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CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
UNIVERSITY OF CALIFORNIA, BERKELEY

# **Light Rail System Safety Improvements Using ITS Technologies**

**Ted Chira-Chavala, Ben Coifman, Dan Empey,  
Mark Hansen, Ed Lechner, Chris Porter**

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UCB-ITS-PRR-97-39**

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# 1. INTRODUCTION

## 1.1 PROJECT BACKGROUND AND MOTIVATION

Whenever light rail vehicles and road vehicles share an intersection, the potential for collisions between the two exists. Experience **has** shown that such collisions are a relatively common occurrence, and probably represent the single greatest hazard associated with light rail operations. Even with this problem, light rail systems are very safe, but they **can** be made safer still if means of reducing such intersection collisions can be found.

**This** report documents research whose purpose was to identify and analyze the effectiveness of countermeasures designed to reduce light rail crashes, with particular focus on collisions with road vehicles at intersections. The research was motivated by several factors. The first is the inherent significance of the problem, in terms of the number of accidents and the costs that they generate. A second motivation was the perceived range of opportunities to reduce the problem. On the one hand, this implied that the research had good prospects of yielding valuable results. On the other, it provided an instructive case study for comparing a wide assortment of countermeasures, some based on mature technologies and others involving state-of-the-art sensors and other innovations. Third, since the trajectory of the light rail vehicles are constrained to the tracks, collisions involving them can be viewed as a simple, special case of the more general vehicle collision problem. **As** such, it is an inviting proving ground for innovative collision avoidance technologies whose ultimate applicability may be far broader. Lastly, at the policy level, the topic **is** an appealing one because it promises benefits to both transit and road users.

This research focused on the Santa Clara County Transportation Agency's (TA's) light rail system. In addition to its convenient location, the system features a large number of shared intersections, and a relatively long history (operation began in **1987**) over which collision experience could be analyzed. Lastly, the TA was highly interested in the research agenda, and therefore proved to be extremely cooperative in sharing collision reports and other relevant information. The TA also participated on an Advisory Committee that met regularly to consider **findings** from the research team, assess the feasibility of alternative countermeasures, and share the TA's experiences in previous initiatives to improve the **safety** of its operations.

## 1.2 PROJECT OVERVIEW

The research proceeded in several phases. First, collision data were analyzed to assess the incidence, causes, and consequences of collisions involving light rail vehicles. This portion of the research employed a variety of statistical and analytical techniques designed to reveal the magnitude and nature of the problem. A hazard analysis revealed whether conditions such as light condition, number of lanes of cross street, and peak/off-peak period make particular

types of accidents more likely. A event tree analysis was used to identify sequences of events leading to collisions, as well as critical events that precipitate the collisions. **An** accident severity analysis used statistical methods to assess the factors that influence whether a collision results in injury or death, or only property damage. Lastly, the costs of the collisions were carefully analyzed. A combination of agency records and published literature was used to estimate costs in **17** different categories--from operator overtime to pain-and-suffering--for a representative sample of accidents. Particular attention was given to the issue of who--the transit agency **or** society at large--bears these costs, since this is critical in determining how collision countermeasures should be paid for.

In the second **phase** of the project, countermeasures were considered. This work involved **a** combination **of** extensive literature review, kinematic analysis of vehicle conflicts in light rail intersections, **and** discussions with TA staff. The literature review examined the human factors literature to better understand the nature of the safety problem at light rail intersections, and inventoried countermeasures, hard (those involving physical devices) and soft, conventional and innovative. Particular attention was given to issues of warning signal design, including modality (visual versus oral), physical characteristics, placement, and potential unintended consequences. The kinematic study focused on the conflict detection times, reaction times, and braking rates required for a motor vehicle encroaching on an intersection to stop short of the zone where **a** collision with a light rail vehicle could occur. Both the literature review and the kinematic analysis were carried out in close consultation with TA staff, who provided guidance on the practicability of the various countermeasures as well as the appropriate parameter ranges for the kinematic work.

The third phase of the project was intended to identify a recommended collision avoidance system for further development and eventual implementation. From the earlier phases of the project, it **was** recognized that critical uncertainties remained, making a definitive recommendation impossible. In particular, the effectiveness of a hypothetical system in preventing collisions proved difficult to project, since it depends how a unique population of drivers--those **who** have failed to respond to warning signals that are already in place at the intersections--will respond to an additional set of actuated warning signals. The third phase therefore focused on an economic risk analysis of a hypothetical system, whose cost and effectiveness **are drawn** from random distributions reflecting the uncertainties involved. The analysis yielded distributions of the net present value and benefit-cost ratio of implementing the hypothetical system in Santa Clara.

### **1.3 REPORT ORGANIZATION**

The following chapters document the research activity summarized above. Chapter **2** documents the accident analysis, including the hazard analysis, event tree analysis, and collision severity analysis. Chapter **3** considers the economic costs of light rail collisions. The

kinematic analysis is presented in Chapter 4, while Chapter 5 summarizes present knowledge concerning the human factors related to light rail collisions, alternative countermeasures, and the design of warning signals. Chapter 6 documents to the economic risk analysis. Conclusions and recommendations are offered in Chapter 7.

## 2. ACCIDENT ANALYSIS

### 2.1 OBJECTIVE

The objective of the light **rail** accident analysis is to systematically determine accident causation of light **rail vehicles (LRVs)**, severity characteristics, and intervention opportunities to **reduce** the crash and injury probabilities. The analysis is **tailored** such that the results **will** provide **useful** input for developing potential accident and severity countermeasures in subsequent tasks. **To** achieve this goal, **the** analysis addresses the following **safety** issues:

- **What** are the chain of events culminating in collisions **between LRVs** and other road users? What are "critical events", which if **could** have been eliminated might have prevented the collision? What are contributing factors of such "critical events"?
- Is each **type of** accidents likely to *occur* under **all** traffic and environmental conditions, or under only some specific conditions? If the latter, what are such "hazard" conditions" for that accident **type**?
- What factors influence the likelihood that each LRV accident involvement **will** result in injuries?

### 2.2 BACKGROUND

#### 2.2.1 Right-of-way

Santa Clara Transportation Agency **began** light rail revenue service in January **1988**. The 20-mile long system **consists** of three **types** of right-of-way (Figure 2.1):

- **Nine** miles in the **freeway** median of State Routes **85** and **87** (a high-speed section).
- **Nine miles** in the medians of arterial **streets** (a low-speed section).
- **1.5 miles** on the downtown transit mall (a very low **speed** section).

Right-of-way outside the transit **mall is** a double-track line, while that on the **transit mall has** a single **track**. **These** three **types** of right-of-way are described below.

##### 2.2.1.1 Freeway Median

This **nine miles** of high-speed operation **is** in the median of State Route **85** and **87**, **south** of the San **Jose CBD**. **It was** opened in **summer 1991**. It is grade-separated, with a 55-mph *speed* limit for LRVs.

### 2.2.1.2 Arterial Median

About nine miles of the light rail track is in the median of two-way arterial streets. The track for this right-of-way is separated from general traffic lanes by curbs or permanent barriers. There are a total of 41 at-grade intersections along this section. One subsection, about one mile long and extending from the freeway trackage to south of the transit mall has 6 signalized at-grade intersections. The speed limit for LRVs on this subsection is 30 mph. The second subsection, which extends northward from the mall to the end of the line, is about 8 miles long with 35 signalized at-grade intersections. The speed limit for LRVs is 30 -35 mph.

### 2.2.1.3 The Transit Mall

The 1.5-mile transit mall section was opened in June 1988. It forms a loop in the center of the San Jose CBD. Streets on the mall are one-way streets. The light-rail track runs on the rightmost side of one-way streets. LRVs and automobiles travel in the same direction, with the former to the right of the latter. There are 10 signalized at-grade intersections and several driveways along this section. Speed of LRVs on the transit mall is limited to 10 mph to accommodate mixed flow of pedestrians, automobiles, and LRVs. The transit mall serves as the major transfer point between light rail and bus services.

## 2.2.2 Traffic Control Devices

Traffic control devices for the arterial-median and the transit mall right-of-ways are described below.

### 2.2.2.1 Arterial Median

Traffic control devices for at-grade intersections along the arterial-median section are shown in Figures 2.2 and 2.3. They typically consist of

- a) LRVs are controlled by red/yellow/white "T" signals on the near side of the intersection and a white "T" on the far side of the intersection. The cycle phasing provides a priority to an approaching LRV over the general traffic.
- b) At intersections where left turns are permitted for vehicles traveling in the lanes parallel to the track, left turns are controlled by turn-arrow signals. In addition, there are active signs installed in the median of the parallel roadway that flash "Trolley Coming" in white to warn motorists whenever a LRV is approaching the intersection. The signal phasing usually provides leading left-turn phasing for left-turning motorists. However, when a LRV approaches an intersection, this usual cycle phasing is interrupted and the leading left-turn phase is skipped just for that cycle. This is to allow the approaching LRV to go through the intersection without delay.
- c) Static yellow train-crossing symbols are displayed at all approaches to each intersection.

### 2.2.2.2 The Transit Mall

At-grade intersections on the transit **mall** are controlled by traffic control devices (Figure 2.4) as follows:

- a) LRVs are controlled by white **"T"** signals.
- b) For motor vehicles in **the** adjacent lane, an active **"No Right Turn"** sign in the median **flashes** (in white) **whenever** a LRV is approaching the intersection.
- c) Static trolley **crossing** symbol and **"No Turn On Red"** signs are displayed for **traffic** on **cross streets**.
- d) Driveways **on** the transit mall are **controlled** by stop signs. Static trolley crossing symbols are displayed **at** driveway locations. Some busier driveways also have active **"No Right Turn"** signs displayed on the **street**.

### 2.2.3 Light Rail Vehicles (LRVs)

The Santa Clara Transportation Agency has 50 light **rail cars** in **service**, each is 88 **feet** long. Up to three **cars** **can** be connected into a train by a single articulation. Each **train** has a control **cab** on either end. **Typical** trains **consist of** two **cars** during **peak** hours and a single **car** during **off-peak** hours.

Each LRV **has** two digitized horns (**high** and low pitch) and **two** digitized bells (**high** and low pitch). The former is sounded in emergency, and the latter when a LRV approaches an intersection. Each LRV **is** equipped with three levels of braking: friction **disk** brakes, regenerative braking, and a magnetic track brake. Under normal operating conditions, a LRV **can** decelerate at 3.5 mph/s. In **an** emergency, the train **can** decelerate at **7** mph **per** second on a level, **dry track**. **Maximum** braking **can** be achieved by moving the control lever to the **MB** (Maximum Braking) position, or by **pressing** the emergency brake button. A LRV operator **could** apply the **MB** brake and proceed **without** stopping. The emergency brake disables the control lever to bring the train to a complete stop-

In addition to **LRVs**, the agency also operates historic trolleys on the transit **mall** on weekends and holidays.

### 2.2.4 System Operation

The light **rail system** operates at 10-minute headway during the **peak period**, 15 minutes during mid-day and **early evening**, and **half** an hour after 8:30 pm. Since the **start of** revenue service in 1988, the only **change** in **service** headway took place in 1991 when midday **service** was changed from 10-minute to 15-minute headway.

## 2.2.5 Chronology of Traffic-Engineering Improvements

Since the **system** inception, **several** traffic-engineering improvements have been implemented or tested to assure safe, smooth **LRV operations**. They include the following:

### Start-up

- e Active "No Right Turn" signs were installed at intersections **on** the transit **mall**.
- e Static **trolley** crossing signs were installed at intersections.
- e Annual operator training **using** the Smith **System of** defensive driving was adopted.

### Nov 1987

- e Three-colored "T" signals **on** the far side of arterial median intersections were changed to a single white "T", and the **near** side three-colored "T" signals were louvered.

### Late 1988

- e Static **left** turn crossing signs (arrow across tracks) were installed at intersections with median trackage.
- e Additional pavement markings were painted on the turn lane ("RXR").

### Early 1989

- e Active "Trolley **Coming**" signs were **installed** at Karina court.

### Aug 1989

- Active "Trolley **Coming**" signs were **installed** at intersections systemwide.

### 1989

- The air horn was changed **from** a heavy-truck-like to digitized train horn.
- **Mars** lights (a bright, oscillating light) were **installed** on top **of** two **LRVs**.

### 1990

- Programmed visibility signal **heads** were experimented on through lanes.

### 1991

- Reflectorized **tapes** were **installed on** two **LRVs**.



## 2.2.6 Accident Experience

### 2.2.6.1 Accident Involvement

Between 1988 and 1993, there were 157 accidents involving LRVs and motor vehicles or pedestrians/bicyclists occurring on the median right-of-way and the transit mall. There have been virtually no LRV crash involvement on the freeway section. Table 2.1 shows the numbers of LRV accident involvement by the accident type and year. Definitions of accident types follow.

- **Left-Turn Accidents.** These are collisions between LRVs and motor vehicles traveling in the same direction, as the latter attempts to turn left at intersections.
- **Right-Turn (Perpendicular) Accidents.** These only occur along the transit mall where the light rail track runs on the rightmost side of one-way streets. They are collisions between LRVs and motor vehicles traveling in the same direction, as the latter attempts to turn right at intersections.
- **Right-Angle Accidents.** These are collisions between LRVs and motor vehicles traveling on the cross street.
- **Driveway Related Accidents.** These collisions usually occur on the transit mall, and involve LRVs and motor vehicles entering or exiting parking garages.
- **Pedestrian Accidents.** These are accidents in which pedestrians are hit by LRVs.

Table 2.1 indicates that left-turn accidents are by far the most dominant accident type, and they account for about 66 percent of total LRV accident involvements in Santa Clara.

