attributed to localized yielding of some of the bridge elements. If one superimposes the torsion and lateral bending stresses for the hook, yield stresses in the vicinity of some torsion bridge elements are obtained for a value about one half of the yield stress for pure lateral bending. The torsion gauges were not capable of recording plastic strains, as was the case for the bending gauges. This lower yield load for torsion indicates the limited lateral strength provided by the hook compared to tension.

The in-situ static test results were not a true replication of the barrier motions. The constraints and loading arrangement caused the barrier to rotate off the ground, deviating from planar motion.

The tension tests indicate that the 25 mm hooks exhibit a 25 kN yield point for the load application illustrated in Figure 3.16. There is some work hardening that occurs as the plastic deformation progresses. The 32 mm hooks yielded at about 20-28 kN and exhibited more work hardening. Figure 3.19 shows the test results for both hook sizes tested. The theoretical load for the onset of yield for these two hook sizes in the
configuration tested are given by the curved beam stress equation:

\[ \sigma = \frac{M}{AR} \left[ 1 + \frac{y}{Z(R+y)} \right] \]  

(3.1)

where: \( M \)=applied moment, \( A \)=cross section area, \( R \)=radius of curvature of original beam curvature, \( y \)=distance from cross section centroid to stress fibre of interest, \( Z \)=cross section property defined by \(-1/A \int \frac{y}{R+y} dA\) and the normal stress definition \( \sigma = F/A \).

The combined expression for the yield load \( F_y \) for the barriers is:

\[ F_y = \frac{\sigma_y}{\frac{R}{AR} \left[ 1 + \frac{y}{Z(R+y)} \right] + \frac{1}{A}} \]  

(3.2)

Accounting for the placement of the bending gauges (30 degrees from the vertical axis), the first yield occurs at a load of 10.5 kN for the 25 mm hook and 21.3 kN for the 32 mm hook. The differences between the calculated and measured yield loads can be attributed to the work hardening as the steel was bent into shape. The larger hook was heated for bending and did not exhibit the degree of work hardening as the 25 mm hook.

Calculations to compare the strength of these joints prior to the testing were based on the fully plastic moment of the hook. For a circular cross section, the fully plastic
moment is given by:

\[ M_{pl} = A \sigma z \]  

(3.3)

where: \( A \) = cross section area of hook, \( \sigma \) = uniaxial yield stress of material, \( z \) = centroid position of half the cross section, relative to centroid of the whole cross section = \( 4r/3\pi \)

The fully plastic moment of the 25 mm hook, calculated for the 260 Mpa steel specified by the MoTH, is 677 Nm and 1420 Nm for the 32 mm hook. This suggests that the 32 mm hook should be twice as strong as the standard hook. The crash tests with these two tests showed how the stronger hook reduced the lateral deflections. This reduction was a result of the stronger hooks ability to resist relative segment rotation. As measured from the final position of the barrier, the stronger hook reduced the maximum joint angle from approximately 10 degrees to 6 degrees, a reduction of 40%.

From the laboratory testing, a calibration of the bending bridge was produced to convert the field data to engineering units. The limited data provided from the torsion gauges were not quantitatively analyzed.
3.4.3 Impact Severity Energy

Data from the crash tests were tabulated with the impact conditions to observe performance features of the barrier. The standard measure used to quantify these off road excursions is the Impact Severity (IS) [8]. This is calculated as:

$$IS = \frac{m(V\sin(\theta))^2}{2}$$  \hspace{2cm} (3.4)

where: $m$ is the vehicle mass, $V$ is the vehicle speed and $\theta$ is the impact angle.

This quantity is the kinetic energy associated with the vehicle velocity normal to the barrier. It was normalized for the graphs by dividing the IS by the lineal density of the barrier (kg/m) and has been labeled the Specific Impact Severity (SIS). This was found to provide a means to combine the data from both the CRB and the CMB together.

The parameters that showed the best correlation with the impact severity were the dissipated friction energy and the vehicle exit angle. The energy dissipated through barrier deflection can be calculated from the area the barrier segments sweep from original placement to final rest position. This area, as seen in Figure 3.20, is the cross product of the vectors connecting the segment ends before and after movement.

$$A = \frac{|\vec{v}_1 \times \vec{u}_1|}{2} + \frac{|\vec{v}_2 \times \vec{u}_2|}{2}$$  \hspace{2cm} (3.5)

where: $\vec{u}_1$ and $\vec{u}_2$ are the vectors connecting the segment end points and $\vec{u}_1$ and $\vec{u}_2$ are vectors connecting the change in the position of end 1 and 2, respectively; $A$ is the area swept out by the barrier.

Figure 3.21 shows the results of the vehicle exit angle when plotted against the SIS and Figure 3.22 presents the deflected barrier energy versus SIS. Attempts to plot maximum vehicle climb on the barrier proved to be ineffective at establishing a good relation with SIS. These results indicate that the planar behaviour of the vehicle and barrier response might be reasonably replicated in a 2D model. A similar analysis of the vertical vehicle climb and SIS did not produce a good correlation coefficient. This underlines the complex interaction of the vehicle with the barrier. The manner in which the front wheel climbs the barrier depends on the tire deflections and front
suspension strength. The loading placed on the wheel can cause component failures in the suspension and deflect the tire off the rim. Unfortunately, these processes are too sensitive to impact and vehicle parameters to be analyzed in a linear manner.

The good correlation indicated in some of these figures provide a means to estimate the impact conditions of a vehicle-barrier collision from post impact evidence. This is important information for evaluating the service conditions of the barrier. Crash testing, such as that suggested by NCHRP 230, only provides an estimate of barrier performance in the field. However, it is the field service that is important for the highway jurisdiction. It has been difficult to estimate the impact conditions for a given collision with the physical data available. The information obtained from this testing can provide some estimate of the Impact Severity with very simple to gather information. For example, the swept area of the barrier can be estimated from an appropriate photograph of barrier positions and then the IS can be calculated with Figure 3.22. Vehicle damage measurements and pavement scuffs provide estimates of the impact and exit angle, respectively. This complements the data available from the swept area and allows for better estimates of the impact conditions. Crush measurements of the direct vehicle damage were found to provide a estimate of the impact angle. Figure 3.23 shows the relationship between the impact angle and the impact angle apparent from crush measurements taken from the last test series. These measurements are limited to the forward portion of the crush profile. Rotation of the vehicle while in contact with the barrier produces a damage pattern indicative of a shallower impact angle as one considers crush towards the rear of the vehicle. An upper bound on the impact angle can be determined from the theoretical limit in equation 2.1:

$$
\psi = \cos^{-1} \left[ \frac{1 - gy(\mu + \phi)}{V^2} \right]
$$

where: $\psi = \text{impact angle}$, $y = \text{lateral distance to the barrier [m]}$, $V = \text{vehicle speed [m/s]}$, $g = \text{gravitational acceleration (9.81m/s}^2\text{)}$, $\mu = \text{road surface friction}$, and $\phi = \text{road camber or superelevation}$.

A threshold for joint separation was identified from the energy applied to the barrier. For the CRB, joint separation was first observed for an impact severity of 35 kJ. The vehicle was smoothly redirected with joint separations present until the IS approached
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Figure 3.20: Swept Area of Barrier Deflection

Figure 3.21: Influence of Impact Conditions on Exit Angle
45 kJ. The conditions of Test 9 (45 kJ) produced a joint separation which was followed by the segment toppling. The vehicle was in contact with the barrier segment which experienced the joint failure. The vehicle loads on the unconstrained segment caused the barrier to rotate rapidly and increased the relative approach angle of the vehicle. This produced an abrupt redirection of the vehicle and the overturning of the segment.
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The first joint separation observed for the CMB occurred at an IS of 65 kJ. Unfortunately, there were no impact conditions tested which were more severe than this and an upper limit for successful vehicle redirection is not known for the CMB at this time.

3.5 Discussion

The crash testing of concrete highway barriers by U.B.C. has provided a significant amount of impact performance data. Twenty six tests were conducted with the 690 mm CRB and 810 mm CMB used in B.C. Vehicles of 900 and 1200 kg (gross weight) were impacted into the barriers at speeds ranging from 60 to 94 km/h and angles of 12-30 degrees.

Vehicles were redirected in all of the test conditions studied. It was found that the barriers could separate at their connections and still provide adequate redirection to the vehicle. There were two conditions for the CRB where the redirection was marginally safe. One occurred at an impact severity where the joints were separating too early in the collision event. The second occurred at a test impact angle more severe than required in NCHRP 230 and is a highly unlikely condition to be encountered in service.

The redirection process is characterized by two significant impulses between the vehicle and barrier. The first occurs when the vehicle first contacts the barrier. The front wheel and fender are pushed towards the road and vehicle rotation away from the barrier commences. As the vehicle rotates, the rear quarter of the vehicle strikes the barrier and produces the second significant impulse. This latter impulse attempts to arrest the vehicle rotation away from the barrier and depends on the position of the vehicle and barrier. In severe impacts, the barrier segment that experiences the second impact may have rotated a significant amount. This will prolong the interval between the two impacts and cause an increase in the exit angle of the vehicle. In addition, the vehicle climb on the barrier may cause the rear bumper to exceed the height of the barrier. This event was noticed for the CRB and resulted in a smaller impulse to retard vehicle yaw. The consequences of this event was continued vehicle yaw away from the barrier after the collision.
The hooks connecting the segments deflect when the segments rotate relative to each other. Identical tests with different hook dimensions showed that a thicker hook provided a stronger connection. The lateral barrier deflection was reduced as a result of the thicker hook, while the vehicle exhibited higher accelerations. The thicker hook should increase the impact severity (IS) thresholds for joint separation which are currently 35 kJ and 65 kJ for the CRB and CMB, respectively.

A curved barrier test section produced no significant change in the vehicle response. The 250 m radius tested represents the minimum horizontal alignment design curve for B.C. highways. The minimum radius possible with the B.C. concrete barriers is 50 m.

An energy analysis of the collision showed a useful relationship between the Specific Impact Severity (SIS) and two parameters that may be determined after a collision. One is the area the barriers sweep through and indicates the energy dissipated by the barrier motion. This can be measured directly at the site or estimated from photographic evidence. The second is the vehicle exit angle which may be more difficult to identify but is sometimes available from marks in the pavement caused by the vehicle contacting the roadway. Estimates of the impact angle may also be possible from the direct vehicle damage profile. This can be used to separate the impact severity into its speed and angle components (given the mass of the vehicle).

The results of this energy analysis has been implemented into an updated version of RHSM by deLeur [26]. This work has been part of the barrier warrant investigation being conducted by the B.C. MoTH Highway Safety Branch.
The analytical procedures developed herein were developed as a means to study vehicle contacts with deflecting concrete barriers. A computer program that incorporates these procedures can then be used to predict the outcome of a vehicle-barrier collision. This information can be utilized by highway engineers when designing highway safety features.

There are many collision parameters that can be identified as design variables for the highway engineer. These variables are associated with either the physical barrier design or the vehicle impact conditions. The segments can be physically described by their dimensions, inertial properties, and joint flexibility. Characteristics of the friction forces that develop on the road-barrier interface must also be included in the barrier descriptions. Variables describing the vehicle include the impact speed and angle, vehicle mass properties, vehicle-barrier friction characteristics, and the structural force-deflection behaviour. The last variable is the most difficult to determine because of the wide variety of vehicles in use.

It is important for a barrier performance model to provide information in a form that has utility to a highway agency. Assessing the results against the performance criteria listed in NCHRP 230 is appropriate for this application. Barrier deflections, vehicle accelerations (to assess the occupant risk), and the vehicle redirection properties are essential to evaluate differences in barrier performance. In addition, the separation of joints within the barrier section is important in evaluating the potential for vehicle penetration.
Other considerations for designing a barrier performance model are the constraints placed on its implementation. The biggest constraint involves the input requirements. The input data should take advantage of available information and must recognize the accuracy of this information. The model should be convenient to use and not require significant computational resources.

Two modelling approaches were investigated in this study. The first was an energy balance approach which is a relatively easy method to model a complex event. A barrier deflection model previously implemented by Ivey et al [19] was modified for use with the B.C. barriers. However, it was found to depend too heavily on a-priori assumptions to be an effective tool and was abandoned. The second approach was a two dimensional dynamic simulation of the vehicle-barrier collision. This showed more promise and is discussed in the following sections.

4.1 Dynamic Model Of Vehicle-Barrier Impacts

A detailed modelling approach was developed to represent the dynamic behaviour of the linked barrier segments and the vehicle during a collision. The barrier segments were modelled to account for frictional loads at the road surface, constraint forces from neighbouring segments, and vehicle contact loads. The vehicle is dynamically modelled as a point mass which experiences external forces from its interaction with the barrier. Details of these two model elements are further developed in the following sections.

Modelling of the B.C. barriers differ from most multibody simulations. The main differences arise from the joint characteristics of the barriers and the nature of the applied loads. Most mechanical linkages or systems (ie. vehicle suspensions, robot manipulators, etc) contain joint assemblies that move in a reasonably defined manner. These systems are designed to move easily so that predefined endpoint motions or forces can be produced. In the case of a highway barrier, the segments are essentially connected by loose fitting pin joints. The slack in the joint is required for assembling different barrier formations and are not subjected to regular motions.
There are two potential sources of loading on a barrier segment. Friction forces act on the barrier from its contact with the road. It will be shown later that these forces are functions of the segment's speed. The other applied load comes from the vehicle contact against the barrier. These loads move along the barrier and are determined from the vehicle deformation and stiffness values.

In addition to external load sources, the linked barriers experience another complex dynamic process. There is sufficient slack within each joint to allow adjacent segments to move independently until this slack has been taken up. In a simplified collision event, the vehicle will first contact one segment. This segment begins to move and eventually contacts neighbouring segments. The results of this motion are discrete dynamic events describing the contact of adjacent segments. As the segments contact and move with adjacent segments, the barrier system's dynamic properties change with the geometry and number of moving segments.

The dynamic characteristics of a vehicle-barrier impact involving the B.C. barrier systems are substantially different than most mechanical systems. These differences were considered to be great enough to exclude existing simulation software from modelling the event. The goal of the modelling program was to produce a design/evaluation tool for the B.C. deflecting barriers. This was decided to be better described in an original software program instead of updating existing barrier models or using a general simulation environment. The formulation to be presented contains several discrete processes and it was decided to implement these with a slightly modified numerical integration routine. The development of new simulation code allows the input and output of the program to be presented in a form appropriate for a specific user. One other advantage of writing a software program over packaged simulation environments is the latter's associated expense/license for the environment software needed to use the simulation.

4.2 Development of the Barrier Model

The motion of the barrier system was developed using the methods described by Wittenburg [36]. He applied bond graph theory to describe the interconnectivity and multibody dynamics of any arbitrary system. A description of this formulation for
the barrier system herein is presented in Appendix C. The major components of the barrier model definition consist of the general equations of motion, joint deflection characteristics, and the friction characteristics of the barrier motion.

The barrier can be considered to be made up of rigid body elements connected together with flexible joints. The assumptions made in the barrier modelling are:

1. The barriers slide on the road surface and no barrier tipping effects are included. The coefficient of friction for the road-barrier interface is independent of speed except for a step change between static and dynamic contact cases. The friction force formulation can accommodate a speed dependent coefficient of friction at the expense of increased computations.

2. Tolerances in the barrier joints (between the hook and eye) provide a small amount of slack. There are three degrees of freedom in these slack joints which then reduce to one degree of freedom upon contact with the adjacent barrier. This approach will be shown to reduce the system degrees of freedom to a minimum while reasonably capturing the kinematics under review.

3. The interaction between the barrier and vehicle is two dimensional, in effect, a vertical wall is simulated. Vertical motions or rotations out of the plane of the road are considered less significant than the in-plane motions. This motion will provide almost all the necessary performance data for the barrier.

The applicability of these assumptions will be discussed further in the following model description.

4.2.1 Barrier Dynamics

The bond graph approach of Wittenburg [36] provides a compact form of describing the interconnection of barrier segments. Using a vector mechanics approach, the dynamics of the barrier are described by the method highlighted in Figure 4.1. As shown in Figure 4.2, the effective forces on the barrier are external forces and moments due to roadbed friction and vehicle contact forces $\vec{F}$ and $M$, hinge forces $\vec{F}^c$ and moments $M^c$, and inertial reactions of the segments.
Interconnectivity matrices $S$ and $T$ describe the relationships between the segments. Matrix $S$ describes which segments are in contact, while $T$ describes which segments are downstream or inboard of a particular component. The form of these matrices for a section of highway barrier is illustrated in Figure 4.1. A series of body fixed vectors are used to identify the location of a segment reference point. The vector may be either $\vec{d}$ or $\vec{b}$ (Figure 4.3) depending on the system type. The $\vec{d}$ vector is only used when the barrier system is anchored to inertial space. It locates the segment hinge points relative to the segment center of mass. The vector, $\vec{b}$ is required when the barrier system has a moving reference frame and is also used in the fixed system case frame. It connects the segment's augmented center of mass to the hinge points.
The augmented mass of a segment is a concept used extensively in the development of the equations of motion (Appendix C). It incorporates all the system masses into the segment's mass. For example, consider the three segments in Figure 4.4 a). The augmented mass of the first segment is locating using its own mass properties and a lumped mass equal to the other two segments. The masses are lumped at the hinge through which these segments communicate with the segment of interest as shown in Figure 4.4 b). Through this process, the augmented mass centers shown in Figure 4.4 c) for the three segments are obtained. Each augmented segment has the equivalent mass of the entire system. This is a mathematical consequence of the equations of motion when using the bond graph notation described. It is not used in the original physical interpretation of the barrier. The reader is referred to Appendix C or Wittenburg [36] for a description of mathematics that lead to this concept.