### 2.2.6.2 Accident Involvement Rate per Train Mile of Service

Figure 2.5 shows trends of LRV accident involvement rates (per train mile of service) for the median right-of-way and the transit mall between 1988 and 1993. The figure indicates that the total accident involvement rate substantially decreased over time, from about 61 accidents per million train mile of service to about 33 accidents per million train mile of service. This reduction came about primarily as a result of the reduction in the rate of left-turn accidents over time.

### 2.2.6.3 Accident Involvement by Location

Figure 2.6 shows the number of LRV accident involvement at various at-grade intersections for 1988-1993. The figure indicates that most at-grade intersections had fewer than 0.5 accidents per year, and that intersections experiencing relatively higher number of accidents had fewer than 1.5 accidents per year.

## 2.3 RESEARCH METHODOLOGY

The *safety* analysis is divided into **two** components: the accident causation analysis and the accident **severity** analysis. The methodology for each is described below.

### 2.3.1 Methodology for Accident Causation Analysis

The accident causation analysis **aims** to determine a **chain** of events **leading** up to each LRV accident involvement, "critical events", and intervention opportunities. We take a view that if at least one of the "critical events" could have **been** avoided or eliminated (by a countermeasure), then the accident could have **been** prevented.

The accident causation analysis consists of two analysis **steps** as follows. In **Step 1**, a statistical analysis of accident data is performed to determine whether there **exist**, for each accident type, some traffic and environmental conditions particularly conducive to its occurrence. If *so*, these traffic and environmental conditions (to be called "hazard" conditions) are identified. In **Step 2**, a case-by-case in-depth examination of each accident within **each** identified "hazard" condition is performed to determine a **chain** of events leading up to the accident. Next, "critical events" **as** well **as** intervention opportunities are determined **from this** identified **chain** of events. Finally, patterns of "critical events" for each accident **type** are determined.

#### 2.3.1.1 Step 1: Identify "Hazard" Conditions for Each Accident Type

Knowledge of "hazard" conditions for each accident **type** (if any) **will** facilitate the development of accident countermeasure strategies in later *tasks*. For example:

- If a certain accident **type** is **known** to occur under all traffic and environmental conditions, then potential accident countermeasures would be required to be **effective** under **all** conditions. **On** the other hand, if a *certain* accident **type** is likely to occur only under a specific condition, then potential countermeasures could be narrowly targeted for that "hazard" condition alone.
- Comparison of probable causes of each accident **type** between Merent "hazard" conditions **would** allow **us** to systematically estimate the accident probabilities, which **may** differ under different "hazard" conditions. **This** in turn could greatly **sharpen** the quantification of the potential **benefits** **of** countermeasures.

The **method** used for **determining** whether "hazard" conditions **exist** for each accident type is a multivariate analysis of discrete events. The dependent variable is the accident **type** (V1), which is defined to have **three** levels: left-turn, right-angle, and other collisions. We limit accident types to **just three** levels here to assure *reasonable sample sizes* for the cells of the contingency table (the data input for the analysis). Such a restriction **does** not apply to other subsequent accident analysis *tasks*.

**Three** candidate independent variables related to the **traffic** and environmental conditions **will** be *examined* in the multivariate analysis. They are:

**V2:** Light condition (daylight or night).

**V3:** Number of lanes of the **cross street** ( $\leq 4$  lanes or  $> 4$  lanes), a proxy for the **traffic** volume at the intersection.

**V4:** **Peak** or off-peak **traffic** period.

The multivariate analysis requires data input in the **form** of a contingency table of the accident frequency, **crossed** classified by the dependent and independent variables.

A multivariate model for a 4-dimensional contingency table for the abovementioned **V1** through **V4** *can be* mathematically expressed below. **Details** of such models *can* be found in Bishop, Fienberg, and Holland (1975).

$$\log(m_{ijkl}) = u + u_1 + u_2 + u_3 + u_4 + u_{12} + u_{13} + \dots \quad (1)$$

where:

$i,j,k,l$  designate the levels of **V1**, **V2**, **V3**, and **V4**, respectively.

$m_{ijkl}$  are estimated cell frequencies;

$u$  is a constant term;

$u_1$  through  $u_4$  are **main** effects of **V1** through **V4**, respectively;

$u_{12}$  is a two-factor interaction between **V1** and **V2**;

and so on.

The interpretation of the model is as follows. **An** estimated model that does not contain any interaction between the accident **type** and at least one of the independent variables **will** indicate that crashes within each accident **type** are distributed at random among **all** conditions (made up of **V2** through **V4**). **This** in turn implies that there **is** no particular "hazard" condition existed **for** any accident **type**, and ~~that~~ crashes within each accident **type** *occur* under all conditions. In **this** case, a potential accident countermeasure may be targeted for **all** traffic and environmental conditions. **On the other hand**, if any interaction term between the dependent variable and at least one independent variable is found to be statistically significant, then **crashes** within each accident **type** are not distributed **at** random, but are dependent on specific levels of that independent **variable**. **As** an illustration, if  $u_{12}$  **is** found to be statistically significant, then it implies ~~that~~ crashes within each accident **type** are not distributed randomly between daylight and night-time in the same proportion as the exposure. In **this** case, **either** daylight **or** night-time **has** to exhibit an over-representation of crashes, and a potential countermeasure *can* be targeted just for the condition exhibiting accident over-representation, or the "hazard" condition.

### 2.3.1.2 Step 2: In-Depth Accident Causation Analysis

In Step 2, a sample of accidents within each identified "hazard" condition (if any) are selected for case-by-case in-depth accident analysis. This in-depth analysis involves an accident reconstruction for each accident using whatever information available from hard-copy LRV accident reports. For each accident, an "event tree" diagram similar to the fault-tree technique (2) is constructed to:

- e Chronicle movements of the LRV and road users involved in each accident, actions of the LRV operator and road user prior to the crash, and status of the traffic control devices.
- e Demonstrate a sequence of events leading up to each crash, in a chronological order.
- Identify "critical events" for the accident from the above sequence of events.

After "event tree" diagrams are constructed for all individual sampled accidents within each accident type, then patterns of "critical events" for that accident type, as well as their contributing factors, can be determined. These "critical events" will provide input for developing intervention strategies.

### 2.3.2 Methodology for Accident Severity Analysis

#### 2.3.2.1 Model Specification

It is well established in the literature that the likelihood of an occupant involved in a traffic accident sustaining injury is influenced by a number of factors. The dominant factor is the magnitude of force acting on the occupant during the impact, for which "Delta-V" is often used as a surrogate variable. Delta V is defined as the change in vehicle velocities before and after the impact. A higher Delta V value implies a greater force, and thus a higher injury probability. Delta V for each vehicle involved in a two-vehicle collision is expressed as:

$$\begin{aligned}\Delta V_1 &= V_c \times M_2 / (M_1 + M_2) \\ \Delta V_2 &= V_c \times M_1 / (M_1 + M_2) \quad \dots\dots\dots (2)\end{aligned}$$

where:

$\Delta V_1, \Delta V_2$  are Delta V values for Vehicles 1 and 2, respectively;

$V_c$  is closing speed between the two vehicles prior to impact;

$M_1, M_2$  are masses of Vehicles 1 and 2, respectively.

Other reported factors that influence the likelihood of injury include: direction of vehicle movements before impact; vehicle type; occupant seating relative to the impact point; restraint usage; occupant characteristics (e.g., age, gender, size).

Logit models are frequently **used** to estimate statistical models of accident severity from accident data. Here, a **binary** logit model is **used** to express the probability of a LRV accident resulting in injury as a function of influencing variables, as follows:

$$P(D=1|\text{accident}) = [1 + \exp(a_0 - a_1X_1 - a_2X_2 - a_3X_3)]^{-1} \dots (3)$$

$$P(D=0|\text{accident}) = 1 - P(D=1|\text{accident}) \dots (4)$$

$P(D=1|\text{accident})$  is probability that the accident results in injury;

$P(D=0|\text{accident})$  is probability that the accident does not result in injury;

$a_0, a_1, \dots$  are estimated coefficients;

$X_1, X_2, \dots$  are independent variable 1, 2, ...

The probability of injury estimated from a logit model ranges from **zero** to 1.0. A **zero** value implies that the accident is **certain** to result in no injury, while a value of 1.0 implies that the accident is **certain** to result in occupant injury. **Most safety** researchers have **used** a probability of 0.5 as the dividing line between expected injury and no injury. That is, if an estimated probability of injury is higher than 0.5, then the accident is expected to result in occupant injury. On the other hand, if an estimated probability of injury is less than 0.5, it is expected that the accident does not result in occupant injury.

### 2.3.2.2 Goodness-of-Fit

For logit models, a "likelihood ratio statistic" (LRS) indicates whether a **set** of independent variables included in the model is statistically significant. A LRS is expressed as:

$$LRS = -2[\ln L(a_0) - \ln L(a_0 - a_1X_1 - a_2X_2 - \dots)] \quad (5)$$

A LRS does not indicate how well the estimated model predicts the observed severity of each accident. **This** can be achieved by comparing, for each accident, the estimated probability with the observed severity. **An** overall predictive capability of the model can then be calculated from Table 2.2.

In Table 2.2, "a" and "d" are the **number** of accidents for which **their** severity levels are **correctly** predicted by the estimated model. **On** the other **hand**, "b" and "c" are the number of incorrect predictions (i.e., the estimated probabilities of injury do not match the observed **severity**). The percent of total **correct** predictions is (a+d) divided by (a+b+c+d). The higher **this** percent of **correct** predictions, the better predictive **power** the estimated model will have.

## 2.4 RESULTS OF ANALYSIS OF "HAZARD" CONDITIONS

The analysis of "hazard" conditions was **performed** on **157 LRV** accidents, which have complete information on **all** four abovementioned variables. These represent about **93%** of **all LRV** accidents for **1988-1993**.

The **analysis** results reveal that, **of the three** candidate independent variables, the **peak/off-peak** variable (V4) was found **to** be not statistically significant in the presence of the other two independent variables. Therefore, **V4** was excluded **from further** multivariate modeling.

The model estimation yields the following "best" **fitted** model:

$$\text{Log}(m_{ijk}) = u + u_1 + u_2 + u_3 \quad (6)$$

where  $u_1$ ,  $u_2$ , and  $u_3$  **are** the **main effects** of the accident *type*, light condition, and number of lanes of **cross street**, respectively. No interaction term (of any order) among V1, V2, and V3 was found **to** be statistically significant. **This** estimated model implies that accidents within each accident type *occur* at random under all conditions (made **up** of the light condition and number of lanes of the **cross street**). Therefore, it was concluded that no **special** "hazard" condition existed for any accident type.

## 2.5 RESULTS OF IN-DEPTH ACCIDENT CAUSATION ANALYSIS

**Based** on the above "hazard" condition analysis results, we selected a sample of LRV accidents within each accident **type** for case-by-case in-depth accident analyses. The number of accidents sampled within each accident **type** is shown in Table 2.3. The results are presented below by the accident **type**.

### 2.5.1 Left-Turn Accidents

As previously mentioned, left-turn accidents are by far the most common, accounting for **101** out of a total of **157** accidents (about **64%**). Figure 2.5 previously indicated that since the **start** of revenue **service**, the left-turn accident rate (per train mile of **service**) has steadily and substantially declined. **Reasons** for such a trend include the following. **First**, there was likely to be the "**learning curve**" for both motorists and LRV operators; the Santa Clara Transportation Agency and the City of San **Jose** also share **this** sentiment. **Second**, the **Santa Clara** Transportation Agency and the City of San **Jose** have been implementing numerous **curt —e—** efforts to **try** to reduce left-turn accidents **since** the **system** inception. **These** countermeasures might have cumulative impact on **left-turn** accidents.

Twenty-wen of these **109** left-turn accidents (or **25%**) were randomly selected for case-by-case in-depth analyses. **An** example of an event **tree** for one such accident is shown in Figure 2.7.

Examinations of the results of the indepth accident analysis indicate that there are four major patterns of left-turn accidents as follows:

### 2.5.1.1 Pattern L1: Left-Turn Drivers Anticipating Leading Green Signal

**Pattern 1 accounts** for 11 out of the **27** left-turn accidents analyzed (or **41%**). These accidents occurred in both daylight and nighttime, **at intersections** where the **cross streets** have four-or-fewer as well as five-or-more lanes.

Essentially, accident motorists had initially waited in left-turn bays of signalized intersections. When the traffic light for **cross-street** traffic turned red, the motorists immediately started **left** turns **against the** red turn arrow. **Because** the left-turn bay is located immediately next to the light rail track, these left-turn vehicles could instantly be on a collision course with approaching LRVs.

**In August 1989**, active "Trolley Coming" signs were installed at at-grade intersections, in an attempt to warn left-turn motorists that a LRV is approaching from behind. We performed an evaluation to determine whether these active signs resulted in a reduction in left-turn accidents (Appendix A). The results indicate that active "Trolley Coming" signs did not show statistically significant impact in reducing the number of left-turn accidents.

Examination of the 11 left-turn accidents of Pattern L1 reveals that such left-turn accidents continued to occur after the installation of active "Trolley Coming" signs. Out of the 11 left-turn accidents of Pattern L1, three occurred within an eighteen-month period before the installation of active "trolley coming" signs (an average of two accidents per year). The remaining eight accidents occurred in a four-year period after the installation of active "trolley coming" signs (an average of two accidents per year).

The indepth accident analysis results indicate that the following are common critical events for Pattern L1.

(a) One critical event is that accident motorists started to make left turns against the red turn arrow, as soon as the traffic light for **cross street** turned red. According to the information available from hard-copy LRV accident reports, these illegal turning actions were as a result of at least two contributing factors:

- Out of habit/familiarity with the leading green signal phasing, the motorists had anticipated receiving a leading left-turn green phase as soon as the signal for **cross-street traffic** turned red. However, when a LRV approached the intersection, this leading left-turn phase was skipped (while the signal for **through traffic** turned green), eliminating left-turn opportunities for motorists wishing to turn left.
- The left-turn motorists had not perceived the LRV approaching from behind or heard its bell prior to making the turn.