The highway barriers herein were assumed to be continuous, unbranched chains. The incorporation of branched barriers is not excluded by this approach, however this is an uncommon occurrence in road construction and is not considered in the current model development.

If a single segment of the barrier is cut at its joints (Figure 4.2), the resulting tractions can be represented as an applied external force and moment acting at the segment
center of mass, constraint forces acting at the joints, and inertial forces.

\[ m_i \ddot{x}_i = F_i + F^c_i \]  
\[ J_i \ddot{\theta}_i = M_i + F^c_i \times \vec{p}_i + M^c_i \]

where: \( \vec{x}_i \) is the position of the center of mass for segment \( i \), \( \ddot{\theta}_i \) is the angular acceleration of segment \( i \), \( \vec{p}_i \) is the vector from the center of mass to the joint where constraint force \( F^c_i \) acts, \( J_i \) and \( m_i \) are the moment of inertia and the mass of segment \( i \).

The constraint forces are eliminated by explicitly solving for them in the force equation, (4.1) and then substituting into equation 4.2. By suitably setting up the definitions for each component of the equation (as described in Appendix C), the final form of the equation is:

\[ [K]\{\ddot{\theta}\} + \{B\}^T\{\dot{\theta}^2\} = \{R\} \]

where \([K]\) and \(\{B\}\) represent inertial properties of the system and \(\{R\}\) describes the external loads.
There are three different kinematic conditions that describe a free standing barrier. The first is the case where all of the elements are in motion. Without a reference to the inertial frame of reference (IFR), the system center of mass, $\vec{r}$, must be determined from:

$$\vec{r} = \frac{\sum_{i=0}^{n} \vec{r}_i}{\sum_{i=0}^{n} m_i}$$  \hspace{1cm} (4.4)

By simultaneously integrating equations (4.3) and (4.4), the complete dynamics of the barrier can be described.

The second kinematic case is where one element of the barrier is connected to the IFR. In this case, equation 4.3 incorporates all the required kinematic information. The contents of $[K]$, $\{B\}$, and $\{R\}$ are different than those used to describe the previous condition because the kinematics explicitly contain the segment position to the IFR.

The situation posed by fixing both ends of the barrier while the center portion moves is more involved. An extra set of equations is required to address the indeterminacy of the system. An effective example of these equations for numerical simulations, suggested by Wittenburg [36], was developed by Baumgarte [37].

The barrier system being investigated has the potential to change between these three systems under special conditions. These transitions occur during impulsive situations. For example, a barrier system not fixed to the IFR strikes a stationary segment. The struck segment may begin moving or remain stationary after the impact. The barrier system changes from the Moving Frame of Reference (MFR) system to an IFR system only if the struck segment does not translate. The inverse can occur if the fixed element(s) in the system break their connection(s) to the inertial frame. These connections may be mechanical or frictional links between the segment and the road. The barrier model described herein exploits these impulsive situations to reduce the complexity of the mathematical description.

### 4.2.2 Joint Connections

The B.C. barriers are essentially connected together by a steel hook-and-eye system. The concrete tongue-and-groove component provides some shear resistance between the segments, but it is essentially a construction aid. Figure 1.2 shows the details of...
the joint. Tolerances within the joints provide up to a 15 mm gap longitudinally, and about 5 mm laterally.

The structure of the B.C. barrier joint poses some difficulties since the number of degrees of freedom within the joint change as it comes in or out of contact with the adjacent section. If we consider two barriers as in Figure 4.5a, the barriers can move with three degrees of freedom (for the planar case). When the barriers are in contact, we can consider the case where the hook rotates on the eye and the hook can deflect in two directions. These three degrees of freedom can be reduced to two if we limit the hook's deformation to one direction. However, we can simplify the joint to one degree of freedom if the joints can be approximated with only pure rotations while in contact.

The joint model developed for the B.C. barrier has some parallels with the model of Walker and Ross [20]. Their model assumed that the joints were pin joints with a defined moment-deflection behaviour. The structure of these joints produce a moment-deflection behaviour which was separated into five response regimes. The moment-deflection curve employed in [20] is exhibited in Figure 4.6. There is an initial period of unrestricted joint rotation due to slack in the joint. This is followed by an elastic response period where complete unloading of the joint can occur. After a yield moment threshold is reached, the joint deflections are resisted by a fairly constant moment. At a point where the barrier edges bind up, a dramatic rise in the resisting moment is predicted. This sharp increase in resisting moment continues for a short period until a limiting moment value is reached which indicates joint failure and no more resisting torque.

The model developed herein is similar to that described above with a few differences. The most significant difference is the manner in which the transition between joint actions is represented. In the developed model, some transitions are considered as a discontinuity which is not the case for Walker and Ross [20]. In both models, each joint is considered independent and the only criteria used for determining the joint torques is the relative position of the two adjacent barriers for the joint. The joint moment-deflection curve for the model herein is displayed in Figure 4.7 for comparison to Figure 4.6. Detailed descriptions for each joint phase is presented below with the relevant mathematical treatment.
Chapter 4. Mathematical Simulation of Vehicle-Barrier Impacts

Figure 4.5: Representation of Concrete Barrier Joints
Chapter 4. Mathematical Simulation of Vehicle-Barrier Impacts

Figure 4.6: Joint Moment Behaviour Used by Walker and Ross [20]

Figure 4.7: Joint Moment - Joint Deflection Characteristics of Proposed Model
**Phase 1: Barrier Recruitment** The process of barrier recruitment will depend on the amount of joint slack and the relative speed of segments. Barrier recruitment starts when all slack in a joint is eliminated because one segment has moved relative to a stationary segment. The resulting contact between the barriers is treated as the impulse shown in Figure 4.8. Assuming no rigid connection to the road, the struck barrier will start moving only if the impact overcomes the resisting friction forces between the road and barrier. If the impulse is insufficient to initiate translation, the segment remains fixed and acts as a rigid link between the moving barrier system and the road.

When the barrier recruitment impact is detected (Fig 4.5b, Fig 4.8), the velocity of the striking (moving) segment’s point of impact is calculated. The speed at the point of impact (in the IFR) is given by:

\[ \vec{v}_{\text{impact}} = \vec{v}_i + \dot{\theta}_i \times \vec{p}_i \]  

where: \( \vec{v}_i \) is the speed of segment \( i \)'s center of mass, \( \dot{\theta}_i \) is the angular velocity of segment \( i \), and \( \vec{p}_i \) is the vector from center of mass to contact point on segment \( i \).

In the reference frame attached to the struck segment,

\[ \{v\}_j = \{v\}_i[A]_{ij} \]  

where \([A]_{ij}\) is the relationship between the inertial \( i \) and local \( j \) reference frame.

The magnitude of the relative velocity between the impact points determines the impulse magnitude while its direction is defined by the mutual normal direction of the surfaces of contact. Since the hook and eye geometry is described by two circular elements, the normal vector at their point of intersection is defined by the center of each element (Figure 4.8).

\[ \phi = \arctan \left\{ \frac{(\rho_j - \rho_i)_y}{(\rho_j - \rho_i)_x} \right\} \]  

where \( \phi \) is the impulse direction and \( \rho \) is the vector from the segments' \( i \) and \( j \) centers of mass to the hinge elements.
Once the impulsive forces acting on the moving barrier section are determined, the change in velocities of the barrier segments can be determined from the integrated equation(s) of motion over the time of impact. The equation:

\[ \int [A] \{\dot{\theta}\} \Delta t + \int \{B\}^T \{\dot{\theta}^2\} \Delta t = \int \{R\} \Delta t \]  (4.8)

produces:

\[ [A] \delta \dot{\theta} = \dot{R} \]  (4.9)

where:

\[ \dot{R}_i = \sum_j \vec{b}_{ij} \dot{\vec{F}}_j + \dot{\vec{M}} \]  (4.10)

where: \( \vec{b}_{ij} \) is the vector from the barycenter (augmented mass center of gravity) of body \( j \) to body \( i \).

By definition, the position of particles during the impulse do not change. Thus, the velocities \( \{\dot{\theta}^2\} \) will become displacements when integrated and disappear for the impulsive period. The \( A \) matrix components, which are functions of segment positions, can be considered constant during the impulse. Applied loads (from dynamic friction and vehicle contact forces) are finite and will disappear when integrated over an infinitesimal period. Equation 4.10, which is for the case of a barrier with a MFR, only includes impulses from barrier impact loads. The \( \{\dot{R}\} \) expression for a barrier defined by an IFR is similarly obtained.
Equation 4.8 will completely define the status of a barrier system defined in the IFR. If the barrier has a MFR, then the change in velocity of the system center of mass must also be calculated from:

\[ \Delta \vec{r} = \frac{\vec{F}}{M} \]  

(4.11)

where: \( M \) is the total moving barrier mass, \( \vec{F} \) is the total external impulse to the moving system.

The process of adjacent segments coming into contact can be exploited as a method to reduce the computer effort of the simulation. Until a segment becomes part of the moving section of the barrier, it is not involved in the calculations. This holds until it is contacted by a moving segment or the vehicle and is loaded beyond its friction constraint forces (as discussed previously). There are two ends of the moving barrier section that are available for recruiting segments and they are both monitored for contact with a neighbouring segment.

**Phase 2: Rotation of Hook-and-Eye** The next stage of barrier motion is depicted in Figure 4.5b. The joint does not resist any rotation during this phase of motion. It is apparent from the figure that any resistance to rotation due to joint effects must create a moment about the rotation axis. The only resistance that can arise from the joint are friction forces from the hook-and-eye or tongue-and-groove contact. The in-situ tests of joint deflection indicated that any friction within the joint is small compared with the friction between the segment and road and can thus be ignored.

In this model, constraint forces within the joint are assumed to be small enough to preclude hook deflection. Hook strain data collected in Test 24 (Figure 3.17) show sudden jumps in hook loads. Comparison of these loads with the barrier motion on the video tape suggests that the low strain values are the constraint loads and the sudden jumps are due to impulses within the barrier section or binding of the instrumented joint. This data supports the assumption that the joint should be modelled as a rigid pin joint. The joint behaviour is allowed to continue in this manner until the corners of the joints bind as depicted in Figure 4.5 c). At this point, the joint begins resisting rotation since the hook must deflect to allow further joint rotation and is considered in Phase 3.

**Phase 3: Binding of Joints** As seen by the geometry of Figure 4.5c), either the hook must deform or the concrete corners must crush to allow the joint angle
to increase. It is recognized that both of these processes take place simultaneously during the actual barrier deflections. However, the process is simplified for modelling purposes.

The joint binding behaviour of the B.C. barrier is divided into an elastic (Phase 3) and plastic (Phase 4) hook response. Since the elastic deflections of the hook are reasonably small, the kinematics of the barrier are assumed to be defined with the same body fixed vectors described in previous sections. This simulates the hook as a rigid-plastic material which is not unreasonable given hook deflection characteristics of Section 3.4.2. The use of this rigid hook behaviour allows the modelling of the joint with one degree of freedom (rotation). Expanding the model to include hook deflection as well as joint rotation requires additional variables and increases the complexity of the entire barrier model.

The rigid description of the hook maintains the pin joint geometry developed in Phase 2. Given this assumption, the concrete corners of the segments must crush to provide any additional rotation. This deformation creates a resisting moment to joint rotation and loads on the hook. The deformation is allowed to progress until the hook loads are sufficient to yield the hook. At this point the plastic hook response governs the joint response. This behaviour is described in Phase 4.

The model of the initial joint binding process is rationalized by the contact geometry. The contact will initially occur on a small area at the edge of the barriers (Figure 4.9). The contact force will start from zero and rapidly increase as the crushed area increases. Crush of the segment corners was observed in the crash tests and minor concrete cracking was noted for joints with small joint angles. This joint behaviour is allowed to continue until the hook experiences a joint load sufficient to produce yielding.

**Phase 4: Joint Axis Movement** Two processes are simulated during the joint's Phase 4 actions. There is a transition from the rigid behaviour of the steel hook to a plastic deformation and movement of the joint's axis of rotation. Both of these events occur during an impulse that locks the segments' corners together. The axis of rotation moves from the hook and eye position to the corners in contact as shown in Figure 4.10. This provides a reasonable approximation of the joint deflection process
for large angles. The hook deforms as the joint rotates further and the resisting forces are determined by the plastic response of the steel hook.

The impulse allows the body fixed vectors of Phase 3 to be changed in one discrete step in Phase 4. It would require considerable modification of the barrier kinematics to describe the hinge locations with continuously variable body fixed vectors. The new location of the hinge allows the deflection of the hook to be modelled with only one joint degree of freedom and reduces the complexity of the simulation.

It is not unreasonable to assume that there is movement of the axis of rotation. It was observed that all the barriers with significant deflections relative to their neighbours exhibited binding contact as described above. It is suspected that this process is not an impulse as implied herein, but a gradual shift from hinge A to B (in Figure 4.10) as the joint elements deflect. This process would be difficult to simulate since the joint position would be a function of time and joint orientation with respect to the barrier reference frame. In all the equations developed, the body fixed vectors (of each segment) describing the system are constant. The use of impulses allow the body fixed vectors to vary in discrete steps and allows the system changes to be easily tolerated numerically.

Modelling the joints through pure rotations limits the treatment of the tensile constraint forces. The motions described in Phases 2 and 3 exclude the axial deformation of the barrier without binding joint motions. This will produce a stiffer barrier response in the model if the hooks actually deflect during the first two phases. The assumption that the hook deflects only when the segments bind is supported by observations that all significant hook deflections occurred in joints where the segment corners were in contact.
The current treatment of the joint forces also excludes the constraint forces from the hook deformations. Since the hook deformation is modelled only by the rotation of the joint, the constraint forces are excluded from the deformation characteristics of the hook. This will introduce a stronger joint deformation because the constraint forces can combine with the joint rotation loads to increase the hook deflection. This effect could not be included without losing the explicit joint moment/deflection response built into the model. The inclusion of constraint forces would require additional degrees of freedom and computer resources to determine the associated barrier deflections.

The manner in which this impulse is modelled is displayed in Figure 4.10. The binding elements are represented as two separate systems of arbitrary size. The impulse is calculated from the system sizes and the relative velocity of the points of binding and is treated as a plastic impact. As long as all segments are moving, there are no other impulsive loads due to static friction. The connection forces in the hook are finite (since the hook is now considered to be deforming). These forces do not yield a contribution to the impulse when integrated over the infinitesimal impulse interval. There will be impulsive forces when the barrier system is linked to the IFR. It is important to note that Phase 3 is an important step prior to this since it slows the relative motion of the segment contact points. Without this condition, the impulse during the joint lock was found to be too violent and created unrealistic barrier velocities.

Referring to Figure 4.10, the contact point velocities are found from:

\[ \vec{V}_i^c = \vec{V}_i + \dot{\theta}_i \times \vec{r}_i \]
\[ \vec{V}_{i+1}^c = \vec{V}_{i+1} + \dot{\theta}_{i+1} \times \vec{r}_{i+1} \]
where the terms are identical to those in Phase 1 except the \( c \) indicates the vectors corresponding to the contact point instead of the hinge.

The segment center of gravity for segment \( i \) is determined from the position vector relation:
\[
\vec{r}_i = \sum_{j}^{n} \vec{b}_{ji}
\]  
(4.13)

and the velocity is then found from:
\[
\vec{V}_i = \sum_{j}^{n} (\dot{\theta}_j \times \vec{b}_{ji})
\]  
(4.14)

Substituting equation 4.14 into 4.12 produces:
\[
\vec{V}_i = \sum_{j}^{n} (\dot{\theta}_j \times \vec{b}_{ji}) + \vec{\rho}_i
\]  
(4.15)

where: \( V_i^c \) is the velocity of the contact point on body \( i = 1, 2 \).

The next requirement is to express the velocity change in terms of the coefficient of restitution.
\[
V_i^c(1 + e) + \Delta V_i^c = V_2^c(1 + e) + \Delta V_2^c
\]  
(4.16)

For a plastic impact \( e = 0 \). From equation 4.15, the change in velocity for the impact point on system 1 becomes:
\[
\Delta \vec{V}_{i,1}^c = \left[ \sum_{j}^{n} \Delta \dot{\theta}_j \times \vec{b}_{ji} + \Delta \vec{\rho}_i \right]_{1,2}
\]  
(4.17)

where all variables are unique to system 1 and similarly for system 2.

It is now required to determine the impulsive force that causes the change in velocity. From equations 4.8 and 4.11, we can determine the change in system velocities as a function of the impulse. From Figure 4.10, we show the impact as occurring between two discrete systems. There is no moment developed about the impact point B so the expression for the impulsive load reduces to:
\[
\vec{R}_i = \sum_{j}^{n} \vec{b}_{ji} \times \vec{F}_j \quad i = 1, n
\]  
(4.18)
If the system in question has no fixation to inertial space, then the only non-zero impulse is on body $n$ for system 1 and body 1 for system 2. If there is a connection for either system, the body connected to the inertial frame will experience an impulse of equal and opposite direction to maintain the system equilibrium and is expressed in $\{\hat{F}\}$. In this situation, the expression for $\hat{R}$ in equation 4.18 must be modified to account for the IFR.

The expression for the $\hat{R}_i$ in a MFR system can be expressed as the multiplication of the elements:

$$\hat{R} = \begin{bmatrix} \{\hat{F}_x\} \\
\{\hat{F}_y\} \end{bmatrix}^T \begin{bmatrix} \{b'_n\}_y, \{b'_n\}_x \end{bmatrix} \begin{bmatrix} 1 \\
1 \end{bmatrix}$$

(4.19)

where: $\hat{F}_{x,y}$ are vectors containing the $x$ and $y$ components of the external impulses to the system under consideration and $b'_{x,y}$ are vectors relating these impulses to the segment acted on by the joint impulse.

Inserting this into the formula for the change in velocity equation 4.17, relating $\Delta \dot{\theta}$ to $\hat{R}$ with equation 4.9 and using equation 4.11 to account for the motion of the system center of mass produces the simplified expression:

$$\Delta \dot{\theta}_a = \{\hat{F}\}_a^T \{K\}_a$$

(4.20)

where $a$ represents system 1 or 2 and

$$\{K\}_a = [A]^{-1} \begin{bmatrix} \{b'_n\}_y, \{b'_n\}_x \end{bmatrix}_a \begin{bmatrix} 1 \\
1 \end{bmatrix} + \begin{bmatrix} 1/M \\
1/M \end{bmatrix}_a$$

(4.21)

Substitution of the appropriate terms for the impact velocities of the two systems produces the final equation representing the impulse between the two bodies.

$$\hat{F} = \frac{\{\dot{\theta}\}^T \{\hat{b}'_n\}_2 - \{\dot{\theta}\}^T \{\hat{b}'_n\}_1 + \dot{\hat{r}}_2 - \dot{\hat{r}}_1}{[K]_1 - [K]_2}$$

(4.22)

After solving for the magnitude of the impulse, the velocity changes of the elements in the two systems can be determined from equation 4.8. If required, the center of gravity for these two systems must be accounted for by equation 4.11 if they are not fixed to the IFR. The new velocities of these systems are calculated and the kinematic description of the colliding joints are modified to reflect the new axis of rotation. The
simulation carries on from this point with the joint resistance to rotation governed by the plastic deformations of the steel hook, as input to the model.

The joint's resistance to rotation is determined by the force-deflection behaviour of the hook. During all the testing, the eyes were undeformed although extensive deflection of the hook occurred in some cases. If one considers the two corners of adjacent barriers acting as a pivot point, the endpoint displacements of the CRB hook are presented in Figure 4.11. These are local coordinates for the male segment's end face with $x$ representing the normal and $y$ the parallel directions. The resulting loads on the hook produce a complex, three dimensional stress state caused by the combined bending (in two planes), torsion, tension and shear. These interact during the hook's yielding and influence the plastic deformations of the hook. A complicated yield criteria would be undesirable to calculate continuously during the simulation as it is also a non-linear process. To avoid the extra computations, the force-deflection criteria for the hook were incorporated into a local force-deflection curve suitable for a given joint configuration.

![Hook Deflection Behaviour During Joint Rotation](image)
The joint geometry developed in this model can be used to determine the hook deflections a-priori with reasonable accuracy. From this displacement history, the hook loads can be calculated. The only requirement for these loads is that they be resolved into a reference system for each displacement point. The local reference frame is aligned to allow one load to be normal to the force-hinge vector as depicted in Figure 4.12. This creates the rotation resisting moment. The other load will be parallel to this vector and contributes nothing to the joint moment. In this manner, any experimental or analytical technique can be used to evaluate the hook behaviour and then reduced to a common form for implementation in the simulation.

It is advantageous to calculate the hook behaviour outside of the barrier model. There are several tools already available, such as the finite element method, which would be more efficient to perform these calculations. The flexibility of the input requirements in this barrier model allow the user to define hook behaviour arbitrarily or from a previous analysis, depending on the design exercise required.

As a further simplification, the tensile tests described in Section 3.4.2 were used to represent hook behaviour. The hook was assumed to deform similar to the deflection curve described in Figure 3.19. This assumption is reasonable for small rotation angles where the transverse hook loads are small compared to the axial load, a situation which was evident from the strain data collected. In these tests, it was apparent that the transverse loads were smaller than the hook extension loads.
The advantages of the previously described joint model allow the complex motion of the B.C. barrier joints to be simplified to single rotations. This allows the equations of motion to be reduced to the minimum number required to describe this system, and allows a simplified hook deformation description to be used as an input. If the joint was required to continue rotating at the eye (Figure 4.5 b), then additional degrees of freedom would be required to account for the hook deflections. If a rigid joint was used, the joints would experience excessive constraint forces. The lateral deflections of the segments would not be tolerated without significant motion of the barrier end points. The shifting of the axis of rotation described above allows the elongation of the barrier to be replicated without additional degrees of freedoms while reasonably replicating the joint motions.

**Phase 5 Joint Separations** An important result of the barrier's lateral deflection is the possibility of joint separation. It has been observed that the steel hooks will deform and, for large joint angles, the hook and eye may uncouple. The importance of this event depends on the time at which it takes place. The test results indicate that the barriers often separate after the vehicle has moved downstream of the joint in question. Tests 16 and 16a involved impact conditions that appeared to be the lower threshold for joint separation. The case where the joint failed produced minimal influence on the vehicle's exit trajectory but a large change in the maximum barrier motion. A more severe situation was demonstrated in Test 9 when the failure occurred while the vehicle was in the proximity of the failed joint. The vehicle caused the unconstrained barrier to topple and this motion caused an abrupt redirection of the vehicle.

The simplest method of modelling the segment separation criteria would be to set a maximum joint angle. Any segment exceeding this criteria would be considered to have separated from its neighbour. However, there is a more formal case that can be developed from the experimental observations. For the test of the stronger (32 mm) hooks, there was an observed lifting of a female barrier section that experienced a large joint angle. This is depicted in Figure 4.13 a). The mechanism by which the segments are lifted involves the joint forces and the hook deflections. When the hook deflects to an angle $\gamma$, (Figure 4.13b) the joint forces on the hook can be resolved into a force normal and tangential to the hook. If the tangential force exceeds the force required to lift the female barrier and the friction forces between the hook and eye,
the eye can slide up the hook. At this point, the moment resisting the joint rotation will only depend on the tangential loads on the hook and eye and can be assumed to be negligible.

The barrier separation model incorporated herein employs this segment lifting criteria. In order to fit into a planar model, no vertical barrier motions occur, but the hook loading mechanism in Figure 4.13 is evaluated. The resisting moment is removed when the loading condition predicts the barrier will ride up the hook. From the current angle of the hook, a rotation angle is calculated that will cause the eye to slide off the end of the hook and uncouple the joint.

A critical factor that must be determined when the joint separation occurs is the location of the vehicle. The simulation is halted if the vehicle is in contact with the barrier segment experiencing joint separation. This condition creates the abrupt vehicle redirection that involves significant three-dimensional motion that can not be replicated within this model. If the vehicle is downstream from the separating joint, then the simulation continues assuming that the barrier section in now only made up of the segments downstream of this decoupling.
4.2.3 Road Surface Friction

Normal and tangential forces are exerted on the barrier from the road surface. The tangential, or friction, forces are related to the normal force by the coefficient of friction \( \mu \).

For the situation where two rough planar surfaces are in contact (Figure 4.14), expressions for the friction force can be found from the energy expression [43]:

\[
P(\bar{x}, \bar{z}, \theta, \dot{\theta}) = \int_A f \sqrt{x_x^2 + x_y^2 + (x_x^2 + y^2)^2 \dot{\theta} + 2\dot{\theta}[x_x x_y - x_y x_x \cos \theta]} \frac{\cos \theta - (x_x \dot{x}_x + x_y \dot{x}_y) \sin \theta}{(x_x \dot{x}_x + x_y \dot{x}_y) \sin \theta} \ dA \quad (4.23)
\]

where: \( f \) is the friction force acting on the area element \( dA \) and is equal to the bearing pressure on the road \( (mg/A) \) multiplied by the coefficient of friction \( \mu \).

The individual friction forces are found by taking the derivative of this expression with respect to the velocity which the forces oppose. For example, in the longitudinal direction:

\[
F_{f_{x}} = \frac{d}{dx_j} P(\bar{x}, \bar{z}, \theta, \dot{\theta}) \quad (4.24)
\]

These friction equations do not have a closed form solution and must be numerically integrated to be used in the simulation. Although this presents a large computational burden, it does allow for different contact areas between the barrier segment and the road to be simulated. It is also apparent that equation 4.23 does not hold for static conditions.

The friction between the road and barrier could be calculated with a simpler model than that described previously. This could be achieved with a line representation of the barrier or defining discrete contact points on the interface. However, the components of the friction loads are determined by the relative magnitudes of the velocity components. Without an area based model to account for the velocity distribution over the interface, these friction components cannot be accurately determined. To provide convenience for the users of the program, the friction force recalculation interval can be controlled to vary the processing effort.
In the current barrier model, there is only one situation where static friction forces are required. This occurs when the vehicle first loads the barrier. The only forces on the first affected segment are due to the vehicle contact road friction. Once this segment begins moving, the other segments' motions are initiated through the recruitment process. Calculation of the static friction forces is not required unless the recruitment impulse is insufficient to start the barrier motion. Appendix E provides the static friction development.

The value of $\mu$ is usually a function of speed and typically has a large gradient as the surfaces in contact move from a static (no relative motion) to a dynamic state. Two values of $\mu$ are common to most interfaces: a dynamic value and a larger static value. For the barriers under study, these values were measured by drag tests. The friction coefficients from these tests are shown in Figure 3.4 and were taken to be $\mu_s \approx 0.85$ and $\mu_d \approx 0.75$. The dynamic value tends to a steady value and was taken to be independent of speed in the following treatment. However, the friction force formulation presented here can accommodate a speed dependent value for $\mu$.

The description of $\mu$ with single values for the static and dynamic conditions creates a discontinuity near zero. Another discontinuity is introduced by the equations describing the barrier's frictional loading conditions. This poses a problem when simulating the dynamics of the behaviour. Numerical integration routines (like Runge-Kutta) will iterate around sudden changes in an integrated variable until its precision constraints are satisfied. Initial barrier simulations with an adaptive step size Runge-Kutta algorithm were found to iterate around the static-dynamic transition points.
However, if one can analytically describe this discontinuity and avoid numerically integrating over this point, the simulation is simplified. Consider the effective force acting on the barrier from the roadbed as the external load increases. Figure 4.15 shows that a sudden increase in the effective (dynamic) force occurs when the external forces overcome the static friction force. The instantaneous change in force is equal to the difference between the external and the dynamic friction forces. Treating this as an impulsive load, one can calculate the instantaneous change of velocity for all segments affected.

![Friction Loading as an Impulse](image)

As the barriers stop moving, the friction force will suddenly increase up to the static value. This brings the segment to a stop and applies an impulsive load to the barrier system. This event may mark a change from a MFR system to an IFR system. An algorithm detecting this event can apply the impulsive load to the surrounding system and continue the simulation for the new system description.

The impulse relation presented above is an approximation of the transition from static to dynamic barrier conditions. The actual barrier motion will be a gradual increase from zero velocity as static friction is overcome. However, the coefficient of friction (as defined here) and the friction model are not defined as the velocity tends towards zero. As a result, the impulse approach provides a convenient mathematical treatment
to bridge the small time interval when the barrier starts (or stops) moving. Figure 4.16 shows the barrier's velocity changes for the actual and the assumed impulse approximation.

![Figure 4.16: Velocity Profile During Static-Dynamic Transition](image)

The vehicle is unaffected as the barriers change between static and dynamic states. The time interval over which the impulsive load acts is very small and the influence on the vehicle dynamics is similarly small.

The impulse treatment of friction is different from the approach taken by Walker and Ross [20] in their sliding barrier simulation. They only defined a single friction coefficient for the barrier-road interface. Numerically smooth transitions were created to simplify numerical integration when barrier velocities changed signs. Ivey et al [19] provided static and dynamic friction effects in their energy balance model. Energy, dissipated by barrier sliding, was calculated from simplified barrier motions and did not provide a time history of the friction forces. Both models used a line contact representation of the segment contact with the road and will be less accurate as the aspect ratio of the segment decreases.

A rigorous treatment of the transition between static and dynamic conditions would require complete documentation of the coefficient of friction as a function of speed. The numerical integral would then include this function in the friction calculation. It would increase the computational effort for the program and, if $\mu_d$ tends to a
steady value, the extra calculations may not always be required. Another reason to avoid a speed dependent description of $\mu$ is the increased documentation of different friction values required as input to the program. It is feasible for highway engineers to determine average friction values for use in the program and bracket the barrier behaviour with upper and lower friction values.

4.3 Vehicle Model Description

A representation for a vehicle that strikes the barrier was developed to interact with the barrier model described previously. This vehicle simulation must be able to accommodate the different sizes of vehicles available and react with the barrier appropriately. The model to be discussed can be programmed for different vehicle characteristics such as size, weight, and stiffness. This is achieved by modelling the vehicle as a point mass with appropriate inertial properties, a chassis definition that can contact an object, and a means to represent the suspension contacts with the barrier.

Variation in materials and designs of automobiles makes it difficult to produce a specific vehicle model. Each parameter describing the vehicle increases the complexity of the mathematical model. As a tool for highway design engineers, the specific response of an individual vehicle make is not necessary. Highway structures must face a myriad of vehicle sizes and types and a facility that incorporates a volume of vehicle configurations with reasonable fidelity is preferred. The law of diminishing returns is quickly encountered when translating a complex structure like a motor vehicle into a mathematical model.

The vehicle model herein incorporates the following assumptions:

1. **Planar Vehicle Motions** The vehicle motions observed experimentally involve all six degrees of freedom for the vehicle. There are some motions which are less significant than others and are omitted in the present study. Vehicle roll, pitch, and vertical motions were excluded in order to simplify the model. While this limits the model's capabilities, it is also recognized that the input
requirements to achieve these additional motions are significant. The most notable of these modelling requirements is an accurate tire/barrier interface model. Wheel climb motions on the barrier are difficult to model (as discussed in Chapter 2) and are omitted in this model development. The objective to produce a generic vehicle model was achieved herein by reducing the vehicle motions to the most significant vehicle motion. This reduces specific data requirements for individual vehicle designs.

2. **No Tire/Roadway Forces** Tire contact with the roadway will create friction loads when the vehicle is in yaw. However, there is limited tire contact with the roadway during impact. Vertical climb of the vehicle was observed experimentally and indicates the redirection process is not significantly affected by tire forces on the road. This model considers that the vehicle is unrestrained except for the contact forces developed with the barrier and precludes tire forces acting on the road.

3. **Two Dimensional Crush** The reaction of the vehicle and barrier is based on the interference of the two dimension description of the vehicle and the vertical plane defining the barrier. As discussed earlier, this excludes vertical loads on the vehicle. Friction between the vehicle and barrier is considered to affect the vehicle's reaction. The normal force calculated from the vehicle's contact with the barrier is used to calculate the friction acting on the contact area.

4. **Stiffness Characteristics** The vehicle structure is assumed to deform in the manner similar to the CRASH [44] model. The contact force is based on the amount of vehicle crushed and the stiffness description developed in previous crash testing research.

These items will expanded upon as the vehicle model is defined in the following sections.

### 4.3.1 Vehicle Dynamics

The gross motions of the vehicle are much easier to describe analytically than those of the barrier. The vehicle’s inertial properties can be assumed to be unaffected by
Chapter 4. Mathematical Simulation of Vehicle-Barrier Impacts

...damage. Mathematically, the dynamics of the vehicle are described by the response of its center of gravity to the external loads;

\[ \ddot{\vec{x}} = \vec{F}/M_{\text{vehicle}} \]

\[ \ddot{\theta} = M/I_{zz} \]

where: \( I_{zz} \) is the moment of inertia about the vehicle's vertical axis, \( M_{\text{vehicle}} \) is the vehicle mass, \( M \) and \( \vec{F} \) are the external moment and forces on the vehicle, \( \ddot{\vec{x}} \) is the translational and \( \ddot{\theta} \) the angular accelerations of the vehicle's center of mass.