(b) Another critical event is that the **LRV** operator could not stop the **LRV** in time to avoid the impending collision. Total time required to stop a **LRV** consists of hazard perception, reaction, and braking times. Hazard perception time is likely to vary from operator to operator. There is not enough detail in the accident reports to determine how/when the **LRV** operators perceived the collision hazard.

#### **2.5.1.2 Pattern L2: Left-Turn Drivers Running Red Light**

Pattern L2 accounts for four out of the 27 left-turn accidents analyzed (15%). They occurred in both daylight and night-time, at intersections where cross streets have four-or-fewer as well as five-or-more lanes. These accidents involved motorists arriving at the intersection in the same direction as **LRVs**, continued into the intersection without stopping after the left-turn arrow had turned red. Such an action could instantly put the motorist on a collision course with a **LRV** approaching from behind.

One of these four accidents occurred during an eighteen-month period before the installation of the active "Trolley Coming" sign, while the other three accidents occurred during the four-year period after the installation of such signs. The results of in-depth accident analyses indicate the following critical events for Pattern L2.

(a) One critical event is that motorists approaching the intersection continued into the intersection and turned left without stopping after the left-turn arrow had turned red. According to the information on the accident reports, this is as a result of left-turn motorists had not perceived a **LRV** approaching from behind or heard its bell. In one of these four accidents, the driver actually stopped on the track after having initiated a left turn, possibly after he/she had suddenly noticed the approaching **LRV** for the first time.

(b) Another critical event is that the **LRV** operator, as with Pattern L1, could not stop the train in time. There is not enough detail in the accident reports to determine when/how the **LRV** operator perceived the collision hazard.

#### **2.5.1.3 Pattern L3: Motorists Turning Left Where Left Turn is Prohibited**

Pattern L3 accounts for eight of the 27 left-turn accidents examined (30%). These accidents involved collisions between **LRVs** and other motor vehicles travelling in the same direction, as the latter made left turns where left turns were prohibited by the display of static "No Left Turn" signs. Two accidents occurred within the first 18 months before the deployment of active "Trolley Coming" sign. The remaining six accidents occurred within four years between late 1989 and 1993 after active "Trolley Coming" sign was installed. Pattern L3 occurred in both daylight and night-time, and mostly at intersections where the cross streets with four-or-fewer lanes.

As with Patterns L1 and L2, these left-turn motorists could be on a collision course with approaching **LRVs** at the instant they initiated left turns.



The results of in-depth accident *analyses* indicate the following critical events for Pattern L3:

(a) One critical event is that accident motorists made illegal left turns *against* posted "NO Left Turn" signs, **as** a result of not perceiving a LRV approaching from behind or heard its bell. Other contributing **factors** for these illegal left turns include:

- e The motorists did not notice the "**No Left Turn**" sign, thus misinterpreting the *green signal* for through **traffic** to be for both straight and left-turn flows.
- e The motorists were distracted by other activities (e.g., looking for a **street address**, following a map, etc).
- e The motorists noticed the "**No Left Turn**" sign, but chose to make illegal **left** turns anyway.

(b) Another critical event **is** that the LRV operator could not stop the LRV in time. There is not enough detail in the accident reports to determine when/how the LRV operator perceived the hazard. Please note that for Pattern L3, unlike Patterns L1 and L2, the LRV operator probably had virtually no clue (or warning) about the attention of left-turning motorists. After all, left-turns were prohibited and there was no left-turn bay at the intersection.

#### **2.5.1.4 Pattern L4: Left-Turn Motorists Misunderstanding Signs, Signals, and Warnings**

Pattern L4 accounts for four of the 27 left-turn accidents examined. These collisions involved accident motorists making illegal left turns **as** a result of not understanding or misinterpreting the signal, signs, or light rail warnings at intersections. These four accidents occurred between 1989 and 1993, **in** both daylight and night-time, and mostly at intersections where the **cross streets** have four-or-fewer lanes.

The results of in-depth accident analysis indicate common critical events for Pattern L4 **as** follows:

(a) One critical event is that the motorists illegally made left turns, **as** a result of not having perceived a LRV approaching from behind. Other contributing factors include:

- e The motorists did not know **what** the white "T" signal meant, thus **starting** to make **left** turns.
- e The motorists had heard the **LRVs** bell, but mistaken the sound to come from the *car* horn of a fellow motorist **from** behind urging him/her to move forward, which he/she did.

(b) Another critical event **is that** the **LRV** operator could not stop the train in time. There is not enough detail in the accident reports to determine when/how the LRV operator perceived the collision hazard.

## 2.5.2 Right-Turn Accidents

There were 13 right-turn accidents from the **start** of revenue **service** to the end of 1993. Right-turn accidents occurred primarily on the transit **mall**, where the light rail **track** runs along the rightmost side of one-way **streets** (with general traffic travels in adjacent lanes to the left of LRVs).

Right-turn collisions involved LRVs and motor vehicles traveling in the same **direction**, as the latter attempted right-turns at intersections. In **all** right-turn accidents, LRVs approached the intersection from behind the accident motorists. **Because** the lane from which motorists make **right** turns **is** located immediately next to the **track**, the turning motorist could be instantly on a collision **course** with the LRV approaching from behind. **Therefore**, accident motorist had little time to react to the collision threat.

Table 2.1 previously showed the trend in **annual** numbers of right-turn accidents since the revenue **service** began in 1988. The table indicates that, unlike the **annual** numbers of left-turn accidents, the **annual** numbers of right-turn accidents are fairly **small**, because the transit **mall** is a relatively short section. Further, **annual** numbers of right-turn accidents have not shown a declining trend over time.

All 13 right-turn accidents were analyzed in depth. Careful examinations of these results indicate two major patterns of right-turn accidents **as** follows.

### 2.5.2.1 Pattern R1: Motorists Turning Right Against Active "No Right Turn" Signal

Pattern R1 dominates right-turn accidents, **accounting** for 11 of the 13 right-turn accidents examined (or 85%). Two common critical events for Pattern R1 are:

(a) One critical event is that accident motorists turned right **against** active signals (flashing white "No Right Turn"). **This is as** a result of the motorists not having perceived LRVs approaching from behind. Other contributing factors include :

- e Accident motorists were familiar with making right turns at intersection whenever the intersection **ahead** is clear of other vehicles and pedestrians, regardless of the **status** of the traffic control **signal**.
- e The motorists did not perceive, or **chose** to ignore, the flashing "No Right Turn" when they saw a **green** signal for through traffic.
- e The motorists followed another vehicle in front who had just **safely** made a right turn **against** the flashing "No Right Turn".
- e The motorists were distracted **by** other activities (e.g., engaged in a **conversation** with a passenger).
- e The motorists were not familiar with light **rail** operations that share **streets** with the general **traffic**. For example, one motorist did **see** a LRV behind her, but

mistakenly thought that she had the right of way **because** she was **ahead** of the **LRV**.

(b) Another critical event is that the **LRV** operator could not stop the **LRV** in time. **This**, plus the **fact** that LRVs usually travel at about 10 mph on the transit mall, suggests that the total hazard perception and reaction time for the **LRV** operator was probably very **small**. There is not **enough** detail in the accident reports to determine how/when the operator perceived the **hazard** prior to the collision.

### 2.5.2.2 Pattern R2: LRV Swinging Out While Turning at Low Speed

Pattern R2 occurred much less frequently than Pattern R1 (only **two** of the 13 right-turn accidents). These two accidents occurred while the **LRV** and motor vehicle were rounding the corner, and the rear of the **LRV** swung outward and hit the vehicle turning right alongside the **LRV**. "Swing-out" is an inherent vehicle design property for long vehicles in low-speed turning.

Critical events for Pattern R2 include:

(a) One critical event is that accident motorists did not perceive (or chose to disobey) the flashing "**No Right Turn**" signal which was activated for the duration required by a **LRV** to complete turning. **As** a result, the motorists had stopped only long enough to let the LRV proceed **ahead** of them. Then, they immediately followed the **turning LRVs** in the adjacent lane (while the latter were ~~still~~ negotiating right ~~turns~~ **against** flashing "**No Right Turn**" signs.

(b) Another critical event is that accident motorists probably did not know that when a LRV *turns* at low **speed**, its rear will swing outward.

### 2.5.3 Right-Angle (Perpendicular) Accidents

Right-angle accidents are collisions between LRVs and motor vehicles travelling on the *cross street*. Between the *start* of revenue **service** in 1988 and 1993, there were 11 right-angle accidents. **All** 11 accidents were analyzed in depth. **Examinations** of the analysis results indicate three major patterns of right-angle accidents **as** follows:

#### 2.5.3.1 Pattern P1: Motorists "Running" Red Light

Pattern P1 includes right-angle accidents which occurred **because** accident motorists "**ran**" the red light on the **cross streets**, entered the intersections and collided with approaching LRVs. **This** is the most common **pattern** for right-angle accidents, accounting for 82% **of all** right-angle accidents (9 out of the 11 right-angle accidents). Pattern P1 *occurred* in both daylight and night-time.

The results of the in-depth accident analysis indicate the following critical events for Pattern P1:

(a) One critical event is that accident motorists **"ran"** the red light on the **cross street**, and **started** to enter the intersection in front of **LRVs**. This is as a result of the motorists not having perceived the LRV before entering the intersection. Many stated that they perceived the **LRVs** for the first time **after** they were **already** in the intersection. Other contributing factors to **"running"** red light include:

- The motorists were **trying** to "beat" the **red** light.
- The motorists **had just** overtaken a vehicle stopping for the red light.
- The motorists were **distracted** by other activities (e.g., watching a construction crew on the side **of** the road).

(b) Another critical event is that accident motorists, after entering the intersection, could not successfully take evasive **actions** to avoid the impending collision with **LRVs**, **because**:

- e **Total** hazard perception and reaction time for accident motorists was too short to successfully brake or swerve the vehicle.
- For **some** motorists, **as soon as** they suddenly noticed approaching **LRVs**, they **sped up** in an attempt to "beat" the **LRVs**. The motorists obviously misjudged speeds of their **own** vehicles and those of the **LRVs**.
- The motorists did not take evasive **actions** while in the intersection.

(c) Another critical event is that the **LRV** operator **could** not stop the LRV **in** time. There is not enough detail in the accident reports to determine how/when the LRV operator perceived the collision hazard.

### **25.3.2 Pattern P2: Intoxicated Motorists**

One of the 11 right-angle accidents **is** a nighttime collision between a LRV and a vehicle travelling on the cross street, while the driver was dozing off. The driver was subsequently cited for driving while intoxicated. Critical events for this crash are:

(a) One **first** critical event is that the motorist went through the red light and entered the intersection at a relatively high speed, due to intoxication and fatigue.

(b) Another critical event is that the LRV operator could not stop the LRV in time.

### **25.3.3 Pattern P3: Traffic Control Signals Were Out at Night**

One of the 11 right-angle accidents examined **occurred** at night and while the **traffic** light **was** out. The LRV **operator stopped** before entering the intersection, sounded the bell, and proceeded. The operator had not seen **the** accident vehicle until after the impact. Apparently, the accident vehicle

did not have headlights on, and was approaching the intersection at a relatively high speed. Critical events for this accident are:

- (a) The **traffic** light was out. **This** made it more challenging for both the motorist and LRV operator to negotiate the intersection.
- (b) The motorist, who was travelling on the **cross street**, did not perceive **the** LRV before entering the **intersection**, possibly due to the distraction created by the out-of-order traffic light.
- (c) The motorist braked hard (~~as~~ **evident by skid marks** on the pavement) once he perceived the LRV. However, the available hazard perception plus reaction time was too **short** for him to avoid **the** collision. There **is** not **enough** detail in the accident report to determine when/how the accident motorist perceived the **LRV**.
- (d) **The** LRV operator had not noticed the motorist before and while proceeding through the intersection, possibly **because** the motorist not having his headlights on.

#### 2.5.4 Driveway Related Accidents

On the transit **mall**, there are a number of driveways located on the right side of the street next to the track. These driveways have **direct** access onto the **street**. Stop **signs** are used to control vehicles exiting driveways.

Driveway related accidents are **collisions** between **LRVs** and motor vehicles entering or exiting parking garages. ~~Between~~ the **start** of revenue service and **1993**, there were **8** driveway related accidents. Five of the eight driveway accidents were examined ~~in~~ **depth**. These **five** accidents all occurred in daylight.

##### 2.5.4.1 Motorists Entering Parking Garages

In four of the five driveway related accidents *examined*, the motorists had been traveling in front **of**, and in the same direction ~~as~~, the **LRVs**. The motorists then made right **turns** into parking garages in front of the **LRVs** approaching from behind. **This** group of driveway related accidents are quite similar to right-turn accidents at intersections. The differences between the two groups lie in the **traffic** control device **used** and the accident location (**intersection** versus mid-block). **Examinations** of the ~~in~~ **depth** accident analysis results indicate the following critical events.

- (a) One critical event is ~~that~~ accident motorists turned right to enter parking **garages** (from ~~the~~ lane adjacent to, and to the **left** of, the **light-rail track**) while **LRVs** were approaching from behind. **This is as** a result of the motorists not having perceived the **LRV** or its bell, possibly due to the following contributing factors:
  - The motorists were focusing their attention on entering parking garages.
  - The motorists were from out of town, and not familiar with the light **rail** operation.

- **The** motorists were distracted by other activities (e.g., listening to the **radio**).

(b) Another critical event **is** that the LRV operator could not stop the LRV in time (while travelling at about **10** mph). We estimated, from the accident reports, that the four accident LRV operators probably applied the brakes ~~at~~ about **5, 10, 10, and 25** feet **from** the collision points, respectively. It **is obvious** that the total hazard perception and reaction times **for** the LRV operators were too short to avoid **the impending** collisions.