Values of the vehicle's inertial properties have been tabulated by Garrott [33] for a wide range of cars. Moments of inertia about the three main axes and center of gravity positions are reported for each car tested as well as general relationships between mass properties and vehicle mass. The products of inertia have not been listed because of the difficulty in measuring these parameters. Products of inertia are required when developing a three dimensional vehicle model and is one reason for limiting the vehicle to planar motions. A major three dimensional vehicle model, HVOSM [21], reduces this problem by assuming the vehicle has two axis of symmetry and thus only one product of inertia. However, substantial documentation has not been identified for any vehicle products of inertia and suggest that three dimensional vehicle models require data that is not easily obtained. In contrast, significant reporting of various vehicle masses and moments of inertia have been reported by Garrot [33] and highlight the feasibility of planar vehicle models.

HVOSM [21] is a sophisticated 3D model of the vehicle that allows motion of the suspension and steering systems relative to the vehicle body. Modelling these components require stiffness and damping characteristics as well as identification of the range of motions for these systems. These parameters will provide vehicle response during normal driving events (an important capability of HVOSM). The usefulness of these features for modelling collision features is less evident. In the experimental study herein, it was found that most impacts studied produced mechanical failures of the suspension or steering components. Thus, incorporating sophisticated vehicle subsystems into a collision model will not provide important response data unless the structure can be accurately characterized. The recurring theme in the vehicle modelling described below is to reduce the vehicle to as simple a model as possible while still capturing the general physics of the process.
4.3.2 Vehicle Crush Model

Background

The deflection of the vehicle chassis and the suspension during a collision develops interaction forces between the vehicle and struck object. The characteristics of the vehicle response depends on the part of the car involved. Accident reconstruction researchers have investigated vehicle deformation processes as a means to estimate vehicle collision speed from structural damage. This ongoing research is developing vehicle deformation models which are evaluated with staged collision data.

There are two approaches to vehicle collision response that are used in the highway safety models like HVOSM, GUARD, and BARRIER VII. One procedure uses the assumption that the energy absorbed by vehicle damage is proportional to the volume of vehicle damage or 'crush' as developed by Campbell [41]. This approach is very popular for accident reconstructionists. Parameters defining the vehicle structure are easily estimated from collision data. The method also allows similar vehicle sizes (based on their wheelbase) to be reasonably characterized by the same stiffness values, allowing a broad application of the collision data. This approach is depicted in Figure 4.17.

![Figure 4.17: Vehicle Stiffness Characteristics](image)

One other vehicle characterization method is to represent the vehicle as a series of discrete springs. Finite areas of the vehicle such as bumpers, wheels, fenders, etc.
are replaced by a spring defining the deflection behaviour of that area. This provides for a more accurate model of the vehicle’s stiffness variation around its periphery compared to the crush model above. However it does require more intensive vehicle characterization to obtain the unique spring parameters around the vehicle.

An effective method for evaluating vehicle collision performance is employed in the HVOSM model [21] and in its refinement by Perera [24]. The vehicle body is represented by a homogeneous body that can be described by the crush approach. This provides generic modelling of the body defined by easily obtained, albeit less specific, stiffness parameters. The vehicle structure is then identified to have stiffer components noted as ‘hardpoints’ which are represented by single springs. Three hardpoints defined within the HVSOM vehicle model are the front and rear axles along with the front bumper. All act independently of the body’s crush model. This hybrid of crush and spring modelling has proven effective for the HVOSM model and has been incorporated into the vehicle-barrier impact model developed herein. Only two hardpoints are employed in this model and they define the front and rear axle of the vehicle. The crush parameters used in this model are defined from collisions where the vehicle bumper(s) are included in the body deformations. These deformations are used to calculate the stiffness parameters for the vehicle body.

One important challenge for modelling a vehicle collision with a roadside barrier is to account for the oblique damage pattern of the vehicle. Stiffness characterizations of vehicles are reported for impact conditions normal to the longitudinal or lateral axis of the vehicle. For example, major databases of vehicle stiffness values were reported by Prasad [39][40] and lists data for front, rear, and side impacts. Any description of oblique impact analysis assumes a correction factor based on the geometry of the principal direction of impact forces related to these stiffness values. Oblique stiffness values have not been experimentally tabulated in any of the reviewed material. One of the latest crush modelling approaches (Perera [24]) still used frontal collision data to characterize oblique vehicle impacts into concrete barriers.

The existing vehicle damage models highlight the difficulty in modelling vehicle collision response. No damage models explicitly define oblique vehicle damage. The performance of HVOSM (discussed in Chapter 2) indicate that a hybrid crush-spring definition for vehicles provide reasonable results for rigid barrier impact simulations. This model is also effective in that existing stiffness models tabulated in sources like
Prasad [39] can be applied to model. This provides a broad vehicle database potential users of the developed vehicle model. The stiffness of hardpoints are not as well reported, but reference to the previous models provides some guidance for their values.

**Vehicle Definition**

The vehicle model developed herein is represented as a rectangular object that interferes with the barrier as shown in Figure 4.18. As they interfere, a new profile is generated to represent the crushed vehicle. Forces are generated from the area of crush relative to the original vehicle outline. These forces are transformed to the vehicle’s and relevant segment’s centers of mass, providing the dynamic variables that drive the simulation.

The vehicle outline is defined mathematically with a linked list of line segments. Each line definition contains its starting coordinates (in the vehicle reference frame), pointers to line segments on either endpoint, and identification of the barrier segment that the segment may be contacting. By adding to this list of line segments, the vehicle deformation process can be simulated geometrically.

In addition to the vehicle’s body deformation, the axles and wheels deform and produce contact forces. The axles are modelled by springs which act along the axle’s axis. Figure 4.18 shows the physical arrangement of these structural hardpoints.

The interaction of the vehicle and the barrier is determined by the interference of their respective boundaries. A line segment representing a barrier segment is transformed to the vehicle reference. This line is compared with the vehicle’s linked list set to determine if an interference exists. This process starts with the first line (defining the front bumper) of the vehicle outline definition. The interference is determined from parametric definitions of the any lines defined by points \([x_1, y_1], [x_2, y_2]\):

\[
\begin{align*}
x_a &= x_1 + T_\alpha (x_2 - x_1) \\
y_a &= y_1 + T_\beta (x_2 - x_1)
\end{align*}
\]  

where: \(a\) is the line segment, \(\alpha\) and \(\beta\) are the \(x\) and \(y\) scalar parameters
Figures 4.18: Linked List Definition for Vehicle

Parametric lines are defined for the vehicle outline \((x_1, y_1; x_2, y_2)\) and a barrier segment \((x_3, y_3; x_4, y_4)\). The value of the parameters \(T\) where these two lines intersect are found from the following:

\[
T_\alpha = \frac{-(x_3 - x_1)(y_4 - y_3) + (y_3 - y_1)(x_4 - x_3)}{-(x_2 - x_1)(y_4 - y_3) + (y_2 - y_1)(x_4 - x_3)} \quad (4.29)
\]

\[
T_\beta = \frac{-(x_2 - x_1)(y_3 - y_1) + (y_2 - y_1)(x_3 - x_1)}{-(x_2 - x_1)(y_4 - y_3) + (y_2 - y_1)(x_4 - x_3)} \quad (4.30)
\]

The parameter \(T\) takes on the value \(0 \leq T \leq 1\) for a point of intersection between the two end points. If both \(T_\alpha\) and \(T_\beta\) are in the interval \([0, 1]\), a new line segment is inserted into the vehicle outline list. This new line represents the entire length of the vehicle contact with the barrier. If the contact length spans two barrier segments, then two line segments are added. All separate barrier segments that contact the vehicle boundary are individually identified in the vehicle definition. This process is required to determine the load sharing between the segments and will be illustrated in the force calculation description to follow.

To avoid an excessive amount of line segments from accumulating, an algorithm to lump essentially collinear segments into a single line was included. These line segments must not be in contact with the barrier to be considered in this process.

The hardpoint spring deflections are calculated in a manner similar to the vehicle boundary deformation. The two line elements representing the front and rear axles are expressed parametrically and compared to the line elements defining the barrier contact surface for these components. When the hardpoint is in contact with the
barrier, the difference between this length and its original length are used for the associated force calculation. The high stiffnesses of these components led to large spikes within the vehicle acceleration histories. The first stiffness values for the hardpoints assumed no elastic rebound and produced acceleration spikes in the vehicle output similar to metal cutting chatter. A 10% elastic rebound in the hardpoint eliminated this problem.

A two surface representation of the barrier presents some limitations on the simulation model performance. Vehicle body contact with one barrier face is a reasonable assumption for the barrier and vehicle geometries observed in testing. However, the hardpoint (or wheel) contact with a second barrier surface cannot fully represent the vehicle motion on the barrier. The vehicle climb on the barrier, mostly arising from the wheel contact with the batter curb causes the wheel to move from the batter curve onto the barrier face. As seen in the barrier profile (Figure 1.2), there is a significant transition from the wheel’s original contact with the batter curb to contact with the vertical face. This transition cannot be incorporated into a two dimensional model without a performance criteria which defines this process. As mentioned in Chapter 2, the climb of tires on concrete barrier faces is still not well represented mathematically. Without a good model for wheel-barrier interactions, the modelling of the wheel-barrier contact cannot be easily represented in a planar dynamics model. A three dimensional model can represent the full geometry of the wheel and barrier and thus simulate the geometric interference of these structures. However, there are still limitations in the modelling the forces for these three-dimensional geometries.

It is recognized that the two dimensional vehicle-barrier model will not completely represent the full vehicle-barrier collision geometry. However, it was determined that developing the vehicle contact faces described above and depicted in Figure 4.18 would still be advantageous. The two surface barrier was required if the original vehicle contact with the barrier was to be observed. The overhang of the bumper from the front wheels and the profile of the barrier allow both vehicle structures to contact the barrier nearly simultaneously (for most impact geometries). This may be important to replicate in simulation analyses. Providing flexibility in the barrier face and vehicle stiffness definitions will allow bounds on the vehicle redirection to be determined for the hardpoint contact. Thus, inaccuracies in the two dimensional
representation can be compensated for by providing the range in which actual collision results will fall.

It is also important to provide hardpoint definitions in a vehicle collision model to account for the stiff behaviour of these structures compared to the body's crush. It was observed in the testing that the wheel would experience a significant amount of the impact loads. This behaviour is supported by the video recordings, extensive wheel marks on the barrier, and vehicle damage profile. The front wheel appeared to stay in contact with the barrier through most of the redirection process. The video images and long wheel loading marks on the barrier confirmed this observation. In addition, most of the vehicle damage was contained to the front fender area. The mechanical structure of the vehicle is such that the impact loads to the vehicle structure will predominantly move through the bumper and its mounting components as well as the wheel and suspension components. The sheet metal structures of the fender do not provide as much crush resistance. Even when the suspension fails, the wheel is pushed back against the subframe where the suspension and motor are mounted. Severe impacts introduced a rotation of the front vehicle structures as shown in Figure 4.19. This deformation pattern would require strong load supporting elements to transfer this load to the vehicle without creating a more substantial deformation profile than observed experimentally.

The vehicle contact forces are calculated using the stiffness coefficients accumulated from the previous research. For the body crush, the parameters required to calculate contact forces are the crush width and crushed area. The original, undeformed vehicle perimeter is used to determine the depth of crush. The crush depth is calculated normal to the deformed surface. This is the method suggested by Fonda [34] to adapt frontal impact data to oblique impacts and provides an isotropic representation of the vehicle stiffness.

As seen in the stiffness parameters (Figure 4.17), there are two coefficients. The ‘A’ is the damage threshold required to produce deformation. This value is used with the length of the contact line. The ‘B’ value is the slope of the stiffness line and is associated with the area crushed. The crush calculation is illustrated in Figure 4.20. This figure also shows how the loads are shared across two (or more) barrier segments when this situation arises. The line elements of the vehicle cannot span a
barrier joint while contacting the barrier. This creates a boundary for determining the crush elements specific to one barrier segment for calculation of the forces.

The crush model in Figure 4.17 was modified to provide some crush history effects on the crush forces. Perera's [24] model used tracking points to determine the total deflection history of specific vehicle components. This requirement has been relaxed slightly herein to only consider the previous depth of crush in the force calculation. The vehicle body is assumed to be a rigid-work hardening plastic material. Thus, the 'A' coefficient for a deflected structure increases as the vehicle collides with the barrier. The value increases with the slope 'B' for incremental increases in crush. This hardening effect compensates for the increased stiffness introduced by the frame rotation depicted in Figure 4.19 and by the deflection of surrounding structures not in direct contact with the barrier (induced damage).

Stiffness values for the hard point values are not well documented. From the study of Labra et al [38], the axles for a compact vehicle were given stiffnesses of 438kN/m. Welch [23] used a value of 87.6 kN for axles on a large (2200 kg) vehicle. There was little other information available in the reviewed literature. The sources of the values used by Perera [24] were not documented and the inference is that the values were varied until agreement was found with the crash test data. All of this information
will be used in the developed model so that an appropriate range of values can be determined for the vehicles tested with the B.C. barrier.

The friction acting between the vehicle and barrier can be calculated after the normal contact force has been calculated. The reported values for this parameter are between 0.25 and 0.5 [23],[42]. Friction is an input variable for this simulation tool and can be varied to observe its influence on the impact performance.

Vehicle crush during an impact is assumed to be independent of the friction forces acting on the deforming surface. This is based on the assumption that the stiffness acts normal to the crush direction and tangential forces do not create shear deformations. Thus, the friction acting on the vehicle body is simply a function of the normal force acting on the barrier. However, the hardpoints are assumed to deform parallel to the local lateral axis of the vehicle. This may not be normal to the direction of the barrier face. This situation requires that the friction forces be accounted for in the hardpoint deformation. Consider the situation depicted in Figure 4.21.
hardpoint deflects at an angle to the barrier face. The friction force is still a function of the normal force on the barrier, but it now has a component which acts along the direction of hardpoint deflection. The force acting along the direction of hardpoint deflection is found from:

$$F_{hp} = F_n \cos(\alpha) - \mu F_n \sin(\alpha)$$  \hspace{1cm} (4.31)

where: $F_{hp}$ is the spring force of the hardpoint, $F_n$ is the normal force from the hardpoint acting on the barrier, $\alpha$ is the difference in the barrier and vehicle angles in the global coordinate system.

The equation can be solved for the normal force given that the spring force is given by:

$$F_{hp} = k_{hp} \Delta l_{hp}$$  \hspace{1cm} (4.32)

where $k_{hp}$ and $l_{hp}$ are the spring constant and length of the hardpoint element.
Once the loads from all vehicle contacts are determined, the resulting forces are equated to a force/moment equivalent on the vehicle center of mass. Loads on the barrier are similarly transformed from their points of application to the segment’s center of mass. These loads were then used to calculate the accelerations of the system elements using the equations of motion presented earlier.

4.4 Discussion

The models described for the deflecting concrete barrier and a striking vehicle have now been developed. The objective of these models was to provide barrier performance information to the highway engineer. Desirable inputs, outputs and performance constraints were identified for the model so that this goal could be achieved.

An energy balance model for the collision was initiated and quickly rejected as method to simulate a vehicle-barrier collision. The model required several a-priori assumptions that made its application as a design tool inappropriate. Important parameters like vehicle crush energy and vehicle kinetic energy changes, which are coupled to the barrier response, were determined before the simulation began and reduced its accuracy and utility.

To analytically describe the collision process, a two dimensional dynamic model was developed. The planar model reduces the analytical description of the event to a minimum to reduce computational resources. The experimental data shows that more complex motions do occur. However, the majority of the desired information and the general behaviour of the process appears to be reasonably approximated by planar motions.

The barrier kinematics were simplified by breaking the joint deflection process into five discrete actions. This allowed the barrier deflection to approximate the observed process while minimizing the degrees of freedom for the system. The five joint phases were separated by discrete joint actions and allowed a system of constant body fixed vectors to represent the barrier positions. This system took advantage of different impulsive conditions to discretely alter any barrier kinematics that would be difficult
to accommodate by a continuously variable body fixed vector system. This kinematic description of the barrier is analogous to a piecewise linear approximation of a continuous process.

The essential component to the barrier kinematic description is the use of only one variable, joint angle, to describe the barrier orientation. The manipulation of this variable within the joint definition allowed the joint rotation resistance to be explicitly determined by the elongation of the steel hook element in the male segments. This representation allows the hook deflection characteristics to be calculated independent of the constraint loads and thus removes this computational burden from the simulation software, albeit with some costs in accuracy.

Only two external loads are required to be calculated for the barrier dynamics simulation - friction forces from sliding on the road and impact loads from the vehicle. Friction loads are calculated by a numerical model of two contacting planes and has a significant computing expense. This computation can be calculated at specified intervals to trade off accuracy to reduce computer run time.

Vehicle contact loads incorporate existing vehicle crush methodology and tabulated vehicle behaviour. This provides access to existing data and eliminates the need for additional test resources to determine input data. The vehicle crush model employed provides a generalized vehicle response that does not depend on specification of individual vehicle features. However sufficient flexibility has been incorporated into the vehicle's input description that special vehicle characteristics may be observed in the impact performance.