#### **2.5.4.2 Motorists Exiting Parking Garages**

One **of** the four driveway related accidents occurred while a vehicle was **exiting** a parking structure and collided with a LRV. Critical events for **this** accident include:

(a) One **critical** event **is** that the accident motorist **came** out of a garage onto the light **rail track**, right in the path of **an** approaching LRV. The motorist said she had not perceived the LRV until the moment of collision.

(b) Another critical event is that the LRV operator could not stop the LRV in time (when travelling at about 10 mph). **We** estimated, **from** the accident report, that the LRV operator probably applied the brakes about **10** feet from the collision point.

#### **2.5.5 Pedestrian Accidents**

There are nine LRV-and-pedestrian accidents from the **start** of revenue *service* to the end **of 1993**. Pedestrian accidents occurred at various **locations** along the light rail system. About **50** percent of pedestrian/LRV accidents occurred on the transit **mall** which **has** high pedestrian concentration. The remaining ones occurred at light **rail stations** and intersection **crosswalks**.

Unlike accidents involving LRVs and motor vehicles, which show **easily recognizable** accident patterns, pedestrian/LRV accidents are usually unique events with diverse causation. As illustrations, four **out** of the nine pedestrian accidents were examined in-depth, and the results are presented below.

##### **2.5.5.1 Pedestrian Accident #1**

**This** accident *occurred* on the transit **mall**. A child darted out of **a** store **from** the **far** side of the **street** onto the light **rail track**, **in** the path of a **LRV**. The LRV operator applied the brakes ~~at~~ about **5 feet from** the collision point, but **could** not **safely** stop the LRV.

##### **2.5.5.2 Pedestrian Accident #2**

**This** accident *occurred* on the transit **mall**. The rear of an LRV **swung** out **while** turning at low speed, and hit a **pedestrian walking** in the same direction as the LRV. The pedestrian with

headphones on was walking **very** close to the **track**. The LRV operator was not aware **that the** LRV **had** hit a pedestrian.

### 2.5.5.3 Pedestrian Accident #3

**This** accident **occurred** **at** a light **rail** station. A pedestrian had just alighted **from** a stopped northbound LRV **at** a station. **She** was in a hurry **as** she **crossed** in front of another southbound LRV (approaching the station at about 15 mph), behind the **rear** of the train she had just alighted. The operator of the southbound **train** applied the brakes **at** about 25 feet from the collision point, but could not stop the train in time.

### 2.5.5.4 Pedestrian Accident #4

**This occurred** at an intersection. A pedestrian on a skateboard (who had been drinking) had **been** waiting in an adjacent lane to **cross** the **street** when a LRV was approaching the intersection at 30-35 mph. The pedestrian suddenly lurched in front of the approaching LRV. The LRV operator applied the brakes at about 50 feet from the collision point, but could not safely stop the train.

In all of these pedestrian accidents, the actions of accident pedestrians caught LRV operators by **surprise**, with little prior warning. **As** a result, the **LRV** operators did not have sufficient time to react to most of these critical situations.

## 2.6 RESULTS OF ACCIDENT SEVERITY ANALYSIS

LRV accidents in Santa Clara, similar to LRV accidents elsewhere **in** the **U.S.**, generally result in very few fatalities or serious injuries. In Santa Clara, about **66** percent of LRV accidents result in property damage only. The remaining 34% were reported to result in some forms of occupant injuries. Of the injury accidents, only three accidents (or **2** percent) resulted in **fatalities** (**all** of the fatal parties were pedestrians or bicyclists), **1** percent in incapacitating injuries, **18** percent in non-incapacitating, and 13 percent in claimed (not apparent) injuries.

For the accident **severity analysis**, LRV accident data from the **Santa Clara** and San **Francisco** light rail **systems** were combined. **The** San Francisco **data** pertain **to all** LRV accidents occurring in **1993**, a total of **107** accidents (Tables 2.4a and 2.4b).

### 2.6.1 The Dependent Variable

The dependent variable for the LRV accident **severity** model **is** a dichotomous variable, defined **as** follows:

Severity =     0 if accident results in no injury  
                  1 if accident results in injury.

## 2.6.2 Candidate Independent variables

As previously mentioned, evidence in the literature strongly indicates that Delta V *is* the dominant factor **affecting** the likelihood of injury in **traffic** accidents. The LRV accident data from the Santa Clara and San Francisco systems do not contain information on Delta V for the LRV or the motor vehicle. **Neither** do they have sufficient information for us to impute Delta V values. Nevertheless, the accident **reports contain** information on **speeds** before the collision for both the LRV and motor vehicle. These **two speed** variables are included in the **severity** modeling, **as** proxies for Delta V.

Altogether, candidate independent variables included in the **severity** modeling are:

- **speed** of LRV
- **Speed** of motor vehicle
- Movement of motor vehicle prior to collision
- Vehicle **type**
- Day/Night
- **Peak/Off-peak period**
- **Signalized/Non-signalized** intersection

**Information** on occupant **characteristics** was not made available to us, and thus **this** class of variables **were** excluded in the model **estimation**.

**Speed** of LRV and **speed** of motor vehicle are continuous variables, and **are** treated **as** such in the modeling.

Movement **of** motor vehicle prior to collision is defined to have three levels: the vehicle **is** traveling in the same direction **as** the LRV and making **a** left turn; the vehicle **is** traveling on **cross street** perpendicular **to** the LRV; and other kinds **of** movements. The three levels are treated in the logit modeling **as** a series of three (0,1) dummy variables. **As** required in **the** modeling, one of these three dummy variables, namely **cross-street** movement, is **omitted**.

Vehicle **type**, day/night, peak/off-peak, and **signalized/non-signalized** intersection are all dichotomous variables. They entered the modelling **as** (0,1) dummy variables.

The accident **severity modeling** was based on a total of **152** accidents **that** have complete information **on** the dependent and independent variables. The **analysis** excludes pedestrian-and-LRV accidents **because** their **severity** causation **is** considerably different from that for collisions **between** LRVs and motor vehicles. **Because** the number **of** pedestrian accidents **is** fairly small in our data **set**, a separate **severity** model for **these** accidents **was** not attempted.



### 2.6.3 Estimated Severity Model

The estimated **binary** logit **severity** model for LRV accidents includes the following independent variables: *speed* of LRV, **speed** of motor vehicle, movement of motor vehicle, and **peak/off-peak**. Table **2.5** **shows** the model estimation results.

We also assess the predictive capability of **this** estimated **severity** model, using a previously described case-by-case **classification criteria** (Table 2.6). The results indicates that, on a case-by-case basis, the estimated model correctly predicts the **severity** of **113** accidents out of **152** accidents (or **74.3%**). This is a reasonably good **correct** prediction rate for a disaggregate logit model.

### 2.6.4 Implications of the Estimated Severity Model

Figures **2.8** through **2.10** show the estimated probabilities of injury plotted **against** motor-vehicle **speed** and **LRV speed**, for **left-turn**, **cross-street**, and "other" vehicle movements, respectively. These **figures** indicate that:

(a) The probability of injury **is** influenced by the LRV **speed**, **speed** of motor vehicle, movement of motor vehicle prior to collision, and whether the accident **occurs** during the peak or off-peak period.

(b) **As** Expected, higher LRV **speed** as well as higher **speed** of motor vehicle **increase** the probability of injury. **This** is **because** higher **speeds** imply greater energy absorbed by the occupant during the impact. Of the two **speeds**, reduced motor-vehicle **speed** **can** lower the probability of injury to a greater extent than reduced LRV **speed**. For example, a reduction in LRV **speed** from **35 mph to 10 mph** **can** lower the probability of injury by about **0.15**. However, a reduction in motor-vehicle **speed** **fi-om** **35 mph to 10 mph** **can** lower the probability of injury by about **0.28**.

(c) The left-turn vehicle movement (that **leads** to left-turn accidents) **can** result in higher probabilities of injury than the right-angle (or **cross-street**) vehicle movement. **This** may be due to a **number of reasons**. **First**, left-turn drivers could be on a collision course with approaching **LRVs** the instant **they** initiated left turns fi-om left-turn bays, **because** left-turn bays are located immediately **next** to the light rail **track**. **Left-turn** accident drivers probably had little time to take evasive **actions**. **On** the other hand, accident drivers traveling on the **cross street** could have more time to **swerve** or brake hard before the collision. **Second**, **LRVs** **usually** struck motor vehicles on the driver's side in left-turn accidents, thus **making** drivers particularly vulnerable to injuries. **In contrast**, **LRVs** could strike virtually any **part** of the vehicle in right-angle accidents.

(d) Vehicles **traveling** on **the cross street** prior to collision (**that** **leads** to right-angle accidents) show lower probabilities of injury than "other" vehicle movement.

(e) Accidents occurring during **peak** hours show higher probabilities of injury than **those** during **off-peak** hours. The reason for **this** is unclear **at this** time.

## APPENDIX A

Active **TROLLEY COMING** signs were installed at *the far side* of intersections in San Jose to warn motorists traveling in the same **direction** as the LRV that an LRV was approaching the intersection. The sign is activated (i.e., lit in white) only **when an** LRV triggers the **detector** in the track on the *approach* to the intersection. **This is similar** to actuated traffic signals **where** loop **detectors** in the pavement detect the presence of vehicles.

Active **TROLLEY COMING** signs in San Jose were installed at intersections where LRVs operate in the ~~street~~ median in August 1989. The signs were installed on streets parallel to the track, **but not on** cross streets. **They** were meant to address only collisions between LRVs and left-turning vehicles. **Analysis** of the accident **data** before the installation of ~~the~~ active signs indicated that some motorists involved in accidents with LRVs made left turns against the red left-turn arrow and static **NO LEFT TURN** sign. The motorists may have been unaware of LRVs approaching from behind. It was believed that **these** active signs could provide timely warnings of LRVs to left-turning motorists.

For the effectiveness evaluation, the before period is from **January 1988** (i.e., the *start* of revenue service) to May 1989, a total of **17 months**. The after period is from October 1989 to **December 1993**, a total of **51 months**. The treatment group consists of left-turn accidents involving motorists traveling in **the** same, **as well as** in *the opposite, direction* of the LRV.

The comparison **condition** consists of other types of **collisions** between LRVs and motor vehicles not **affected** by the active **TROLLEY COMING** signs. These include: right-angle

accidents (in which the motorists traveling on cross streets which received no active signs) and right-turn accidents (along right side-running sections). The comparison condition is included to account for possible confounding effects of two external factors.

The first factor includes changes in train miles and traffic volumes between the before and after periods. Annual train miles of service increased, and the traffic volume in Santa Clara also changed during the evaluation period. The comparison condition assumes that these changes have proportionally affected the frequencies of left-turn accidents (the treatment group) and other accident types (the comparison group) over the evaluation period. The second external factor is the "learning curve" effect over time. The comparison condition assumes that the "learning curve" phenomenon equally applies to left-turn accidents and other accident types.

Period	Number of LRV Accidents	
	Left Turn	Other Accident Types
Before (1/88 - 5/89)	26	6
After (10/89 - 12/93)	72	27

$$\text{Odds Ratio} = \frac{72 \times 6}{26 \times 27} = 0.62$$

This odds ratio indicates the degree of effectiveness of the treatment as follows:

- e  $R < 1$  implies that the treatment is beneficial in reducing accidents at the *treated* intersections.
- e  $R > 1$  implies that the number of accidents increases at the *treated* intersections.
- $R = 1$  implies that the treatment has no impact (neither beneficial nor harmful).

$H_0$ :  $R = 1$  (the change has no impact on accidents)

$H_1$ :  $R < 1$  (the change has reduced the number of accidents), or  
 $R > 1$  (the change has increased the number of accidents).

$$Z_{obs} = \frac{\ln(R)}{\sqrt{\left(\frac{1}{B}\right) + \left(\frac{1}{A}\right) + \left(\frac{1}{b}\right) + \left(\frac{1}{a}\right)}}$$

When the change has no impact, and  $H_0$  is true,  $Z_{obs}$  is distributed as a standardized normal variable.

$$Z_{observed} = -0.945$$

$$Z_{critical} (0.05 \text{ level}) = -1.645$$

The evaluation results reveal an odds ratio of 0.62, which implies that the installation of active TROLLEY COMING signs has been accompanied by 38 percent fewer left-turn

**accidents** than expected. **However**, this **odds ratio** is **not** statistically **different** from 1.0. Thus the **active TROLLEY COMING signs** have **no significant impact** in reducing left-turn **accidents** in **San Jose**. The **observed** 38 percent fewer left-turn **accidents** in **the after** period was probably **due** to random **variation**.