The vehicle-barrier impact model has been developed to provide the general impact response data required by a highway department to analyze highway safety. This is achieved by modelling a specific vehicle-barrier collision and simulating the vehicle and barrier dynamics that occur. The information required to describe that collision has been minimized as much as possible to facilitate an efficient computer code while maintaining the physical representation of the event. The significant inputs to describe the barrier component of the model are:
• **Segment Dimensions:** length, base width, face width, bottom surface area, mass, moment of inertia - there can be various segment properties within the barrier assembly studied

• **Joint Characteristics:** joint locations, joint slack, hook deflection characteristics

• **Road Interaction:** static and dynamic coefficient of friction

• **Barrier Geometry:** number of segments, initial joint angles

The significant vehicle inputs to the model are:

• **Vehicle Dimensions:** length, width, axle locations, center of mass, mass, moment of inertia

• **Contact Information:** body stiffness (front, side, and rear), axle deflection stiffness, coefficient of friction on barrier face

• **Impact Conditions:** speed, angle, position on barrier

These variables will accommodate almost any roadside construction design to be simulated with any two-axle vehicle. Limitations on the accuracy will depend on the validity of the input data, particularly for the vehicle. The next chapter provides a discussion of the model validation, sensitivity to the input parameters and its applicability to highway safety engineers.
Chapter 5

Simulation Model Verification

The objectives of this chapter are to discuss the accuracy and limitations of the vehicle-barrier simulation model developed in the previous chapter. The sensitivity of the model output to important input parameters is also presented. Results provided by the simulation are compared with appropriate experimental data to demonstrate how well the simulation model approximates the actual collision events.

5.1 Current Model Implementation

The segmented concrete barrier impact model (SCBIM) developed herein approximates a vehicle collision into a B.C. highway barrier using planar dynamics. The vehicle stiffnesses are obtained from accident reconstruction databases and the barrier characteristics are based on experimental data collected during this study. Some features of the model used to conduct the verification study are mentioned here for clarity.

- The barrier impact model developed in Chapter 4 was coded into a program that currently operates on a personal computer. This program uses a graphical user interface to define the barrier, vehicle, and program control variables. Figure 5.1 shows a typical collision definition created by the user. NCHRP 230 evaluation data consisting of vehicle redirection values (vehicle yaw, center of gravity trajectory, vehicle yaw rate, and exit speed), occupant flail space
calculations (interior impact velocity and ridedown accelerations), and barrier deflections are summarized in one text file. Detailed data on the vehicle and barrier dynamics are also saved on the disk drives for later analysis. An additional summary file is created that describes the vehicle, barrier, and simulation parameters.

- A Fourth-Order Runge-Kutta integration routine is used to integrate the equations of motion developed in Chapter 4. This algorithm has an adaptive step size component which is controlled through a user defined precision value. Smaller precision values will provide a better numerical approximation to the equations of motion at the expense of increased computation time. A limit on the maximum step size has been incorporated to ensure that routine does not ‘step’ over important events that occur over short time periods in the simulation.
• The joint deflection curve for the steel hooks is based on the deflection data obtained in Section 3.4.2. This assumes that the uniaxial test data reasonably approximates the hook forces during joint rotations. No lateral hook loading is considered.

• The barrier dynamics are limited to that for a moving reference frame. This prevents the barrier kinematics from being defined explicitly with a inertial reference frame. Barrier segments are not included in the simulation unless they are moving or are in contact with the vehicle. Once the barriers are in motion, they cannot form closed kinematic chains or take advantage of the impulsive stopping forces described in Section 4.2.3.

• The friction acting between the barrier and the road surface is calculated from three surface integrals. These integrals were evaluated with different grid sizes to determine the most efficient precision to use. Figure 5.2 summarizes these calculations.

![Figure 5.2: Precision of Friction Calculations](image)

The present form of the model was used to conduct a series of simulations. The purpose of these simulations was to evaluate the accuracy of the model and its sensitivity to input parameter variations. The results of this procedure and a discussion of the results is presented in the following section.
5.2 Verification Program

The accuracy and sensitivity of the vehicle-barrier simulation model were determined by conducting many simulation runs. The task was broken into two components which separated the vehicle and barrier variables. First, a program to determine the vehicle model's effectiveness was performed. The model performance to variations in the input parameters was observed during a series of simulations. Table 5.1 is a list of the two vehicle sizes simulated (Plymouth Fury and Honda Civic) and the parameters which were varied for each vehicle. Two references simulations that agreed well to experimental data were used as baselines. The references were rigid vertical wall impacts for the Plymouth Fury and Honda Civic listed by Perera [24]. The rigid wall data provided a means to observe vehicle performance independent of the barrier definition.

Table 5.1: Vehicle Model Verification Program

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Conditions</th>
<th>Vehicle</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plymouth Fury</td>
<td>Integration</td>
<td>Honda Civic</td>
<td>Integration Precision</td>
</tr>
<tr>
<td></td>
<td>Precision</td>
<td>Honda Civic</td>
<td>Friction</td>
</tr>
<tr>
<td>Plymouth Fury</td>
<td>Contact Friction</td>
<td>Honda Civic</td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>Plymouth Fury</td>
<td>Moment of Inertia</td>
<td>Honda Civic</td>
<td>Vehicle Body Stiffness</td>
</tr>
<tr>
<td>Plymouth Fury</td>
<td>Vehicle Stiffness</td>
<td>Honda Civic</td>
<td>Hardpoint Stiffness</td>
</tr>
<tr>
<td>Plymouth Fury</td>
<td></td>
<td>Honda Civic</td>
<td>Vehicle Mass</td>
</tr>
</tbody>
</table>

The second task was to conduct a similar sensitivity investigation for the barrier variables listed in Table 5.2. These simulations were compared to a baseline simulation representing Test 26 (1200 kg vehicle / 20 degrees / 80 km/h).

The sensitivity of the model output to the variable changes was observed through figures displayed in the following sections. The percentage change of the output values (referenced to the baseline simulation results), were plotted against the parameter variations.
Table 5.2: Deflecting Barrier Model Verification Program

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRB</td>
<td>Integration Precision</td>
</tr>
<tr>
<td>CRB</td>
<td>Road-Barrier Friction</td>
</tr>
<tr>
<td>CRB</td>
<td>Joint Slack Distance</td>
</tr>
<tr>
<td>CRB</td>
<td>Vehicle-Barrier Friction</td>
</tr>
<tr>
<td>CRB</td>
<td>Joint Stiffness</td>
</tr>
</tbody>
</table>

5.2.1 Vehicle Model

Two vehicle types were simulated during the vehicle model verification: a Honda Civic (900 kg) and a Plymouth Fury (2000 kg). Reference simulations were used for all the comparative analysis presented. These references were based on:

- Stiffnesses for the front, side, and rear structures obtained from the databases developed by Prasad [39],[40].
- Hardpoint stiffnesses of 438000 N/m for the Fury [42] and 87500 N/m for the Honda [21].
- Vehicle moments of inertia obtained from the relation developed by Garrott [33].
- Coefficient of friction between the vehicle and barrier set to 0.3.
- Vehicle geometry recorded during the experimental study described in Chapter 3.

Five output variables were used to observe the vehicle’s reaction to changes in the model definition: Exit Angle (vehicle yaw), Exit Angle (trajectory of the vehicle center of mass), Vehicle Yaw Rate, Vehicle Exit Speed, and Lateral Wall Loading (maximum values).

Both vehicle definitions compared well with the data presented by Perera [24] using a modified HVOSM. Figures 5.3 and 5.4 show the lateral loads recorded for these
impacts and generated by HVOSM and SCBIM. The figures show that the planar SCBIM model provided data comparable to the three dimensional HVOSM model for the vehicle-rigid wall test data. It is particularly important for the model to reproduce the two impact pulses due to the front and rear of the vehicle striking the barrier. Both figures show good correlation between the magnitude and timing of the pulses simulated and those measured. These results were thus deemed acceptable as the reference conditions for the following discussion.

Figure 5.3: Comparison Of Experimental and Simulated Lateral Wall Loading for Plymouth Fury

The results of the following vehicle sensitivity simulations highlighted two output parameters that were the most sensitive to model input data. Both the vehicle exit angle (yaw) and the vehicle yaw rate produced the greatest fluctuations as the model description was changed. They could vary +/- 100% when the remaining output variables changed less than 50% for the same parameter variation. The exit yaw angle was susceptible to these large percentage variations because it tended to be a small value, typically less than 10. Thus a small variation produced a large percentage change in output. However, the trajectory of the vehicle center of mass was a smaller number and this variable was not as sensitive to the input variables.

Details of the model sensitivity to the parameters listed in Table 5.1 are now presented.
Integration Precision: The Runge-Kutta integration scheme employed in this model estimated the error at each time step to determine the appropriate subsequent step size. A precision value of 0.01 (default value) required about 3 minutes of computer time while 0.0005 required 63 minutes. The smaller step sizes, achieved by smaller precision values will reproduce the equations more accurately.

Both vehicle models simulated proved to produce consistent performance over a range of integration precisions. Except for vehicle exit yaw and yaw rate values, the reviewed variables showed little change (below 10%) for the precision values studied. The Fury model did exhibit a 140% change in yaw rate between the coarse and fine simulation precisions. This may be attributed to the stiffness of the hardpoints. The Fury had very stiff hardpoints, relative to the Honda, and this added stiffness produced the differences between integration precisions. This was evident in the secondary impact of the rear axle shown in Figure 5.5. The coarser precision will not allow the integration routine to follow abrupt events (like hardpoint contacts) as well as finer precisions. Aside from the yaw rate, the simulation output appears very consistent as shown in Figure 5.6. This figure shows the influence of the precision parameter, plotted on a logarithmic scale, had on the Fury simulation results. It shows that the output parameters exhibited a steady state as a finer precision value (moving left
on the graph) was used. Only minor variations of about 15\% from the reference are observed in these figures.

![Graph showing lateral acceleration over time with different integration precision](image)

*Figure 5.5: Effect of Integration Precision on Vehicle Accelerations*

![Graph showing change in output with varying integration precision](image)

*Figure 5.6: Effect of Integration Precision on Simulation Accuracy*
Vehicle Stiffness: The vehicle response should be strongly related to its structural deflection characteristics. This was studied in two ways: individual changes to the Honda’s body and hardpoint stiffnesses and simultaneous variation of both parameters for the Fury. The Honda exhibited a stronger dependence on body stiffnesses than on hardpoint stiffnesses. Figure 5.7 shows how multiples of the reference stiffness, plotted on the horizontal axis, influence the output.

The exit speed and center of gravity trajectory were hardly affected by significant (order of magnitude) stiffness changes. However, the lateral acceleration, yaw rate and yaw at exit were strongly affected by the stiffness. As expected, lateral accelerations were directly related to the vehicle stiffness. They doubled for the tenfold increase in the body stiffness plotted in Figure 5.7.

The influence of the hardpoint stiffness on vehicle redirection is similarly plotted in Figure 5.8. The general trend observed was that all exit parameters increase with increased hardpoint stiffness. Performance trends close to the reference position were less well defined, but the changes were not prohibitively large.

The Fury simulations showed a less direct relation between model output and vehicle stiffness (Figure 5.9). In these simulations, body and hardpoint stiffnesses were varied by the same factor. Except for vehicle yaw and yaw rate, the tenfold stiffness variation
produced minor output variation. It is also interesting to note that the less sensitive variables remained very close to the reference condition, even at the largest stiffness values.
A large variation in yaw rate (150%) was observed when the stiffness was doubled, dropping off with progressively stiffer vehicle definitions. This behaviour is due to the interaction of the vehicle and barrier, particularly the second impact. The yaw rate of the vehicle (away from the barrier), due to the initial front bumper and fender contact with the barrier, should increase as the vehicle stiffness increases. A corresponding increase in the opposing yaw moment is expected during the second impact of the rear of the vehicle with the barrier. The increase and decrease of the yaw rate for increasingly stiff vehicles arises from the difference in stiffness between these two parts of the car. It appears that (given proportional variations in the stiffness of the vehicle components) the magnitude of the second impact does not increase as fast as the initial impact. As the stiffness increases, the second impact magnitude increases and acts against the positive yaw rate. In addition to this affect, the moment of inertia will act against the initial vehicle yaw and tend to reduce the exit yaw rate.

The exit yaw varied substantially (+/-50%) for the small variations around the reference stiffness. This translates to an exit yaw angle ranging from 2 to 6 degrees. Since the allowable exit condition is about 14 degrees, the model fluctuations are not critical when compared to the acceptable barrier performance.

The results displayed in Figures 5.7 and 5.9 suggests that small errors in the stiffness data will not substantially vary the results. Yaw and yaw rate can be highly variable for this range, but increasing the precision of the integration routine may reduce some of this variability. The model sensitivity to vehicle stiffness is an important feature given that stiffness values are not available for every vehicle model. There are generic stiffness values for vehicles [44], based on wheelbase, that will have some discrepancy from the actual stiffness desired. The results displayed here indicate that these generic vehicle stiffness values may provide reasonable estimates for modelling a variety of automobiles.

**Vehicle-Barrier Friction:** The friction between the vehicle and the barrier was varied from $\mu = 0$ to $\mu = 0.75$ for both vehicle models. The results of the simulations are illustrated in Figures 5.10 and 5.11. As expected, the exit speed varied inversely with friction. The vehicle trajectory and lateral accelerations remain constant compared to the large variations in the yaw and yaw rate. It is interesting to note that the yaw values exhibit the opposite trends between the two vehicle types. The Fury simulations exhibited larger exit yaw angles as the friction increases, whereas the Honda's
The mass of the vehicle appears to affect its response for identical changes in friction. Consider the trajectory, exit speed, and acceleration results for the Fury (Figure 5.10). The trajectory and acceleration values were essentially constant, while the exit speed varied about 30% as the friction coefficient increased from 0 to 0.5. The Honda showed larger variations for these variables, most notably in the lateral acceleration. This effect can partly be attributed to the smaller vehicle mass of the Honda. Having less inertia than the Fury, it would be more sensitive to variations to contact loads.

It is difficult to determine a single value for the coefficient of friction between the barrier and the vehicle. Rubber, steel, and plastic surfaces can be in contact with the barrier simultaneously. Each surface has unique friction characteristics, but it is difficult to calculate the contribution of each surface without substantially increasing the vehicle model sophistication. The current vehicle-barrier models appear to use average values of $\mu = 0.25$ to 0.5 for body structures and $\mu = 0.5$ for hardpoints. Their results and those obtained for this model appear to suitably reflect general
vehicle response with rigid barriers. Allowing the user to vary this parameter allows an expected range of vehicle behaviour to be bracketed.

**Vehicle Inertial Properties:** The inertial properties of the vehicle, mass and moment of inertia about the vertical axis, were varied less than +/-50% around the default values selected for this model. Since the user can determine these parameters more accurately than any other model input parameter, uncertainty in their values should be well within this variation. Both vehicle simulations produced fairly consistent results, although the Honda did vary more than the Fury. The model appears to be more sensitive to the moment of inertia than to the total vehicle mass. This is attributable to the most sensitive exit parameters, vehicle yaw and yaw rate, which are directly influenced by the moment of inertia. In addition, the second impact of the rear of the vehicle will be influenced by the vehicle yaw rate at the time of impact. The magnitude of this impact influences both the redirection and occupant accelerations. The output variations of the most sensitive variables (exit yaw and yaw rate) were sufficiently less than the NCHRP 230/350 exit condition thresholds to be of little concern.
In summary, the vehicle model developed for this deflecting barrier model appears to perform reasonably well and thus deemed suitable for use with a deflecting barrier model. The most sensitive vehicle parameters observed were the vehicle yaw and yaw rate as the vehicle exits the barrier. These parameters are important for evaluating the redirection performance of the barrier and should be monitored closely. The vehicle’s center of gravity trajectory appears to be a reasonably stable quantity with respect to input errors and should be also be considered in redirection evaluations.

The variability of the yaw and yaw rate may be improved by repeating the sensitivity analysis with a finer integration precision. The precision results in Figure 5.6 show that simulations with a smaller precision value (about an order of magnitude smaller) have a steady output for further variations of this parameter. This stability may be reflected in the model response to some of the other variables studied above.

### 5.3 Comparison of Simulation Results with Experimental Data

The validity of any theoretical model is best demonstrated by comparing its output to data obtained experimentally. Table 5.3 is a set of test conditions used to evaluate the abilities of the SCBIM simulation model. These test conditions represent some of the crash tests described in the Chapter 3. A range of impact severities have been chosen to provide insight into the model’s performance for different impact conditions.

The acceleration traces of the vehicle are compared to the simulation results obtained for two test cases. The data from Test 23 and 26 are presented with the corresponding simulations in Figures 5.12 and 5.13. They show that the model replicates the early part of the collision very well. The initial acceleration pulses are essentially the same length and magnitude. The second pulse is not as well simulated. The simulation predicts this impulse to occur later than the empirical data. Part of this discrepancy may be due to the vehicle motions not represented in the model (roll, pitch, climb). In addition, the approximation of the barrier as two contact planes for the vehicle body and axles may also produce the longer delay between the two vehicle acceleration pulses.
Table 5.3: Test Conditions Simulated for Model Verification

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Vehicle Speed</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[kg]</td>
<td>[km/h]</td>
</tr>
<tr>
<td>CMB</td>
<td>900</td>
<td>60</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>60</td>
</tr>
<tr>
<td>CMB</td>
<td>900</td>
<td>80</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>80</td>
</tr>
<tr>
<td>CMB</td>
<td>900</td>
<td>94</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>93</td>
</tr>
<tr>
<td>CRB</td>
<td>900</td>
<td>80</td>
</tr>
<tr>
<td>CRB</td>
<td>1200</td>
<td>80</td>
</tr>
<tr>
<td>CMB</td>
<td>900</td>
<td>75</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>80</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>80</td>
</tr>
<tr>
<td>CMB</td>
<td>1200</td>
<td>65</td>
</tr>
</tbody>
</table>

Vehicle yaw during an impact is presented for Tests 23 and 26 in the Figures 5.14 and 5.15. The plots show a good agreement between the vehicle redirections predicted by the simulation and those observed experimentally. The vehicle simulations for the small vehicles (Volkswagen Rabbit, Honda Civic) did not agree as well with the experimental data than the larger vehicle (Chevrolet Citation, Plymouth Reliant). This was encountered for other performance variables like the vehicle accelerations, barrier deflections, etc. in the subsequent sensitivity study.

An important aspect of the exit conditions is the yaw rate at exit. As mentioned in the experimental results, the vehicle was often observed rotating after leaving the barrier. As shown in Figures 5.14 and 5.15, the vehicle yaw at exit is in close agreement with the experimental data.

The lateral barrier deflections measured and predicted are presented in Figure 5.16. These represent the Plymouth Reliant / 80 km/h / 20 degree impact conditions. The simulation reproduces a reasonable approximation of the deflected shape of the barrier. The model was able to predict similar lateral deflections as well as the length of the affected barrier. Better approximations are anticipated with further investigation of the vehicle and barrier parameters entered into the simulation.

The results of the simulations listed in Table 5.3 are compared to experimental data in three graphs: Vehicle exit angle and two plots of maximum barrier deflections for
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Figure 5.12: Comparison of Vehicle Acceleration - Volkswagen Rabbit / 80 km/h / 20 deg

Figure 5.13: Comparison of Vehicle Accelerations - Plymouth Reliant / 80 km/h / 20 deg
Figure 5.14: Comparison of Vehicle Yaw - Volkswagen Rabbit / 80 km/h / 20 deg

Figure 5.15: Comparison of Vehicle Yaw - Plymouth Reliant / 80 km/h / 20 deg
the two barrier sizes (CMB and CRB).

The exit angle and vehicle trajectory are shown with the experimental results in Figure 5.17. The simulated and experimental data are plotted with markers. The data for both barriers are presented and normalized using the Specific Impact Severity (SIS). The experimental results are those for vehicle yaw at exit. The simulation results have shown that the exit yaw angle is one of the most susceptible variables to model parameters while the exit trajectory is more stable. This behaviour is obvious for the values plotted in Figure 5.17. The model yaw values tend to conservatively predict the exit angle, while the trajectory data tends to underestimate the observed exit conditions. The boundaries sketched in show that the model can reasonably bracket the exit angle between these two parameters, except at low impact severities.

The barrier deflection results are presented in Figures 5.18 and 5.19. The results indicate that the model conservatively predicts the maximum barrier deflections until joint separations are encountered. Deflections beyond 50 cm were usually recorded with joint separations, but the model did not duplicate this behaviour. As seen in Figures 5.18 and 5.19, the model underpredicts barrier deflections for these circumstances. The model did predict some joint separations during some simulations, but
these situations were less frequent than those observed experimentally. All joint separations resulted in aborted simulations due to the proximity of the vehicle to the joint affected. The continued barrier deflections were not calculated and limited the model results for these conditions.

5.3.1 Sensitivity of the Deflecting Barrier Model

Performance of the deflecting barrier model to various input variations was conducted for a baseline impact of 20 degrees / 80 km/h / 1200 kg vehicle. The same output variables monitored for the vehicle model were used for the deflecting barrier model. In addition, the maximum barrier deflection is also presented as an output variable in the following discussion to provide a measure of the barrier model performance.

The results of the each parameter evaluation have been tabulated into two graphs. The first describes the vehicle rotational behaviour and includes vehicle yaw, yaw rate, and center of gravity trajectory at exit. The other graph presents the translational behaviour of the vehicle and barrier. The variables plotted on this graph are lateral and longitudinal accelerations (as calculated by the flail space model), exit speed, and the maximum lateral barrier deflection.
Figure 5.18: Comparison of CMB Simulated and Observed Barrier Deflections

Figure 5.19: Comparison of CRB Simulated and Observed Barrier Deflections
Integration Precision: The same Runge-Kutta integration routine was used for the deflecting barrier simulations as for the vehicle verification study. As before, very little influence was noticed for most variables. Only the lateral occupant accelerations and the barrier deflection showed any appreciable change with integration precision.

The reference case (precision=0.005) required about 2 1/2 hours of computer time. The coarsest precision took 1 1/2 hours while the tightest precision case took 1 1/2 days on a 486-50MHz personal computer.

Barrier/Road Friction Values: There are two friction parameters to be studied for the deflecting barrier model. The barrier resistance to sliding depends on both the static and dynamic coefficients of friction between the barriers and the road. Both values were varied and are presented in the following graphs.

The static coefficient had no effect on the vehicle exit conditions and only a minor influence on the barrier deflection. As seen in Figure 5.20, there is a small change in the barrier deflection for a substantial change in the static coefficient of friction. This is not too unexpected as the change in static friction has little effect on the energy dissipated by the barrier. The present transition between static and dynamic friction assumes no energy loss. If the increased friction was used to represent the breaking of mechanical links to the road (if the segment was bolted to the roadbed, for example), the energy dissipated would be incorporated into the impulsive friction calculation and a more noticed effect on barrier deflections would be observed.

The variation of the dynamic friction coefficient had a more pronounced effect on the model output. As seen in Figures 5.21 and 5.22, the vehicle and the barrier were affected by changes in this parameter. As noted for the vehicle model, the vehicle exit conditions most affected were the yaw and yaw rate. The exit angle (yaw) tended to decrease with increasing friction while the opposite occurred with the exit yaw rate. The maximum barrier deflection was markedly affected and is seen to vary over 240%. As expected, it decreases with increasing friction. The exit speed and occupant ride down accelerations were not significantly affected, decreasing with increased dynamic friction.

The impulsive treatment of the barrier’s transition from static to dynamic conditions appeared to produce acceptable results. The calculated barrier speed at the end of
Figure 5.20: Influence of Static Coefficient of Friction on Barrier Deflection

Figure 5.21: Influence of Dynamic Coefficient of Friction on Vehicle Rotations
the transition interval was very small, consistent with a small time interval for the impulse to act. The influence on the vehicle dynamics was also minor. For example, the barrier and vehicle kinetic energy changes were insignificant (less than $2 \times 10^{-6} J$) compared to the total system energy (94 kJ). The convenience introduced by this approach will not significantly affect the final barrier rest positions.

**Vehicle-Barrier Friction**: The coefficient of friction between the vehicle and barrier was varied between 0.3 to 0.5 to observe the influence this would have on simulation performance. The results of these simulations are shown in Figures 5.23 and 5.24. As observed before, the yaw and yaw rates were the most influenced by the friction value. The longitudinal occupant ride-down accelerations increase with increased friction as expected. Both the lateral accelerations and barrier deflections are reduced as friction is increased. This suggests that more energy is directed parallel to the barrier as the vehicle-barrier friction increases. This is supported by the reduction in the lateral ride-down acceleration.

**Joint Slack Conditions**: The slack within the joint connections was varied between 0 and 5 mm to observe the affect of this barrier variable on simulation output. The default value used throughout the simulation study has been 2 mm.
Figure 5.23: Influence of Vehicle-BARRIER Friction on Vehicle Rotations

Figure 5.24: Influence of Vehicle-BARRIER Friction on Vehicle Translations
Chapter 5. Simulation Model Verification

The results of the simulations with various joint slack conditions are presented in Figures 5.25 and 5.26. There were two cases which the joints separated and the simulation was aborted. The first was the case with no slack. The joints failed early in the simulation so that exit conditions were not calculated and are not included in the graphs. The other case was for the largest slack condition (5 mm) and represents the last case (5 mm slack condition). The joints separated but exit conditions could still be calculated and were included in the graphs.

The vehicle rotation variables show no clear trends as the joint slack is increased. They vary within a 50% range for a change of +/- 1mm in the slack conditions. The trajectory seems relatively unaffected compared to the yaw and yaw rate values.

Translation variables are less sensitive than the rotational vehicle behaviour to increased joint slack and tend toward steady state values. The vehicle exit speed is unaffected, however, the occupant ride down accelerations vary. The lateral accelerations tend to increase with the slack amount while the longitudinal values decrease.

There was a slight trend for the barrier deflections to increase as the slack amount is increased. The barrier deflection was artificially low for the 5 mm joint slack condition because of joint separation. The simulation terminated at this point and did not calculate the final deflection of the barrier which would have been greater than previous condition. These results are similar to those provided by Ivey et al [19] and Walker and Ross [20]. Their barrier deflection models also predicted increases in barrier deflections when the joint slack is increased. The difference between these models and the model herein is that they defined a rotational freeplay in the joint, whereas the SCBIM uses a translational freeplay allowance.

**Joint Stiffness:** The stiffness of the joints is entered into the model as a force deflection curve for the hook. A comparison of the two hook types tested experimentally was conducted numerically to observe the changes that the thicker (and) stiffer hook produced. The experimental results indicate that the maximum barrier deflection was reduced by 10%, occupant accelerations increased 22% while the joint rotations were reduced by 40%.

Simulations with the standard and thicker hook were conducted for the same impact conditions observed experimentally (1200 kg vehicle, 80 km/h, 20 degree impact). The
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Figure 5.25: Influence of Joint Slack on Vehicle Rotations

Figure 5.26: Influence of Joint Slack on Vehicle Translations
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The differences between the two simulations were: maximum barrier deflection reduced 6%, occupant accelerations were unaffected and joint rotations reduced 15%. These changes were not as large as those observed in the experiments, however, the thicker hook did decrease the joint rotations and the total barrier deflection as expected. Although not incorporated here, the thicker hook will reduce the amount of slack in the joint which should also decrease barrier deflections.

5.4 Discussion

The model developed to simulate impacts with the B.C. concrete barriers has been shown to provide reasonable agreement with the experimental data. The vehicle contact model which was developed from the CRASH [41] model and HVOSM [21] has been shown to provide excellent results for vehicles contacting rigid walls. The vehicle model appears quite robust in that it can tolerate a range of error in input variables without dramatically changing the output.

The effectiveness of the vehicle model with the shaped deflecting barrier is not as good as for the rigid wall. The contact geometry, as well as the planar representation of the three dimensional event tended to produce a greater delay between the predicted acceleration pulses than observed experimentally. However, given this limitation, the performance of the model is still reasonable and should provide useful information for those investigating deflecting barriers. There are some conditions that the model reproduced quite well (Plymouth Reliant / 80 km/h / 20 degrees) providing good agreement with exit conditions and barrier deflections.

Simulation and empirical data have been compared and shown to agree reasonably well. Plots of the exit angle and barrier deflections show that the model tends to overpredict these parameters. Joint separations were not appropriately predicted by the simulation and thus under predicted barrier deflections for higher severity impacts. Predicted vehicle acceleration and yaw histories demonstrates that the model extends the vehicle redirection process compared to experimental data. However, the figures presented also show results which are very encouraging for a model of a complex dynamic event.
One of the shortcomings in the present model is the manner in which slack is simulated in the joint. Currently, once the model detects contact between two segments, the point of contact is used as the hinge point until binding of the concrete corners is detected. This appears to overly constrain the early parts of the barrier deflection. Because there is a loose fit between the hook and eye, there can be some relative motion of these components along the longitudinal barrier axis after they have come into contact. This would provide more free rotation of the barriers than is permitted in the current model. The lateral constraints of the concrete tongue-and-groove and the slack in the hook and eye suggest that a sliding constraint between the segments may be more appropriate as illustrated in Figure 5.27. This will require some additional degrees of freedom for the model and has not been implemented in the current model.

Another area that should be investigated further is the impact of the rear of the vehicle with the barrier. The stiffness and integration precision sensitivity studies showed that these variables strongly influence the model output. Figure 5.5 demonstrates how the second impact can be affected causing variations in the output. Other variables, such as barrier contact geometry and vehicle hardpoints, are important to this event and should be also investigated.

The results presented in this chapter are encouraging. The sensitivity plots for the vehicle-rigid wall and vehicle-deflecting barrier showed that the model provided reasonable results. Except for vehicle yaw and yaw rate, the model provided consistent relations between output data and the input variables. The model accuracy can be improved by studying more of the parameter sensitivities and their interactions.
These improvements can be achieved without requiring substantial changes to the underlying model.
Chapter 6

Conclusions and Recommendations

An evaluation of the concrete highway barriers used in the province of British Columbia has been presented. Experimental testing and theoretical modelling techniques were used to observe vehicle and barrier responses during a collision. Vehicle crash tests were used to observe the collision event and the data collected has been compared to the results of a computer simulation model. The conclusions and consequences of this research work are outlined in the following sections.

6.1 Experimental Testing

The crash test program was designed to observe the B.C. barriers over a range of impact conditions and to obtain specific information to quantify their behaviour. The list of objectives directing this study, presented in Chapter 1, is now reviewed to assess the project’s success.

The most significant objectives were to study the barriers over a range of impact conditions and identify the response of the vehicles and barriers. The data collected during this testing is unique in terms of its subject and the level of study. As deflecting concrete barriers have been typically used for temporary protection of construction zones in most jurisdictions, their limited exposure to traffic has not warranted a deflecting barrier test program of this size.
Chapter 6. Conclusions and Recommendations

The literature reviewed in Chapter 2 presented previous experimental investigations of deflecting barrier. Most of the presented data was gathered (Table 2.2 [12, 13]) for test speeds above 90 km/h and little data has been documented for impact angles other than 25 degrees. It is also apparent from Table 2.2 that none of these barriers have been subjected to a significant number of tests. The B.C. barrier test data covers a range of test angles and speeds, allowing potential service evaluation aids to be developed. The barrier response curves for Specific Impact Severities (SIS) presented in Chapter 3 could not have been developed without the data gathered in this research.

There are some limitations in the test data presented herein. One of the most significant issues is the lack of high speed (above 80 km/h) data. As discussed earlier, limitations of the test facility precluded significant testing beyond this threshold. Some work was completed for the CMB, but more should be done for this barrier along with the CRB.

Another purpose for crash testing the B.C. barrier was to evaluate unique implementation features of the CRB. The application of concrete barriers as general purpose roadside barriers in B.C. presents some unique collision possibilities. The barriers have terminal sections that introduce the potential of increased impact angles and reduced upstream mass. The impact angle dependence has not been significantly addressed by other test agencies and the upstream mass issue had not been identified in any reviewed research. The limited tests discussed in Chapter 3 identified some performance features of the CRB for these test conditions. Although Table 2.2 lists one impact angle of 40 degrees, no data could address deflecting barrier response for impact angles beyond the NCHRP suggested 25 degrees. Two tests described herein are now available for review as well as two more which illustrate the influence of the upstream mass. Although more tests are necessary to completely understand these issues, the data collected herein present their initial documentation.

The remaining objectives were to quantify specific barrier parameters i.e. road-barrier sliding friction and joint deflection behaviour. Several tests were developed to acquire this data. The barrier friction tests provide some general data for the barrier. Coefficients of friction were obtained, but only the translational friction forces were measured. The size of the barriers made more detailed testing prohibitive. Alternative testing approaches, such as scale models, may be worth exploring in future studies.
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The information obtained was useful for the subsequent modelling component of the research and provided expected friction values for the model.

Joint deflection research was studied with three different test approaches. All of these involved mounting strain gauges on the connection hooks to monitor the hook deflections. Crash tests, in-situ static tests, and controlled tension tests were used to measure the joint deflection force-deflection behaviour, as well as observe how the hook dimensions would affect the barrier’s collision behaviour.

There has been no prior description of crash testing two different joint constructions under identical test conditions. The reported data in Chapter 3 are the first (to the author’s knowledge) report of this kind. In addition, the quasi-static in-situ tests are a new approach to quantifying joint behaviour. Analytical predictions of joint capabilities have been developed by other researchers, but they have not been confirmed with test data. The experimental approaches herein proved incomplete, as the barrier motions during the in-situ testing did not fully represent the collision behaviour of the barrier. However, some minor modifications to the procedures would provide better data for this work. The laboratory tension tests were important to measure the specific response of the two different hooks employed in the crash tests. The crash data could not be interpreted without knowing the relative increase in joint strength. This information was also useful in the barrier simulation model developed in this research program.

The objectives defined for the experimental study have been achieved with some success. The compiled test data are a significant contribution towards the global database on deflecting concrete barriers. This will improve the understanding of their service performance and assist in calibrating any simulation models. Data from the test program has already been adopted by the B.C. MoTH in their modified RHSM model [26]. The stronger joint design tested is currently being implemented by MoTH in some of the newer barrier installations. There are some limitations in the data collected, however, some new test procedures have been demonstrated and further research is encouraged. Suggestions are presented in a following section.
6.2 Computer Simulation Model

A mathematical model of a vehicle colliding with a B.C. barrier was a major goal of this project. The model construction was identified as consisting of several components. The significant modelling features were barrier kinematics, joint deflection behaviour, sliding resistance loads, vehicle collision modelling, and a vehicle-barrier interaction description. The successful completion of these modelling tasks would provide a simulation tool to analyze the collision event. Some of the constraints placed upon the modelling project included the integration of as much existing data as possible (not limited to the experimental data collected herein) and the development of a reasonably efficient and convenient computer program.