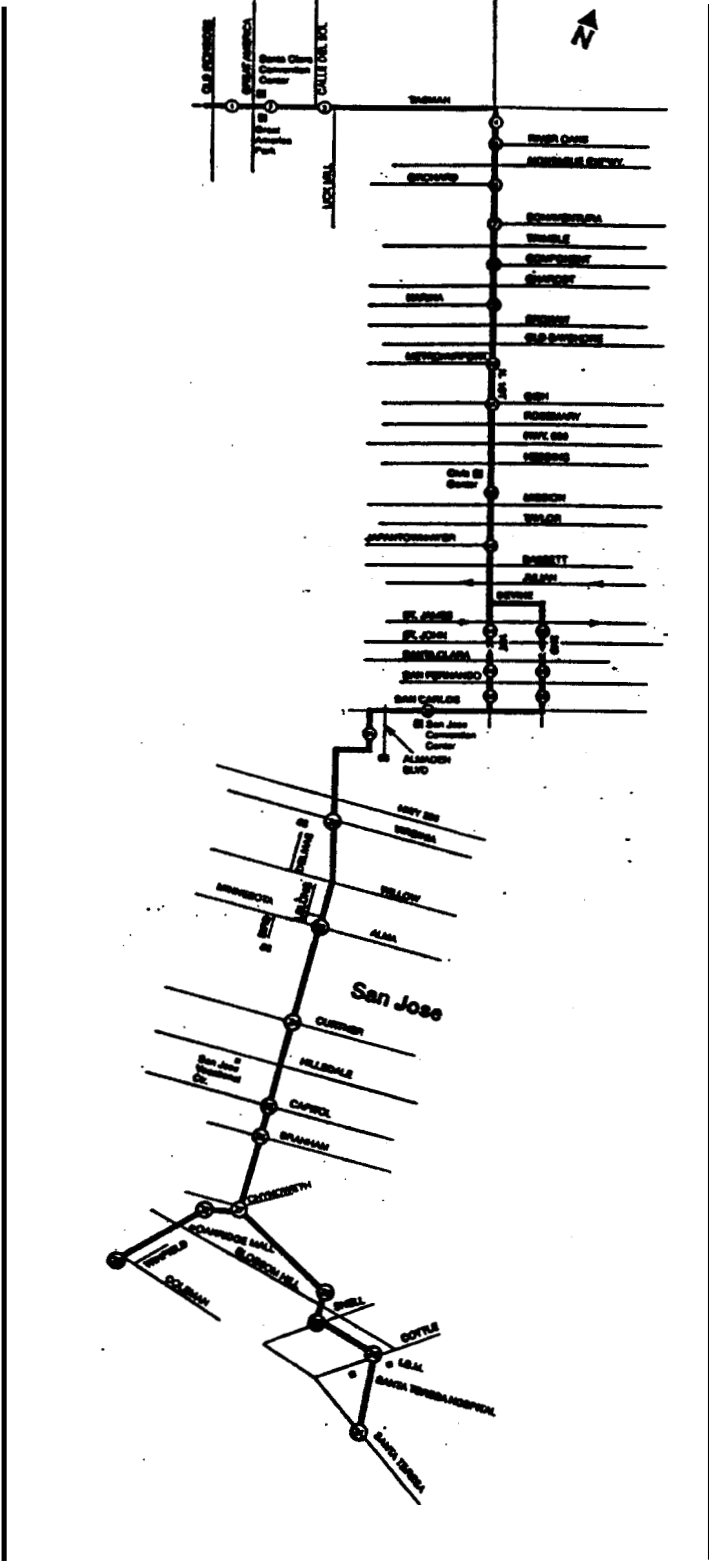


Figure 2.1 - Diagram of Light Rail System in Santa Clara

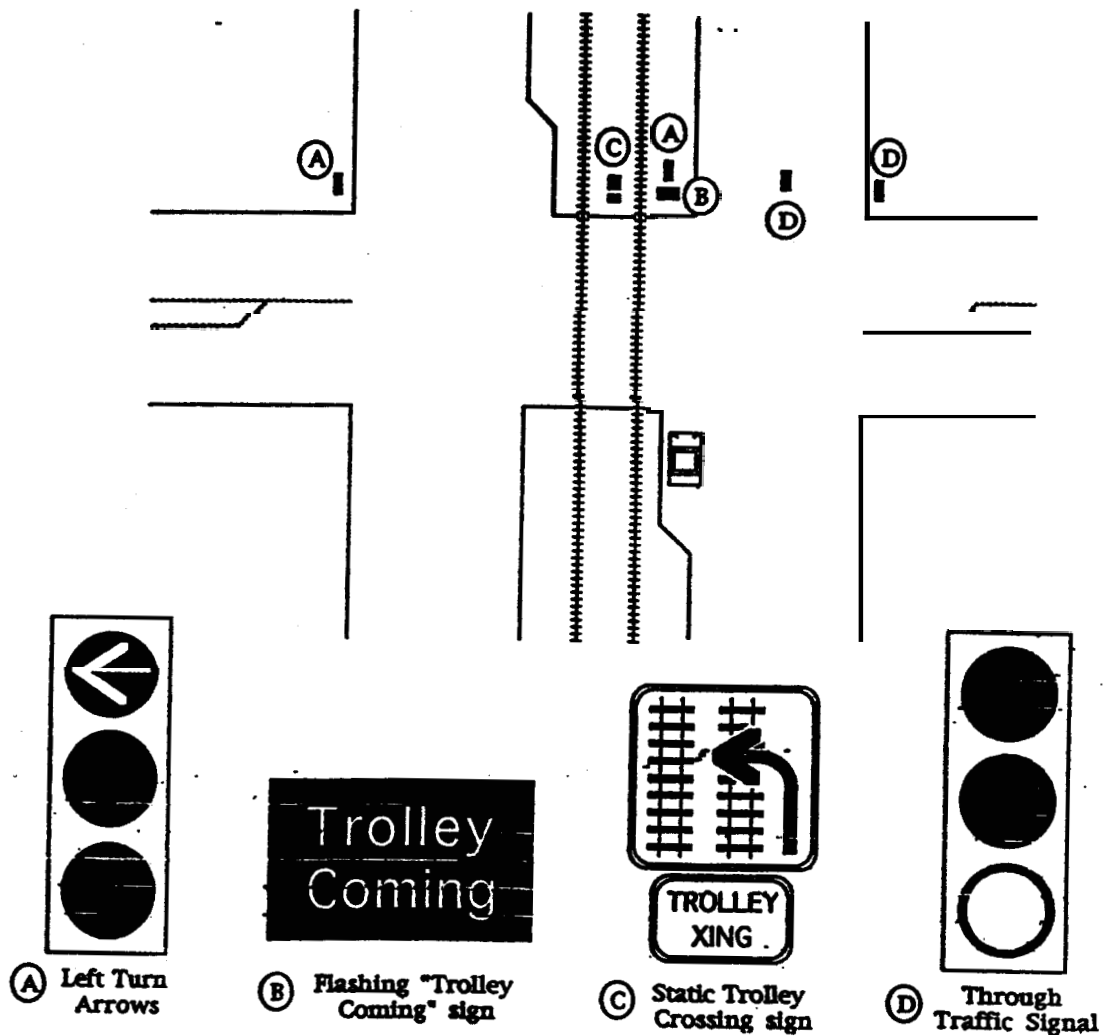


Figure 2.2 - Signs and Signals at a Typical Arterial Intersection with Median LRT Line

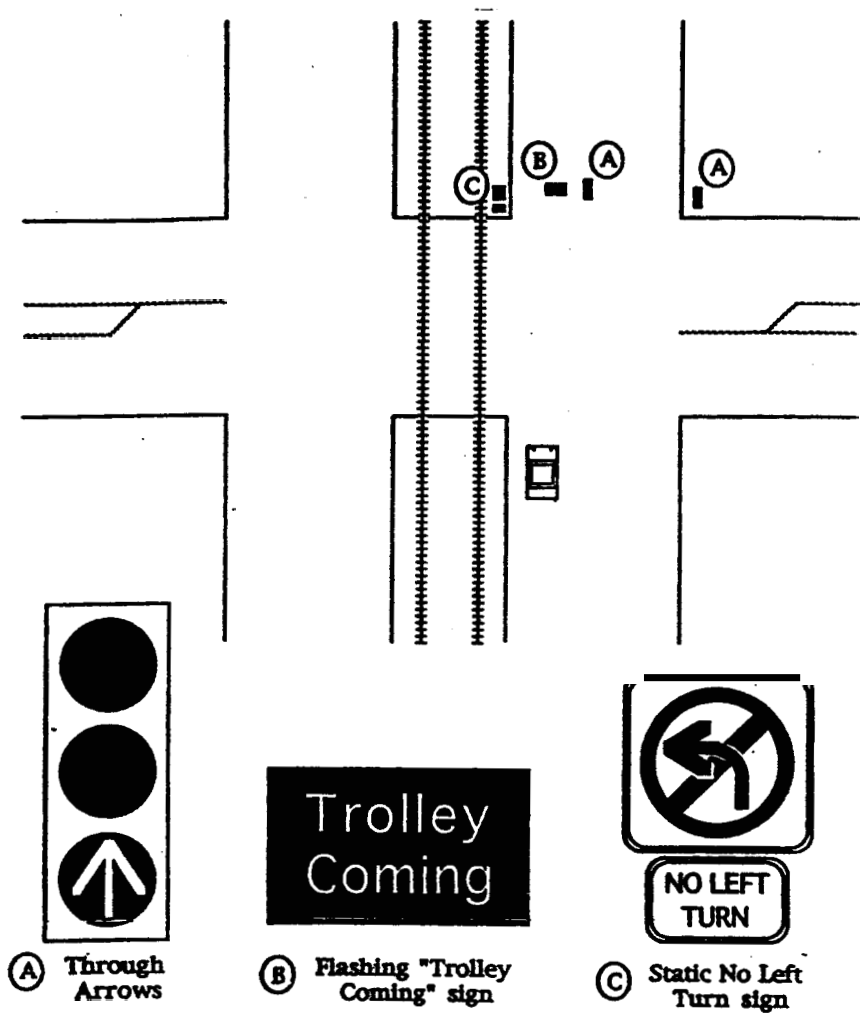


Figure 2.3 - Signs and Signals at a Arterial Intersection with LRT and No Left Turns Allowed



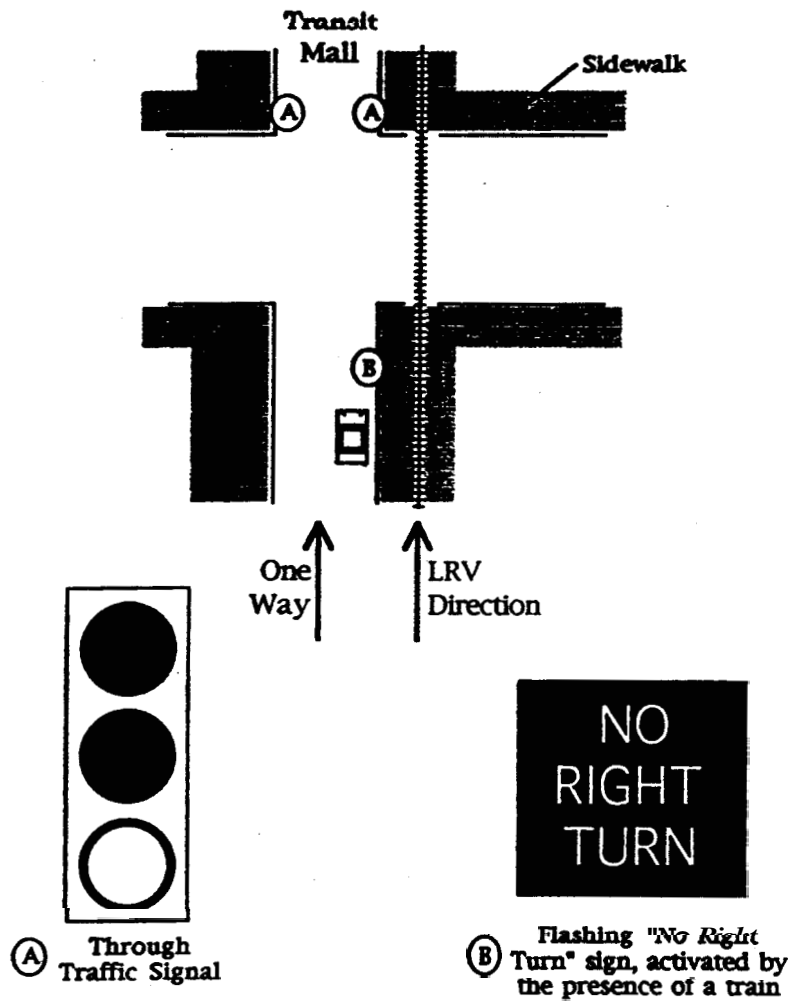


Figure 2.4 - Signs and Signals at a Typical Transit Mall Intersection

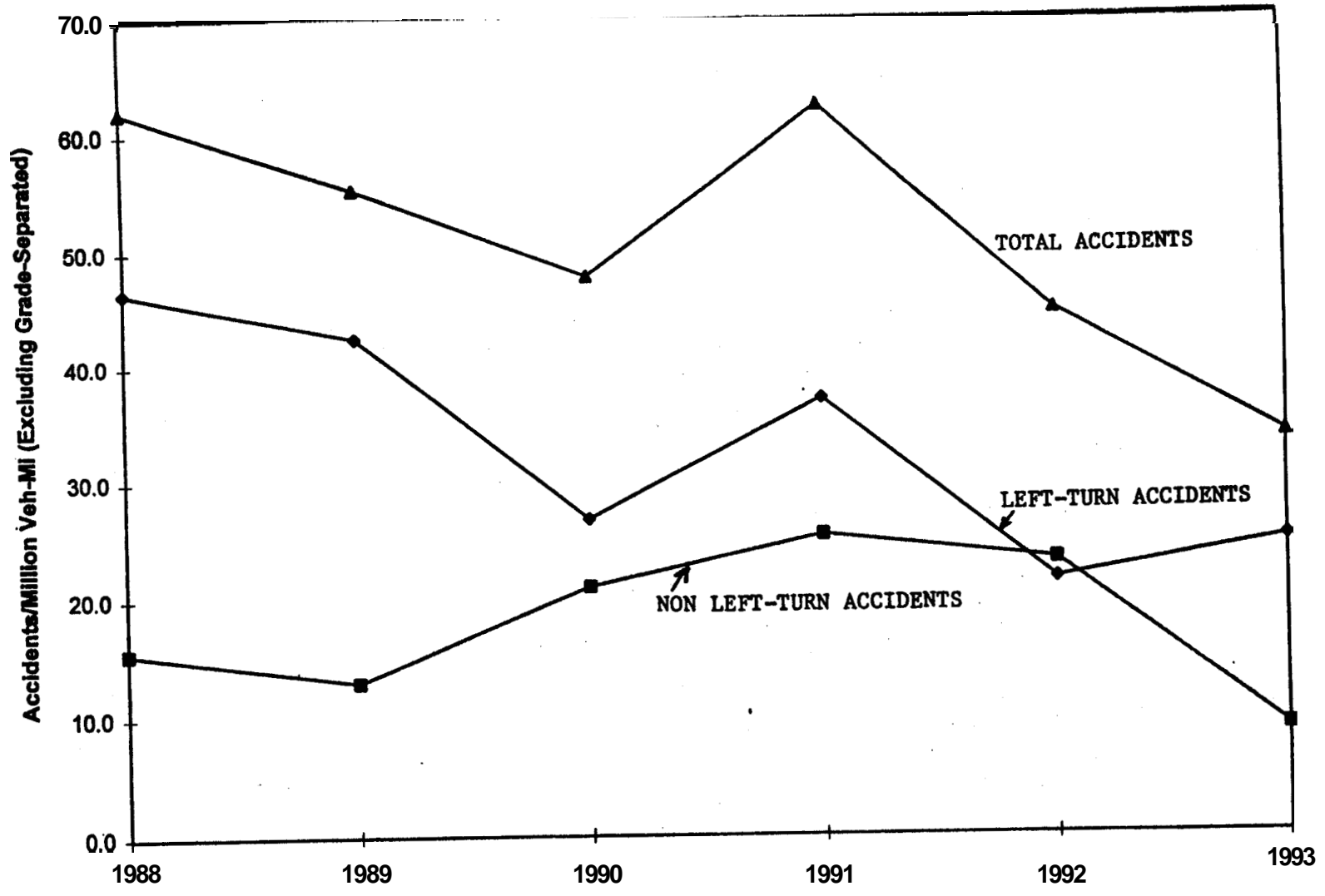


Figure 2.5 - Trends in Number of Accidents per Train-Mile of Service, 1988-1993

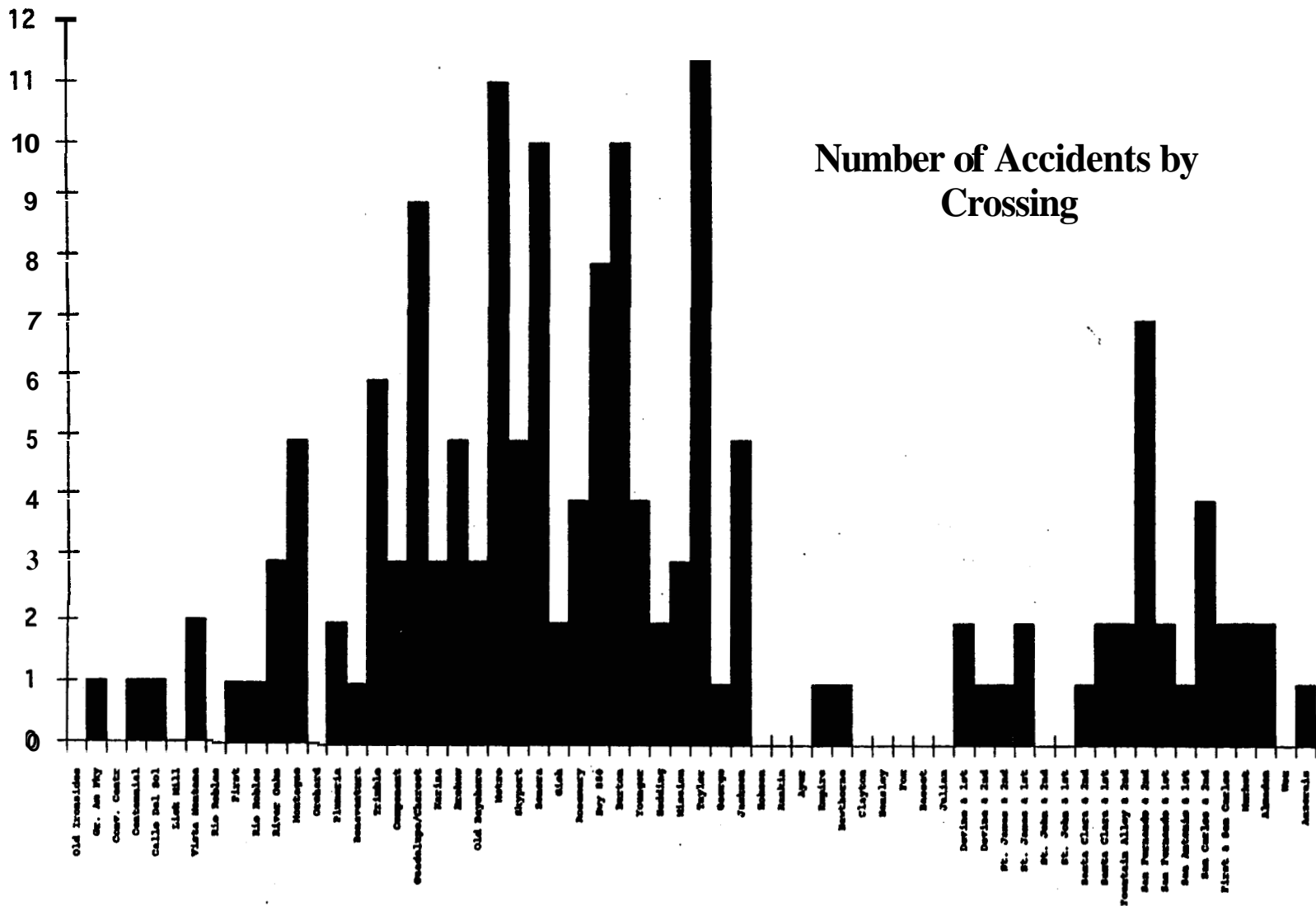


Figure 2.6 - Number of Accidents at Individual Intersections in Santa Clara

Date	time	Cross st.	Conditions
3/11/90	1:19 PM	Taylor	Day, Rain, Wet

35

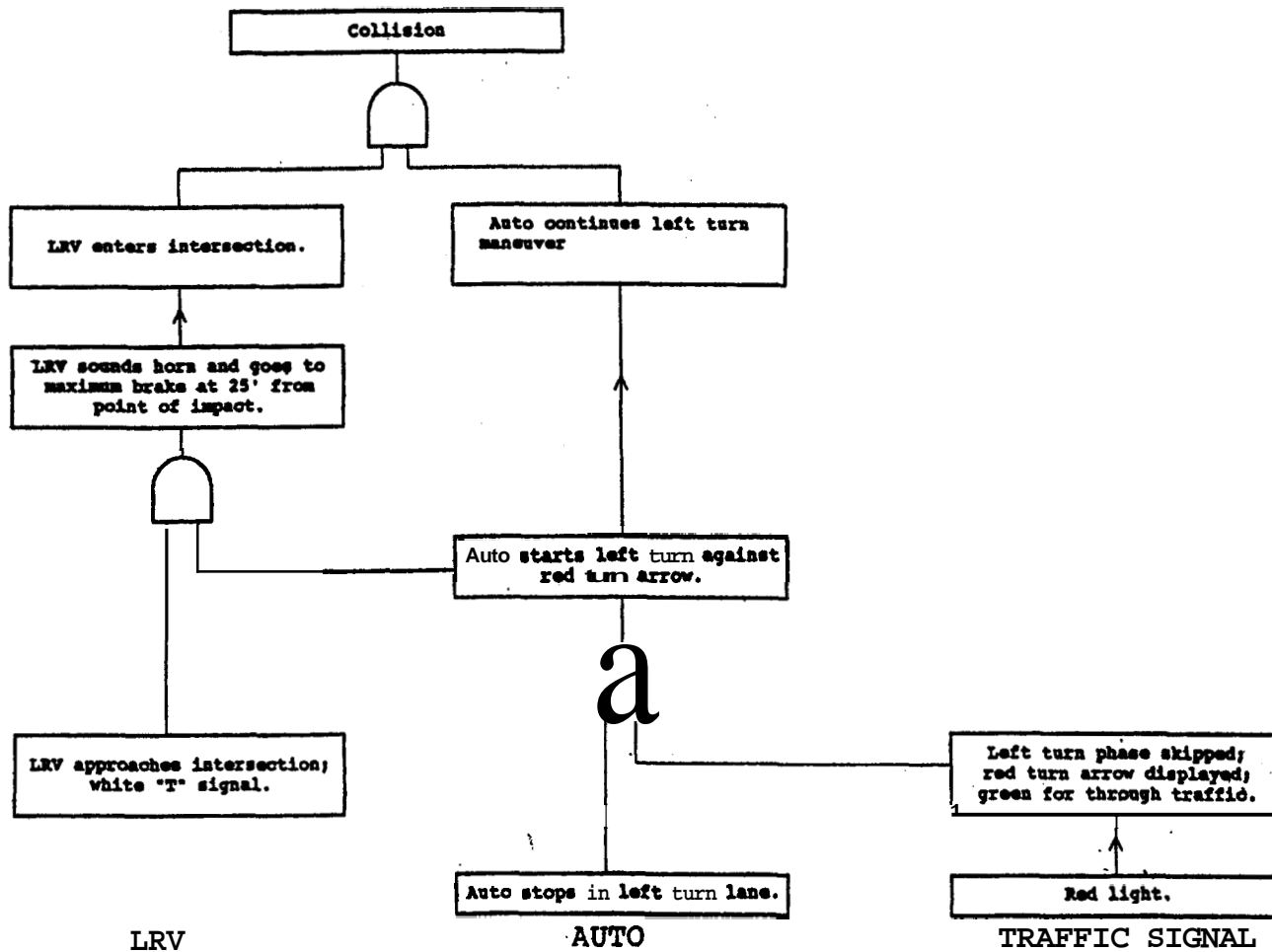


Figure 2.7 - Example of "Event Tree" for a Left-Turn Accident

$$Pr(\text{injury}) = 1/(1 + \exp(3.15 - 0.0257 \cdot \text{LRSpeed} - 0.0469 \cdot \text{VehSpeed} - 1.327 \cdot \text{LeftTurn} - 0.121 \cdot \text{OtherType} - 1.110 \cdot \text{PeakHour}))$$

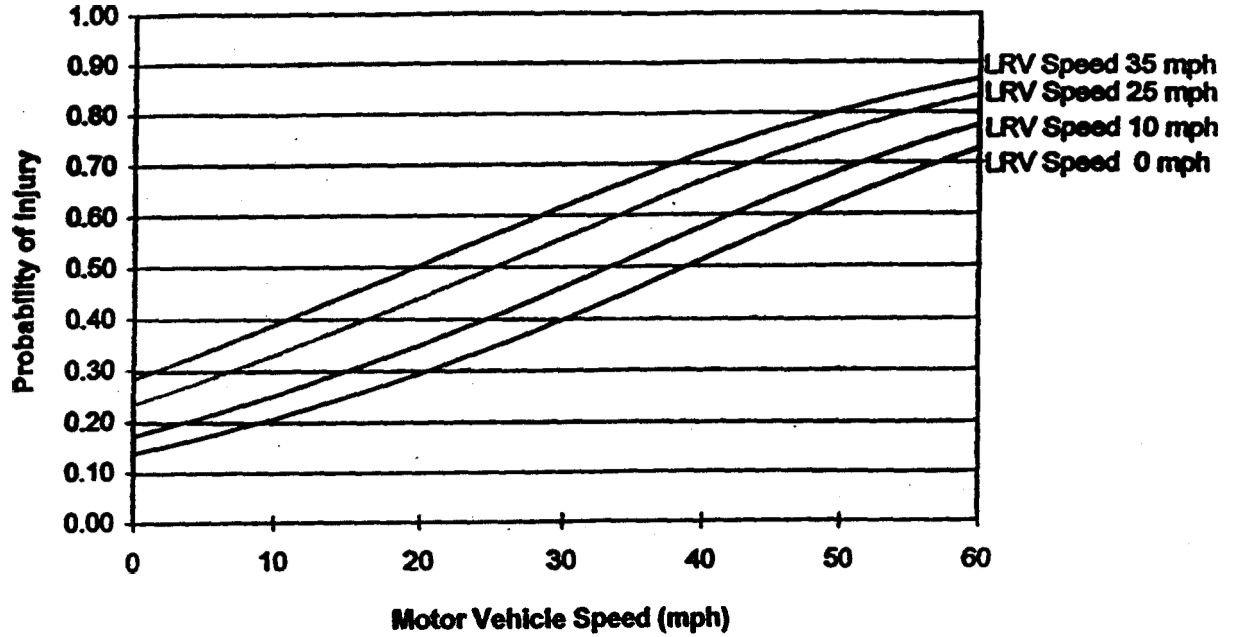


Figure 2.8a - Estimated Probability of Injury  
(Left-Turn Movement, Off-Peak Period)

$$Pr(\text{injury}) = 1/(1 + \exp(3.15 - 0.0257 \cdot \text{LRSpeed} - 0.0469 \cdot \text{VehSpeed} - 1.327 \cdot \text{LeftTurn} - 0.121 \cdot \text{OtherType} - 1.110 \cdot \text{PeakHour}))$$