The assessment of the model's effectiveness was the final objective of the research. Both the vehicle impact model and the deflecting barrier model required an assessment of their performance. The following is a review of the ability of the developed models to meet these objectives.

Barrier kinematics were implemented through an effective multibody dynamic modelling approach discussed in Wittenburg [36]. From this basis, a unique programming application was developed to recreate the barrier model. Physical attributes of the barrier joints and their behaviour were modelled and integrated into the basic formulation. This approach provided for arbitrary description of the barrier configuration without any special preparation by the user. The developed program allows for many of the geometric and inertial properties of the barrier to be defined by the user. This provides flexibility to the user for studying variations in the barrier design and their influence on collision performance. The convenient formulation of the barrier allows the mathematical system definition to be modified easily and is exploited in the joint model developed for the B.C. barriers.

An original joint description method has been presented to represent some of the complex motions of the barrier joints. Similar to previous researchers ([19],[20]), different regimes of joint behaviour are identified. However, the transition between these regimes has been modified to account for the discontinuous behaviour these systems exhibit.
The joint model herein presents three contributions to existing modelling attempts. The first is the ability for the model to only identify individual segments that are involved in the model. This is achieved by allowing some amount of translational free play in the joint. Previous models had rotational slack in the joints, however, this only eliminated joint torques within the system. Constraint forces could still be transmitted between segments. The current model allows the model to exclude stationary segments until contacted by adjacent units.

The second joint feature of note is the use of impulse analysis techniques to provide transitions between appropriate joint regimes. This allows the contact between adjacent segments to be considered as a momentum problem. This provides a more stable integration process since less time is spent iterating around discontinuities in the mathematical system definition.

The last contribution of the joint model is the multiple joint constraint definition. This feature allows the model to integrate throughout the collision even though the axis of rotation between the segments may shift. Without this implementation, the barrier kinematics could not have been reduced to the minimum degrees of freedom possible for this type of structure.

Modelling the friction between the barrier and the road was required for the collision simulation. Calculation of the resisting forces is based on the sliding contact of two planes and was one of the most computationally demanding components of the model. A unique feature of the developed model is the manner in which the a discontinuous variation in the coefficient of friction was incorporated without creating numerical integration problems. The transition from a static to dynamic barrier condition was approximated as an impulse. This provided a convenient method to include the large gradient in the friction coefficient near zero velocity.

The final modelling objective for the barrier was to define the interaction between the barrier and vehicle. This goal was fulfilled by defining two contact planes between the vehicle and the barrier. A coefficient of friction was used to define tangential barrier loads. The contact planes allow the initial contact geometry of the vehicle tire and bumper to be replicated on the barrier. A comparison of the initial vehicle accelerations predicted by the model with the experimental results demonstrated the success of this assumption. The coefficient of friction approach employed in
Chapter 6. Conclusions and Recommendations

this interface model has been implemented in previous models. The sensitivity of the model to this parameter follows reasonable trends and does not introduce any unstable model responses.

The modelling of the vehicle-barrier interface does have some limitations, most noticeably the delay between the significant vehicle acceleration pulses measured empirically and discussed in Section 5.3. The modification of the associated parameters has not been thoroughly investigated. Further research may provide better results for this particular response feature.

An important component of the total deflecting barrier model is the vehicle impact model. The inclusion of this component separates the present model from previous analytical descriptions of deflecting concrete barrier models. Earlier deflecting barrier models only incorporated known impact loading data and did not account for the interaction between the two systems.

A modified vehicle crush model, based on the CRASH [41] algorithm, was shown to provide good impact descriptions of vehicle collisions with the rigid vertical wall. The subsequent implementation with the deflecting barrier model did not agree as well with experimental results. The differences noted for the latter case is a combination of the vehicle and barrier model limitations. However, the overall performance of the vehicle model shows promise and may be improved with further work.

After the vehicle-barrier collision model was developed, the performance of this model was reviewed through parameter variations and comparison of the results with empirical data. The purpose of this exercise was to identify the limitations and abilities of the simulation package. Reports of this type of data for barrier impact simulation models have not been identified by the author and present new information for this research area.

One objective of the model performance study was to observe vehicle response to different input parameters. Vehicle input variables like structural stiffness, mass properties, barrier contact friction, and the precision of the integration routine were varied and plotted with important model outputs. This exercise was completed using a rigid vertical wall description for the barrier to separate the deflecting barrier description
from the vehicle response. General response of the vehicle model was encouraging and suggests that small errors in the input would not seriously influence the results.

Finally, the response of the entire simulation package to input parameter variations was studied. Barrier variables like sliding friction and joint connection descriptions were used to observe the effectiveness of the model. The results of the model are encouraging and demonstrate its capability to become a design tool for highway engineers. The results of this exercise suggest that the model has a tendency to provide conservative estimates of the vehicle response and barrier deflections. It appears feasible to improve the existing model performance with further research into the combination of parameters that most effectively describe collision. The interaction components of the vehicle and barrier, the two contact planes and contact friction, are two important parameters that may be refined to achieve this goal.

A significant contribution of the collision model research was the reduction of the model complexity. This was achieved by reducing the process to planar dynamics and reducing the degrees of freedom within the barrier to a minimum. The planar dynamic assumption does not appear to dramatically influence the model performance. It provides all the data required for NCHRP test evaluation except for vaulting of the barrier and vehicle rollover. This omission can be partially addressed using the available empirical data.

The reduction of model complexity is important for developing the model into an effective research and design tool. Analytical models can be very complex, providing very accurate results of a physical process. These models are also typically expensive to operate. In contrast, models may incorporate simplifications that reduce its description of the process but make its operation more economical. Given reasonable assumptions, the latter modelling approach may be a more effective tool. Many different system configurations can be simulated, providing a quantity of data for review. Situations, like that faced by highway jurisdictions, preclude sophisticated and detailed modelling. These are situations that involve poorly defined input requirements. For highway barrier impacts, accurate modelling of the vehicle descriptions is very expensive when a myriad of changing automobile models are in service. These situations are best addressed with generic modelling of these parameters, allowing the accuracy of the model to be studied by parameter variations and repeated simulations.
Chapter 6. Conclusions and Recommendations

6.3 Recommendations for Further Work

Resources for this barrier evaluation program were not capable of exploring all the possible research inherent to this dynamic process. Both the experimental and theoretical components of the study could be expanded to further document the dynamics of a vehicle-barrier collision. The following is submitted as a partial list of the many issues that could be pursued further.

1. **Experimental Crash Testing** - The range of test conditions reported in Chapter 3 developed a substantial database for the B.C. barriers. Additional testing should be implemented to study the barrier effectiveness for more severe impacts. The test vehicles selected should also include larger vehicles such as pickups or minivans which are a considerable component of the vehicle population.

Experimental studies of the joint deflections characteristics and the influence of different joint constructions could be explored. Of particular note would be a method to prolong or eliminate joint separation. A conceptual design of the author, depicted in Figure 6.1, would allow the hook to deflect and absorb energy during joint rotation. It would then lock onto the eye and provide sufficient axial strength to prevent barrier separation.

2. **Service Condition Evaluation** - The highway department in B.C. has little service documentation of the barrier because of the difficulty in collecting enough collision data to estimate the impact conditions. The relationships defined in Section 3.4.3 now provide a tool capable of connecting post-impact barrier positions with impact speed and angle estimates. Because of the minimal data collection requirements, the initial site inspection can be reported by the repair crew. This reduces the travel requirements of a trained investigator. This information would be very useful for assessing the barrier design criteria for changing vehicle populations.

3. **Barrier Warrant Development** - The B.C. MoTH currently uses a simple warrant for the CMB. Using the crash and simulation data now available, a better defined warrant defining the need of a CMB can be developed.
4. **Cost Benefit Barrier Need Assessment** - The situation currently faced by the B.C. MoTH for developing a cost-benefit approach to roadside safety can now be better assessed. Before the development of this model, they could analyse most of the variables for an off road vehicle excursion, except for those involving a concrete barrier. This model provides more detailed collision data that can provide the comparative estimates for the cost of vehicle-barrier impacts.

5. **Improve Barrier Joint Definition** - Simulations conducted with the present model cannot reproduce the joint separations that were observed in the crash tests. Further work to refine or replace the current separation criteria should be conducted to improve the usefulness of the model.

6. **Vehicle-Barrier Modelling in Three Dimensions** - The current model only treats the barrier as a vertical wall. This feature does not allow for the vertical actions of the vehicle to be assessed during the simulations. If the increased computational requirements are acceptable, a three dimensional model of the impact should be developed similar to HVSOM. This modelling may require extensive research into the tire-barrier interaction to define the vertical motions on the barrier. This enhancement to the model will also increase the vehicle description requirements for the model which may reduce the applicability of the program when all the required parameters are not known. This is offset by
better understanding the redirection behaviour and observing high risk events like vaulting or vehicle rollover. The vertical loads on the barrier may also influence joint separation events and the sliding forces of the barrier on the road.

7. **Oblique Vehicle Stiffness Characterization** - The currently implemented stiffness characteristics were obtained from previous crash data. This data, however, is not specific to oblique collisions and may not be the best representation available. Specific research to quantify the oblique crush behaviour of the vehicle would improve the simulation's accuracy and provide much needed information for other areas of vehicle safety research. This will become increasingly important if three dimensional crush is to be predicted in future models.

8. **Assess Appropriate Vehicle Exit Conditions** - The NCHRP recommended procedures for assessing barrier performance could be clarified regarding exit angles. NCHRP Reports 230 [8] and 350 [9] require that the vehicle exit the barrier at less than 60% of the impact angle. This may not be the best definition as it does not define the exit angle as the trajectory of the center of mass or the vehicle yaw. As seen in the model sensitivity study, the exit yaw was more susceptible to model parameters. This sensitivity should be verified experimentally to determine which angle is more appropriate. Coupled with this is the vehicle exit yaw rate. The experiments with the B.C. barriers showed cases where the vehicle could continue to rotate towards or away from the traffic after exiting the barrier. This yaw rate should be studied in the context of vehicle dynamics when contacting the road surface. Bounds on the direction and magnitude of vehicle yaw rates after leaving the barrier may be an appropriate refinement to the redirection criteria.

### 6.4 Summary

The B.C. Ministry of Transportation and Highways' concrete roadside and median barriers have been analyzed experimentally and numerically. The quantity of the tests reported herein is a significant increase in the deflecting concrete barrier tests reported at the start of the project. Specific tests beyond the scope of NCHRP 230 (and
350) provided some interesting insights into segmented barrier performance. Impact analysis methods, useful for service evaluations of the barrier, were developed from the experimental studies. The simulation methodology employed highlights how a discrete joint submodelling can be used to simplify the system degrees of freedom and still retain a good replication of the physical processes occurring. A simulation tool with potential uses by highway departments employing deflecting concrete barriers has also been developed.
References


[23] Welch, R.E., Concrete Safety Shape Simulations with Program Guard, Federal Highway Administration Report No. FHWA-RD-78-90, 1977


[27] Bryden, J.E. & Bruno, N.J., Movable Concrete Median Barrier Risk Analysis, Transportation Research Record, 1233:1-10,


[42] Labra, J.J., Calcote, L.R., Bronstad, M.E., Investigation of Canadian Concrete Guardwall Performance, Southwest Research Institute Report No. 03-4685-209, 1977


Appendix A

B.C. Highway Barrier Information

Modified copies of specification drawings for the B.C. Ministry of Transportation and Highways (MoTH) concrete roadside barriers are presented on the following pages. These drawings have been simplified and are presented for information only to provide details of general construction and connection systems.

The Roadside Barrier Index Warrant for the B.C. MoTH is also included. This nomograph shows the variables used to determine the need for a barrier. It has been simplified for display on one page.

The reader is referred to MoTH for more detailed drawings and barrier warrant information for these barriers.
Figure A.1: Concrete Roadside Barrier - Male

Elevation
End Detail
Male Unit

End View - Male Unit

Plan End Detail Male Unit

213

690

550

25

2500

Pick-up points
Void

Elevation - Male Unit

Providence of
British Columbia

Ministry of
Transportation
and Highways

B.C. Concrete Roadside Barrier
Male - 690 mm high

All Dimensions in mm

Specification
Drawing No.
10-SP323
Appendix B

Test Vehicle Information

Vehicle Information For Test 23 - VW Rabbit / 79 km/h / 20 degrees

Table B.1: Vehicle Measurements For 1980 Volkswagen Rabbit

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<thead>
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<th>b</th>
<th>c</th>
<th>d</th>
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<th>f</th>
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<th>Inertial [kg]</th>
<th>Test (with Occupant) [kg]</th>
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<td>571</td>
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<td>M2</td>
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Vehicle Damage: CDC 020 - RFEW - 2

All Measurements in m, refer to Figure B.1 for dimension references.
Figure B.2: Vehicle Damage Schematic (Test 23)
Figure B.2: Vehicle Photographs Before Impact (Test 23)
Appendix B. Test Vehicle Information

Figure B.3: Vehicle Photographs After Impact (Test 23)
Appendix C

Development of Equations of Motion

The following dynamic development was based on the multibody dynamics theory described by Wittenburg [36].

Let an interconnected multibody system of \( n \) elements be represented in the graphical form shown in Figure C.1.

The hinges or joints are numbered from \( i \) or \( j = 0, n - 1 \) where \( i = 0 \) is the connection between the inertial frame and the first (or root) body. The arcs connecting the hinges are used to define the topology of the system. Referring to Figure C.2, the following vectors can be defined:

- \( c_{i-1,i} \) is the vector from the C of G of body \( i - 1 \) to the hinge connecting body \( i \).
- \( d_{ij} \) is the vector connecting the inboard hinge of body \( i \) with the C of G of any other body \( j \).
- \( b_{ij} \) is the vector connecting the barycenter of body \( j \) with the barycenter of body \( i \).

The barycenter of a body in a multibody system is defined as the center of mass of the body if the total system mass was lumped onto the body. All the component masses connected to the body through the hinges are lumped at the corresponding hinge point. This hypothetical body is referred to as an augmented body.
Appendix C. Development of Equations of Motion

Figure C.1: Multibody System

Figure C.2: Body Fixed Vectors in a Multibody System
Appendix C. Development of Equations of Motion

The morphology of the system is described through the interconnectivity matrices $S$ and $T$. The first matrix describes how the bodies are connected and the second describes which bodies lie between the first body and a given body. Refering to Figure C.1, the element $S_{ij} = +1$ when arc $j$ points away from hinge $i$ and -1 for the reverse case. The value of $S_{ij}$ is 0 for all other elements. Similarly, the element $T_{ij} = -1$ if arc $i$ points toward body $i$ and lies between body $j$ and body 0. An additional vector $S_0$ is used to define the hinge to inertial (body 0) space. This vector is redundant in most cases since there is usually only one connection to inertial space and is evident in the $S$ matrix as the -1 value in the first row.

For the barrier system under study, the form of these matrices is:

$$S_0 = \{ 1 \ 0 \ 0 \ \cdots \ 0 \} \quad (C.1)$$

$$S = \begin{bmatrix}
-1 & 1 & 0 & \cdots & 0 \\
0 & -1 & 1 & \cdots & 0 \\
0 & 0 & -1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & -1 \\
\end{bmatrix} \quad (C.2)$$

$$T = \begin{bmatrix}
-1 & -1 & -1 & \cdots & -1 \\
0 & -1 & -1 & \cdots & -1 \\
0 & 0 & -1 & \cdots & -1 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & -1 \\
\end{bmatrix} \quad (C.3)$$

The $S$ and $T$ matrices are the inverse of each other and this property is used to simplify the development of the equations of motion.

To identify if an arc $s_i$ lies between one body, $s_j$ and the root body, the following shorthand is used:

- $s_i \leq s_j$ implies arc $s_i$ lies between arc $s_j$ and the root body and can be equivalent to $s_j$
- $s_i < s_j$ implies $s_i$ is between the root body and arc $s_j$ but cannot be equal to $s_j$
- $s_i \not< s_j$ implies that $s_i$ does not lie between the arc $s_j$ and the root body
Appendix C. Development of Equations of Motion

The dynamics for the system are developed through the balance of external and inertial forces. Isolating one element of the barrier as in Figure C.3, the equation of motion for translation is given by:

$$m_i \ddot{x}_i = F_i^e + F_{i-1}^c - F_{i+1}^c$$  \hfill (C.4)

from the definition of $S$:

$$F_{i-1}^c - F_{i+1}^c = \sum_{a=1}^{n} S_{ia} F_a^c$$  \hfill (C.5)

so in matrix form:

$$[m] \{\ddot{x}\} = \{F\} + [S]\{F\}^c$$  \hfill (C.6)

where: $\{\ddot{x}\}, \{F\}, \{F\}^c$ are vectors containing arrays for acceleration, external forces, and constraint forces and the matrix $[m]$ is a diagonal matrix which contains mass of body $i$ in position $m_{ii}$

The rotational motions for the body are defined as:

$$\dot{H}_i = M_i + \sum_{a=0}^{n} (\vec{c}_{ia} \times \vec{F}_a^c + M_a^c)$$  \hfill (C.7)

where: $\dot{H}_i$ is the rate of angular momentum change and $\vec{c}_{ia}$ is the body fixed vector from the center of mass of body to hinge $a$ (if present) and $M$ is the applied moment.