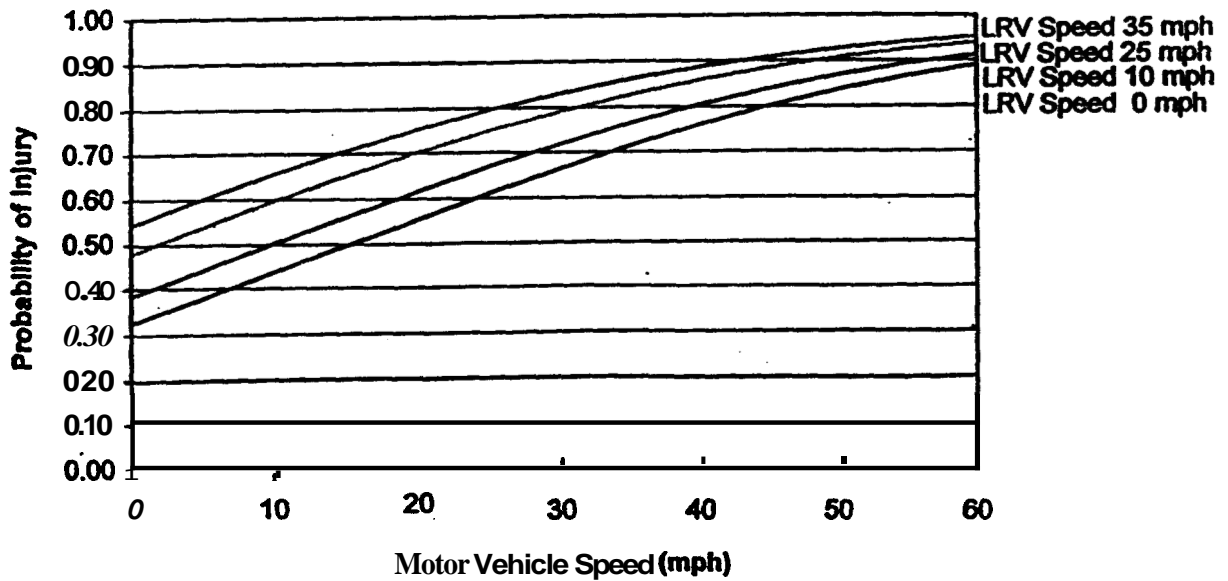


Figure 2.8b - Estimated Probability of Injury  
(Left-Turn Movement, Peak Period)

$$Pr(\text{injury}) = 1 / (1 + \exp(3.15 - 0.0257 \cdot \text{LRSpeed} - 0.0469 \cdot \text{VehSpeed} - 1.327 \cdot \text{LeRTurn} - 0.121 \cdot \text{OtherType} - 1.110 \cdot \text{PeakHour}))$$

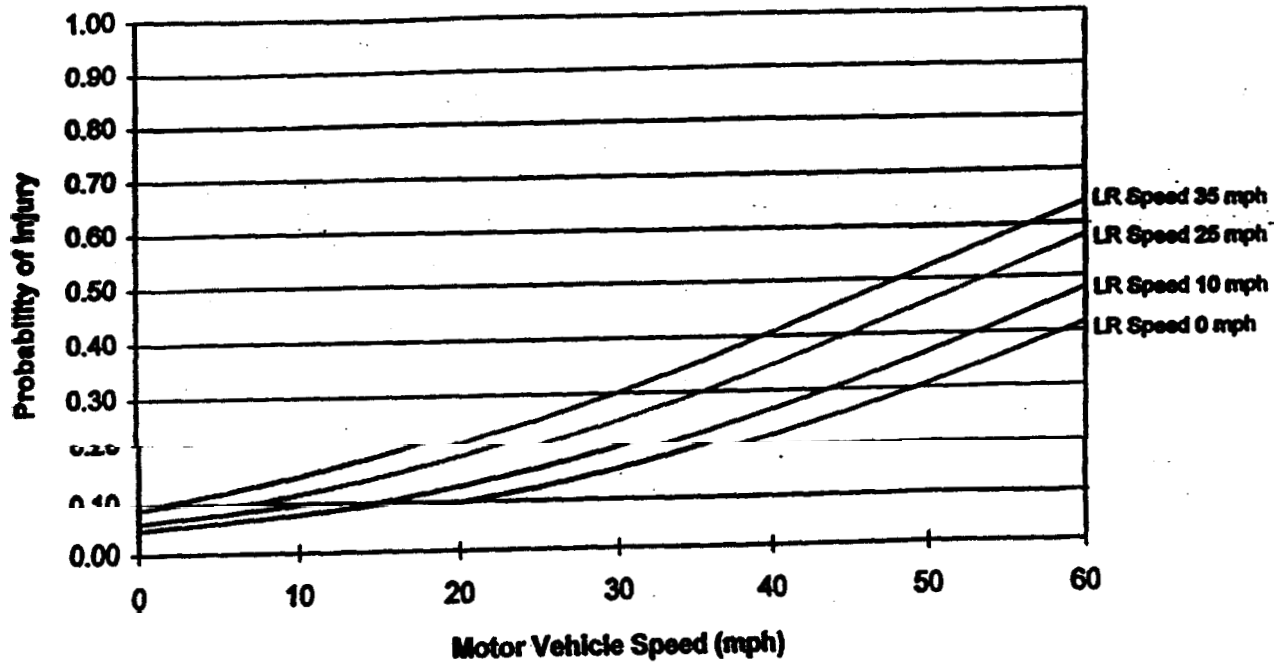


Figure 2.9a - Estimated Probability of Injury (Perpendicular Movement, Off-Peak Period)

$$Pr(\text{injury}) = 1 / (1 + \exp(3.15 - 0.0257 \cdot \text{LRSpeed} - 0.0469 \cdot \text{VehSpeed} - 1.327 \cdot \text{LeRTurn} - 0.121 \cdot \text{OtherType} - 1.110 \cdot \text{PeakHour}))$$

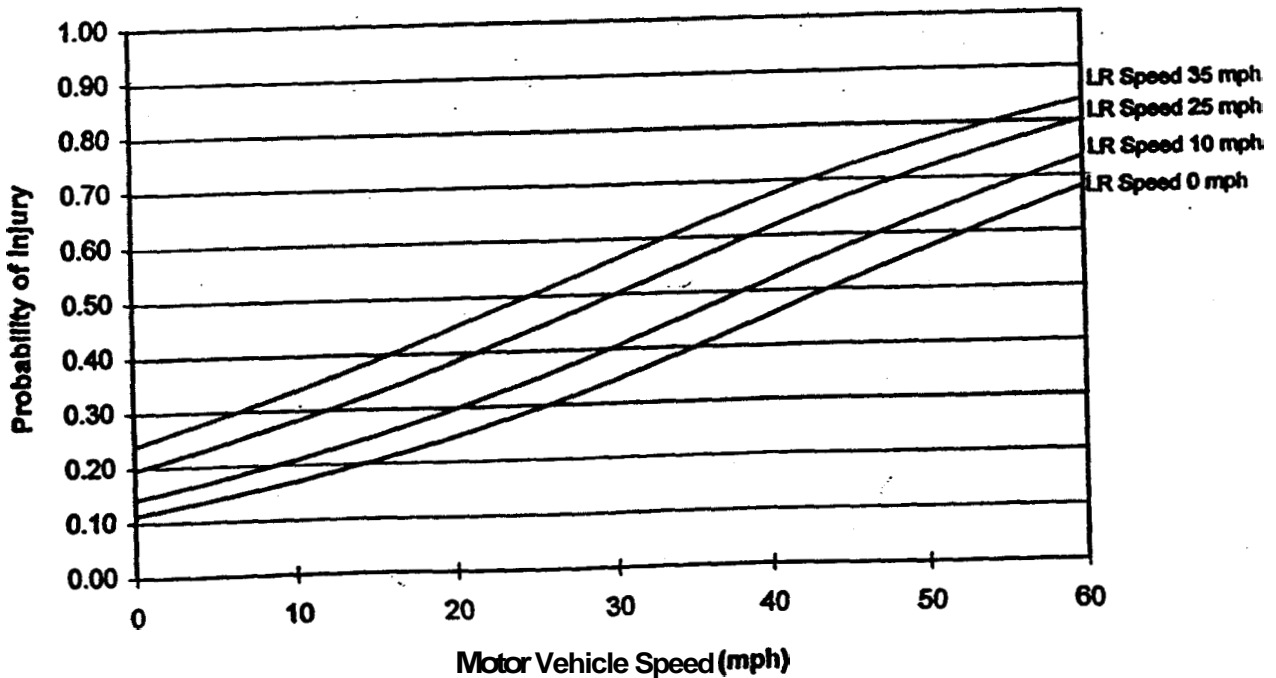


Figure 2.9b - Estimated Probability of Injury (Perpendicular Movement, Peak Period)

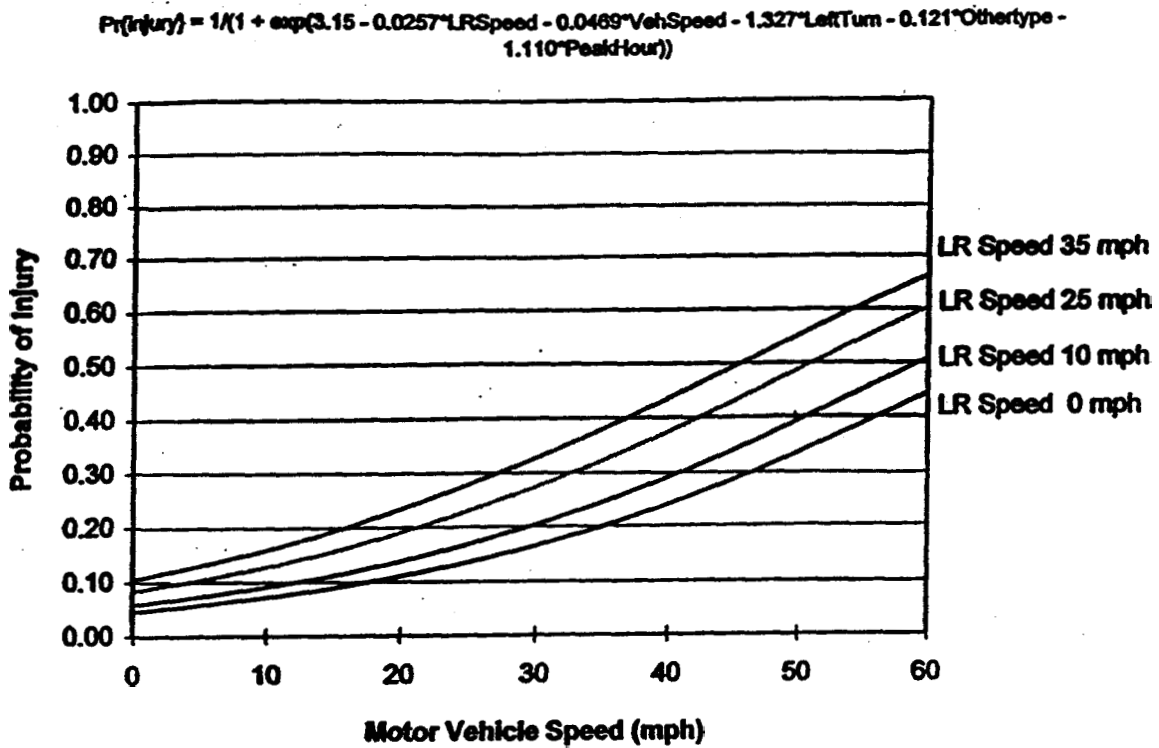


Figure 2.10a - Estimated Probability of Injury  
('Other' Movement, Off-peak Period)

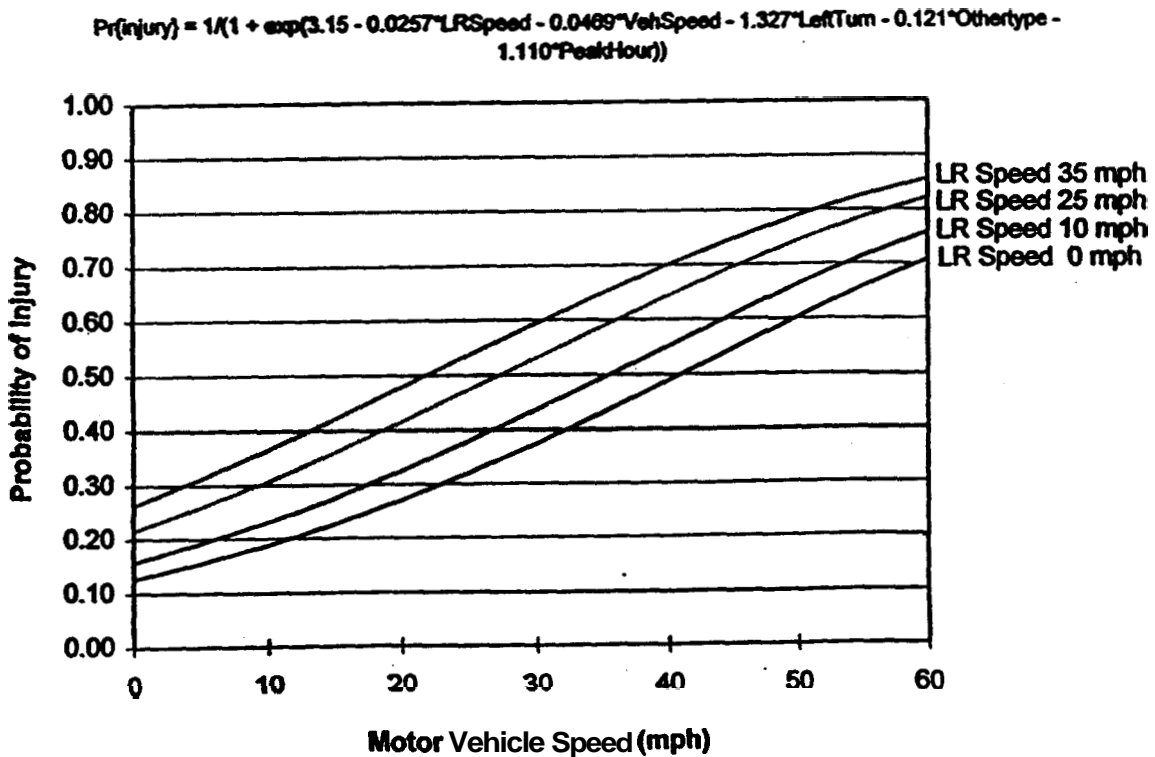


Figure 2.10b - Estimated Probability of Injury  
('Other' Movement, Peak Period)