Using the identity above in C.5:

$$\{\dot{H}\} = \{M\} + [\vec{C}] \times \{F\}^c + [S]\{M\}^c$$  \hfill (C.8)
Appendix C. Development of Equations of Motion

where: $[\ddot{C}] = [S][\ddot{c}]

We can use the property $[S][T] = [I]$ to solve for the constraint forces explicitly in equation C.6. When substituted into equation C.8, we obtain the equation of motion for the system:

$$\{\ddot{H}\} = [\ddot{C}][T] \times \left(\{[m]\ddot{r}\} - \{F\}\right) + [S]\{M\}^c$$

(C.9)

This equation will apply for both the case when body 0 is fixed in inertial space or if the system has a moving frame of reference. The difference between arises from the description of the $\ddot{F}$ term.

At this point, the equation of motion is defined but it can be expressed in a more convenient form based on the bond graph definitions above.

The position of body $i$'s center of gravity is given by the expression

$$\ddot{r}_i = \ddot{r}_o - \sum_{j=0}^{n} \ddot{d}_{ji} \quad i = 1 \ldots n$$

(C.10)

The matrix of vectors $[\ddot{d}] = [\ddot{C}][T]$ so we can now write:

$$\{\ddot{H}\} + [\ddot{C}][T] \times ([m][\ddot{C}][T])^T \{1\} + [\ddot{C}][T] \times \{[r_o][m]\{1\} - [F]\}
= \{M\} + [S]\{M\}^c$$

(C.11)

where: the vector $\{1\}$ is a vector with elements of 1 and carries out the required summation shown in equation C.10.

The summation of $([\ddot{C}][T] \times [m][\ddot{C}][T])^T \{1\} = [\ddot{d}] \times [m][\ddot{d}]^T$ has the following 4 cases

$$[\ddot{d}] \times [m][\ddot{d}]^T = \begin{cases} \sum_{k=1}^{n} m_k \ddot{d}_{ik} \times \ddot{d}_{ik} & i = j \\
\ddot{d}_{ij} \times \sum_{k=1}^{n} m_k \ddot{d}_{jk} & i < j \\
\sum_{k=1}^{n} m_k \ddot{d}_{ik} \times \ddot{d}_{jk} & j < i \\
0 & otherwise \end{cases}$$

(C.12)

With these formulations, it is now convenient to introduce the vector $\ddot{b}$ into the definition. From Figure C.2, it can be seen that:

$$\ddot{d}_{ij} = \ddot{b}_{ij} - \ddot{b}_{ij}$$

(C.13)

$$\sum_{j=1}^{n} \ddot{b}_{ij} m_j = 0 \quad i = 0, \ldots n$$

(C.14)
Appendix C. Development of Equations of Motion

From these expressions we can rewrite the terms in equation C.12:

$$\sum_{k=1}^{n} m_k \vec{d}_{jk} = \sum_{k=1}^{n} m_k (\vec{b}_{j0} - \vec{b}_{jk}) = M \vec{b}_{j0}$$  (C.15)

where $M = \sum_{i=0}^{n} m_i$

The resulting terms described in C.12 can be expressed as:

$$\sum_{k} m_k \vec{d}_{ik} \times \vec{d}_{ik} \quad i = j$$

$$M \vec{d}_{ij} \times \vec{b}_{j0} \quad i < j$$  (C.16)

$$M \vec{b}_{j0} \times \vec{d}_{ji} \quad j < i$$

$$0 \quad \text{otherwise}$$

If we define the result of C.16 as the quantity $g_i$ then C.9 becomes:

$$\dot{H}_i + g_i - \sum_{j=0}^{n} \times (m_j \vec{r}_{j0} - \vec{F}_j) = M_i + \sum_{a=1}^{n} S_{ia} M_a^c$$  (C.17)

The next step is to explicitly describe $\dot{H}$ in terms of the parameters given. The definition of $\dot{H}$ is (Figure C.4):

$$\dot{H} = \int \rho \times \vec{\rho} \, dm$$  (C.18)
Appendix C. Development of Equations of Motion

If we use the inboard hinge as the reference point, the vector \( \vec{d}_{ii} \) is the difference from this point to the CG. If \( \vec{p} \) is the vector from the new reference point to \( dm \), then \( \vec{p} = \vec{p} - \vec{d}_{ii} \) and is shown in Figure C.4.

\[
\vec{H} = \int (\vec{p} - \vec{d}_{ii}) \times (\vec{p} - \vec{d}_{ii}) \, dm
\]
\[
= \int \vec{p} \times \vec{p} \, dm + m_i \vec{d}_{ii} \times \vec{d}_{ii} \quad (C.19)
\]

When equation C.19 is combined with the term \( \sum_{k \neq i} m_k \vec{d}_{ik} \times \vec{d}_{ik} \) in equation C.16, the result is an expression for the rate of change of the angular momentum for the body \( i \), given the body's augmented mass properties and treating the point of reference as the inboard hinge point.

We can describe the segment inertial properties, \( (K) \) based on the augmented body, as the following:

\[
K_i = J_i + \sum_{k=1}^{n} m_k \left( \vec{d}_{ik}^2[I] - \vec{d}_{ik} \vec{d}_{ik} \right) \quad i = 1 \ldots n \quad (C.20)
\]

where \( J_i \) is the moment of inertia of the original body about its CG.

The resulting expression for the change in the body’s angular momentum about the inboard hinge is:

\[
\vec{H}_i + \sum_{k=1}^{n} m_k \vec{d}_{ik} \times \vec{d}_{ik} = K_i \cdot \dot{\omega}_i + \omega_i \times K_i \cdot \omega \quad (C.21)
\]

We can simplify the following:

\[
\sum_{j=1}^{n} \vec{d}_{ij} \times \vec{r}_0 = \sum_{j=1}^{n} \left( \vec{b}_{ij0} - \vec{b}_{ij} m_j \times \vec{r}_0 \right) \quad (C.22)
\]

\[
= \vec{b}_{i0} \times M\vec{r}_0
\]

therefore:

\[
K_i \dot{\omega}_i + \omega_i \times K_i \cdot \omega_i + M \left[ \sum_{j:s_i<s_j} \vec{d}_{ij} \times \vec{b}_{ij0} + \vec{b}_{i0} \times \left( \vec{r}_0 + \sum_{j:s_i<s_j} \vec{d}_{ji} \right) \right] \quad (C.23)
\]

\[
+ \sum_{j:s_i \leq s_j} \vec{d}_{ij} \times \vec{F}_j = M_i + \sum_{a=1}^{n} S_{ai} M^c_a
\]

\[
\vec{b}_{j0} = \dot{\omega}_j \times \vec{b}_{j0} + \omega_j \times \left( \omega_j \times \vec{b}_{j0} \right) \quad (C.24)
\]
Appendix C. Development of Equations of Motion

\[
\vec{d}_{ji} = \vec{\omega}_j \times \vec{d}_{ji} + \omega_j \times (\omega_j \times \vec{d}_{ji})
\]  

(C.25)

So now the final form becomes:

\[
K_i \dot{\omega} + M \left[ \sum_{j:s_i < s_j} \vec{d}_{ij} \times (\omega_j \times \vec{b}_{i0}) + \vec{b}_{i0} \times \sum_{j:s_j < s_i} \omega_j \times \vec{d}_{ji} \right] = M'_i + M_i + \sum_{j=1}^{n} S_{ij} M^e_j
\]

(C.26)

where:

\[
M'_i = -\omega_i \times K_i \omega_i - M \sum_{j:s_i < s_j} \vec{d}_{ij} \times (\omega_j \times (\omega_j \times \vec{b}_{j0})) + M \vec{b}_{i0} \times (-\vec{r}_0 + \sum_{j:s_j < s_i} \omega_j \times \omega_j \times \vec{d}_{ji}) - \sum_{j:s_i \leq s_j} \vec{d}_{ij} \times \vec{F}_j
\]

(C.27)

One final simplification is to define an inertial matrix \( K \) that represents the left hand side of C.26.

\[
K_{ij} = \begin{cases} 
K_i & i = j \\
M(\vec{b}_{i0}[I] - \vec{b}_{j0}[I]) & s_i < s_j \\
M(\vec{d}_{ji}[I] - \vec{d}_{ij}[I]) & s_j < s_i \\
0 & \text{otherwise}
\end{cases}
\]

(C.28)

For the case when the system moves relative to the inertial frame, then the equations of motion have to be modified. The change comes about because of the change in the \( \vec{r}_0 \) term must be explicitly solved. The result produces a similar equation of motion as before but the \( K \) matrix is modified as follows:

\[
K_i = J_i + \sum_{k=1}^{n} \left( \vec{b}_{ik}[I] - \vec{b}_{ik} \vec{b}_{ik} \right)
\]

(C.29)

\[
K_i = \begin{cases} 
K_i & i = j \\
M(\vec{b}_{ij} \vec{b}_{ij} - \vec{b}_{ji} \vec{b}_{ij})[I] & i \neq j \\
\end{cases}
\]

(C.30)

and the new expression for \( M'_i \):

\[
M'_i = -\omega_i \times K_i \omega_i - M \sum_{j=1}^{n} \vec{b}_{ij} \times (\omega_j \times (\omega_j \times \vec{b}_{ji})) + \sum_{j=1}^{n} \vec{b}_{ij} \times \vec{F}_j
\]

(C.31)

As compared to equation C.20, the equations are similar except that the vectors \( \vec{d} \) have been replaced with \( \vec{b} \). This identifies the relationship of the bodies relative to
Appendix C. Development of Equations of Motion

the inertial frame. For the fixed frame case, a simple kinematic relationship based on
the body vectors $\mathbf{d}$ is required. For the moving frame, the $\mathbf{b}$ provides a center of mass
reference reference for the body.

These two expressions define the general equation of motion for the barriers, but
since the barriers considered herein only exhibit planar motion, the equation can be
simplified to eliminate the out of plane accelerations produced in the cross products.
For the general 3-D case, the $K$ term is a matrix of $3 \times 3$ submatrices containing the
full inertial tensor of the augmented body. When this is reduced to the planar case,
the final form for the equation is:

$$[A]\{\dot{\theta}\} + \{B\}^T\dot{\theta}^2 = [S]\{M\}^c + \{R\} \quad (C.32)$$

where $[A]$ and $[B]$ contain inertial properties of the barrier and $R$ is the external load
vector on the barrier. They are described in the following section.

C.1 Plane Motions

The system of equations for plane motions can be determined by expanding the cross
products and discarding components out of the plane of interest.

Beginning with the term $K_i$, this is a $3 \times 3$ matrix expressed in equation C.20. Only
the element $K_{i33}$ is of interest for planar motions. For the fixed frame system:

$$K_{i33} = J_{zz} + M \sum_{k=1}^{n} d_{ikx}^2 + d_{iky}^2 \quad (C.33)$$

and for the moving frame system:

$$K_{i33} = J_{zz} + M \sum_{k=1}^{n} b_{ikx}^2 + b_{iky}^2 \quad (C.34)$$

Carrying out the expressions from equation C.28:

$$A_{ij} = \begin{cases} 
M \left( b_{j0x} d_{ijx} + b_{j0y} d_{ijy} \right) & i < j \\
M \left( d_{jix} b_{i0x} + d_{jiy} b_{i0y} \right) & j < i 
\end{cases} \quad (C.35)$$
These are the coefficients for the terms with $\dot{\theta}$. Now looking towards the $M'$ term equation C.27, the first term becomes zero. The first two summation terms will expand out to produce coefficients associated with $\dot{\theta}^2$:

$$B_i = \begin{cases} -M \left( d_{ij} \dot{b}_{0y} - d_{ijy} \dot{b}_{0x} \right) & i < j \\ -M \left( b_{i0x} d_{jtx} - b_{i0y} d_{jtx} \right) & j < i \end{cases} \quad (C.36)$$

The summations in the original equations are accomplished when the matrices $[K]$ and $[B]$ are multiplied by the vectors $\{\dot{\theta}\}$ and $\{\dot{\theta}^2\}$.

The term in the braces in equation C.27 can be reduced to:

$$B_i = \begin{cases} M d_{ij} b_{0y} s_i < s_j & i, j = 1 \ldots n \\ M d_{ij} b_{0x} s_j < s_i & i, j = 1 \ldots n \end{cases} \quad (C.37)$$

Similarly, for the moving frame of reference system:

$$B_i = \sum_{j \neq i} \left( -b_{ijx} b_{jtx} + b_{ijy} b_{jtx} \right) \quad (C.38)$$

$$A_{ij} = \begin{cases} K_i & i = j \\ M \left( b_{ijx} b_{jtx} + b_{ijy} b_{jty} \right) & i \neq j \end{cases} \quad (C.39)$$
Appendix D

Barrier Testing Protocol

NCHRP Reports 230 and 350 provide guidelines for the testing and evaluation of roadside safety devices. There are different types of roadside hardware considered in these reports: breakaway poles, crash cushions, work zone traffic control structures, etc. The highway barriers utilized by the B.C. MoTH are covered by the longitudinal barrier testing and evaluation criteria.

NCHRP 230 was under review when this research program began. Final release of the test protocol in NCHRP 350 was not released until 1993, at which time the test portion of the program was completed. Thus, NCHRP 230 was used as the guideline for the research herein.

It is important to note that the research herein was not restricted to the test conditions of NCHRP 230 and is reflected by the different test speeds, angles and vehicles described in Chapter 3. Table D.1 shows the test conditions described in NCHRP 230 and 350 which are applicable to passenger vehicles. This can be used to determine the relationship between the test conditions described in Chapter 3 and these two reports.

The service levels referred to in Table D.1 were introduced in NCHRP 350. Increasing service levels indicates higher severity impacts due to the traffic characteristics of the roadway. Level 1 represents an urban environment, while level 5 represents a highway with large commercial vehicles. Level 3 represents the highest risk level roadway for passenger vehicle traffic only.

The differences between the two programs are highlighted in Table D.1. In addition to the service level definitions in NCHRP 350, it also has different vehicle sizes than
Table D.1: Test Conditions Required in NCHRP Reports 230 & 350

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<td>820</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>820</td>
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<tr>
<td>Medium</td>
<td>1023</td>
<td>n/a</td>
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<tr>
<td>Large</td>
<td>2050</td>
<td>2000</td>
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<tr>
<td><strong>Length of Need Test Conditions</strong></td>
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<tr>
<td><strong>(Speed [km/h] / Angle [deg] / Mass [kg])</strong></td>
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<tr>
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<td>96 / 25 / 2050</td>
<td>100 / 25 / 2000</td>
</tr>
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</table>

NCHRP 230. The test instrumentation, procedures, and evaluation criteria are essentially identical in the two reports. NCHRP 350 provides optional occupant risk methods to supplement the barrier assessment.
Appendix E

Determination of Static Friction Forces

The calculation of the static coefficient is derived using the impulse assumption for the static-dynamic barrier condition. Consider a barrier segment loaded by the vehicle. Figure E.1 illustrates the loading experienced by the barrier. The vehicle contact loads will be directly opposed by the friction between the barrier and road. The change in velocity of the segment, due to the 'impulse' will be in the same direction as the applied loads. The equations are simplified by the fact that all three velocities can be expressed as a function of the lateral barrier load $F_y$.

\[
\begin{align*}
\Delta \dot{x}_x &= F_x \Delta t \\
\Delta \dot{x}_y &= F_y \Delta t = \frac{m_{\text{vehicle}} F_x}{m} \Delta t \\
\Delta \omega &= \frac{a - F_y b}{J} \Delta t = \frac{F_y (a - \mu b)}{J} \Delta t
\end{align*}
\]

By calculating the friction forces acting on the segment for these velocities, (assuming the static coefficient of friction) the friction behaviour shown in Figure E.2 is found. These curves are independent of speed and thus can be assumed to represent the static friction threshold. Since the thresholds depend on the load application point, they are monitored until the static friction load is exceeded. The assumed impulse that causes the barrier segment to begin moving is calculated by multiplying the static friction threshold force by the difference between the static and dynamic coefficients of friction.

The main advantage of the impulse approach for friction is the stability it introduces into the computer model. By approximating the transition as an impulse, there is less
Appendix E. Determination of Static Friction Forces

Figure E.1: Loading Applied to Segment

Figure E.2: Friction Force Response to Moving Vehicle Loading to One Segment
chance for numerical iterations around the time of a change of the system's status. Instead, the program takes one step through the discontinuity, changes to appropriate barrier state and continues without further iterations. The developed model uses a step size limit (user supplied) to prevent excessively large impulse intervals.