**Table 2.1 - Number of Light Rail Accidents by Accident Type and Year**

Accident Type	Number of Light Rail Accidents						
	1988	1989	1990	1991	1992	1993	Total
Left-Turn	18	23	14	19	13	14	101
Right-Turn	2	1	4	2	4	0	13
Right-Angle	1	2	3	2	1	2	11
Driveway	0	2	1	1	3	1	8
Pedestrian	1	1	1	4	1	1	9
Other/Unk	2	1	2	4	5	1	15
<b>Total</b>	<b>24</b>	<b>30</b>	<b>25</b>	<b>32</b>	<b>27</b>	<b>19</b>	<b>157</b>



**Table 2.2 - Model Predictive Capability Calculation**

	<b>Predicted probability <math>\geq 0.5</math> (Event Does not Occur)</b>	<b>Predicted Probability <math>&lt; 0.5</math> (Event Occurs)</b>	
<b>Event Observed</b>	a	c	a+c
<b>Event Not Observed</b>	b	d	b+d
	a+b	c+d	N

**Table 2.3 - Number of Accidents Used in Fault-Tree Analysis**

Accident Type	Number of Accidents	
	Observed/Total	Sampled and Used
Left-Turn	109	27
Right-Turn	13	13
Right-Angle	11	11
Driveway	8	5
Pedestrian	9	4

**Table 2.4a. Observed Severity of Light Rail Accidents  
in Santa Clara County**

Vehicle Movement	Maximum Observed Injury Severity					Total
	Fatal	Incap.	Non-Incap.	Claimed	PDO	
Left-Turn	0	0	20	15	71	106
Right-Angle	0	1	2	2	9	14
Motor Veh. - Other	0	0	4	2	24	30
Ped/Bike	3	1	4	1	7	16
<b>Total</b>	<b>3</b>	<b>2</b>	<b>30</b>	<b>20</b>	<b>111</b>	<b>166</b>

**Table 2.4b. Observed Severity of Light Rail Accidents  
in San Francisco**

Vehicle Movement	Injury	PDO	Total
Left-Turn	2	21	23
Right-Angle	3	21	24
Motor Veh. - Other	6	49	55
Ped/Bike	5	0	5
<b>Total</b>	<b>16</b>	<b>91</b>	<b>107</b>

**Table 2.5- Estimated Parameters for Logit Model,  $P(D=1|Accident)$**

<b>Variable</b>	<b>Estimated Coefficient</b>	<b>Standard Error</b>
<b>Intercept</b>	-3.153	0.811
<b>X<sub>1</sub></b>	0.026	0.023
<b>X<sub>2</sub></b>	0.047	0.021
<b>X<sub>3</sub></b>	1.327	0.658
<b>X<sub>5</sub></b>	0.121	0.841
<b>X<sub>6</sub></b>	1.099	0.440

**Table 2.6 - Predictive Capability of Estimated Severity Model**

	<b>Predicted Injury: P(D=1)≥0.5</b>	<b>Predicted No Injury: P(D=1)&lt;0.5</b>
<b>Observed Injury</b>	<b>9</b>	<b>38</b>
<b>Observed No Injury</b>	<b>10</b>	<b>114</b>
<b>Total</b>	<b>19</b>	<b>152</b>

*Overall Correct Prediction = (9+104)/152 = 74.3%*

### 3. ACCIDENT COST ANALYSIS

#### 3.1 SUMMARY

This report estimates the full **costs** of collision accidents on the **Santa Clara County** light rail system in **San Jose**, California. Per-accident **costs** are estimated both for the transit agency (including **both** direct and stafftime **costs**) and for **society as** a whole.

A *summary* of **cost** categories identified for **this** analysis is given in Table 3.1. Direct **agency costs** for each accident were estimated from agency records whenever possible. Estimates of typical staff time spent per accident were provided by light rail division *staff*. Rider delay per accident was also estimated **from** agency records. **Other costs** incurred by individuals, **as well as** emergency response **costs**, were estimated using **national data** (Miller et al., 1991) **as summarized** in Table 3.2. Average **costs** per accident were then calculated based on whether or not the accident resulted in injury and the type of vehicular movement in the accident.

A breakdown of average **costs** by agency and non-agency categories and by accident severity is given in Table 3.3. **Costs** by **cost** category are given in more detail in Table 3.4. Direct and indirect **costs** to the transit agency averaged **\$2,568** overall, including **\$1,872** for a non-injury accident and **\$3,972** for an injury accident. Additional **costs** to **society**, including pain and suffering, totalled **\$7,238** for each non-injury accident and **\$202,439** for each injury accident.

**Overall**, the most substantial component of agency **costs** was vehicle damage (**\$3,915** per accident), followed by claims administration (**\$1,174**) and legal **costs** (**\$874**). **On** average, however, **\$4,311** of the **agency's** total **costs** were recouped from the other party involved in the accident. Legal **costs** and claims paid tended to be **infrequent** (less than **10** percent of all accidents) but relatively large, averaging **\$9,161** and **\$2,969** respectively, in **cases** where they did *occur*. Transit agency **costs** were found to be highly sensitive to the likelihood of having to pay a large claim for bodily injury. **No** claims greater **than** **\$16,000** were recorded in the **data set**, but inclusion of a hypothetical **\$300,000** claim would have increased net agency **costs** from **\$2,568** to **\$6,544** per accident.

Catastrophic **insurance** was also a relatively substantial **cost** when calculated on a per-accident basis (**\$660** in 1993), but it is not clear that a reduction in accidents would lead to a near-term reduction in **insurance costs**, **so this** was not included in the total **cost** estimate. Agency staff time and driver overtime **costs** were smaller but *still* substantial, at **\$593** per accident. Costs were not **substantially** greater for minor injury than for non-injury accidents. *Also*, no measurable long-term impact on ridership was found.

Injury-related **costs** were by far the greatest component of **costs** not borne by the agency. Injury-related **costs** averaged just over **\$200,000** per accident, including **pain** and suffering. (**This** figure is skewed by the few severe injuries and fatalities; **costs** were much less for minor injuries.)

Emergency response, rider delay, and road user delay **costs** were a relatively minor component except in property damage only accidents. Emergency response **costs** averaged **\$154** per accident; rider delay averaged **46** passenger-hours or **\$397**.

## 3.2 INTRODUCTION

The **purpose** of **this** report is twofold: *first*, to provide a **methodology** for **estimating** the **costs** of collision accidents on light **rail systems**, and *second*, to present a **case** study of light **rail** collision **costs** on the Santa Clara County Transportation Agency (SCCTA), located in **San Jose**, California. Comprehensive collision **costs** are estimated both to the **TA** and to **society as a whole**.

While light **rail** transit **has** a good **safety** record, there are opportunities to **further** reduce the number and severity of accidents involving light rail vehicles. In selecting countermeasures to **use**, however, the benefits of accident reduction **must** be weighed **against** the **costs** of implementation.

To **perform** such an assessment, integrated models of collision **severity**, and **cost** are required. These models must be sensitive to the **effects** of countermeasures in reducing the incidence and severity of collisions involving light **rail** vehicles and must reflect the **cost** savings of such reductions. Therefore, the results of the **cost** analysis will be **used** in conjunction with the results of the accident analysis (Chapter **2**) and countermeasure analysis (Chapters **4** and **5**). After assessment of the potential effectiveness and real-world feasibility of these countermeasures, it will be possible to **use** the results presented in **this** chapter to **assess** the economic value of countermeasures, both in the aggregate and by **cost** category. When such estimates **are** combined with estimates of countermeasure **cost**, a rational basis for selecting which countermeasures to implement **will** be established.

## 3.3 BACKGROUND

### 3.3.1 Safety Investment

*Safety* investment decisions **can** be based on a **variety** of criteria (Cheany **et al.**, **1976**; Federal Highway Administration, **1986**):

(1) **Cost-benefit ratio**: total **costs** and total benefits are quantified in dollar values, and investment is made to the point where incremental investment **equals** the incremental benefit **obtained**. While theoretically **appealing**, cost-benefit analysis **is** rarely applied. Many **benefits** of accident **reduction** are difficult to label with a dollar value, and attempts to do so **can** be highly controversial.

(2) **Cost-effectiveness**: projects are ranked based on the amount of **safety** improvement **per** dollar spent. If a fixed level of resources is available, projects are completed in ranked **order**, starting with the **most** cost-effective, until resources are **used** up. In **this case**, the benefits do not have to

be monetized; they *can* be lives saved, injuries prevented, etc. **An** example of cost-effectiveness analysis is the prioritization of railroad-highway grade crossing improvements.

(3) Threshold **safety** level: a minimum acceptable level **of safety** is *set*. **This** is commonly done based on a comparison to analogous **systems** or to previous system **performance**. **An** alternative approach, rarely utilized in practice, is to conduct an explicit risk-benefit analysis (Cheaney **et al.**, 1976).

(4) Industry **and** government standards -- both **formal** and informal -- for vehicles, **stations**, traffic control devices, and operating procedures are followed. Rather than prescribing an acceptable level of **safety**, these standards promote behavior and decisions on the part **of managers** and line personnel consistent with "safe" operation.

(5) **On an** ad-hoc, perceived-need basis.

In practice, transit agency decisions in matters related to **safety** are characterized by the **last** two of these approaches. Since light rail technology extends back to the streetcar era, there is extensive experience on which to base standards for safe equipment, facilities, and operations. **With these as** a baseline, individual agencies take further **steps** to increase **safety** by responding to problem areas revealed by the occurrence of accidents and **near-misses**, **as well as** the perceptions of agency personnel.

Cost-benefit analysis cannot and should not replace these procedures, but it *can* extend the capabilities of **transit** operators to identify cost-effective **actions** to improve **safety**. **Analyses** of the incidence and severity **of light rail** collisions will, at a **minimum**, validate more subjective assessments of **safety** problem areas, and may substantially alter them. Evaluations of the economic **costs** of these events make it possible to determine whether resources should be redirected to **safety** from other ~~uses~~ and if *so*, how such resources should be spent. Furthermore, by distinguishing **costs** to the agency from **costs** to **society**, it is possible to determine when a safety expenditure **is** in the agency's own narrow self-interest and when it may be appropriate for society to encourage or subsidize such an expenditure. The latter **is** particularly important in light of the increased flexibility of regional planning agencies in **allocating** federal transportation funds resulting from ISTEA legislation, **as well as** increasing pressure from the Clinton Administration that all transportation investments using federal funds undergo cost-benefit analysis (Office **of** the President, 1993).

### 3.3.2 Accident Cost Analysis

A growing body **of** literature **exists** on the **costs of** highway crashes. Studies by the National **Safety** Council, the National Highway and **Traffic Safety** Administration, and the Federal Highway Administration have attempted to quantify the total **societal** losses, both economic and non-economic, due to highway accidents (National **Safety** Council, 1994; National Highway Traffic and **Safety** Administration, 1987; Miller **et al.**, 1991). The most recent study, *The Cost of Highway*



*Crashes*, estimated the annual comprehensive **cost** to be \$334 billion in 1988 (Miller et al., 1991). As the authors point out, **this** represents the maximum rational investment in highway *safety* above and beyond current levels. The present study draws on **this** work for a number of **costs** which could not be found directly.

While considerable *safety-related* work has been done in the transit field, to the best of the authors' knowledge no thorough *study exists* on the **costs** of *crashes* involving transit vehicles. Also, while previous **reports** have recognized the need for evaluating transit *safety* measures on a **cost-effectiveness** basis (Jones et al., 1977), a methodology for doing so has not yet been proposed.

### 3.3.3 System Accident History

Through 1993, a total of 166 collision accidents with motor vehicles, pedestrians, and bicyclists have occurred on the *system*. Of these, **fifty** have resulted in one or more minor injuries, two in a severe injury, and three in a **fatality** (one was a possible suicide). Collision accidents per vehicle-mile have steadily declined to **nine per 100,000** vehicle-miles in 1993. **This** compares favorably with other light **rail** properties (Federal Transit Administration, 1988-1993). **Part** of **this** decrease, however, was due to the opening of the fully grade-separated section in 1991 which increased train-miles travelled without increasing exposure to **collisions**. See Task Report 1.2, Accident Analysis, for a more detailed description of accident characteristics.

## 3.4 METHODOLOGY

For **this** analysis, accident **costs** are broken down into two categories: **costs** which accrue directly to the transit agency, and **costs** which are borne by ~~all~~ other elements of *society*. Agency **costs** can be further categorized as ~~direct~~ disbursements per accident, ~~direct~~ disbursements per year, or time contributions by agency employees. Categorization may vary *among transit* agencies; for example, some process claims in-house while others contract out for claims work. The **cost** categories identified for **this** analysis are *summarized* in Table 3.1.

Direct agency **costs** for each accident were estimated from agency records whenever possible. Estimates of typical stafftime spent per accident were provided by light **rail** division staff. Rider delay per accident was also estimated from agency records. Other **costs** incurred by individuals, as well as emergency response **costs**, were estimated using national data from *The Cost of Highway Crashes*. Average **costs** per accident were then calculated based on whether or not the accident resulted in injury. Ideally, **costs** would be broken down using a more refined injury scale (including differentiation by minor **injury**, severe **injury**, and **fatality**); however, a **lack** of **data** on severe injuries precluded **this**. **Costs** were also tabulated based on accident **type**. Disaggregation of **costs** by accident characteristics should be helpful in assessing the cost-effectiveness of specific countermeasures.

### 3.4.1 Direct Agency Costs

*1. Property damage; 2. Claims Administration; 3. Claims Payments; 4. Claims Received (Subrogation); 5. Legal Expenses.* Itemized **data** were available from agency records for July 1990 through the end of **1993**, a total of **76** accidents. SCCTA **contracts** with an outside adjustor to estimate **damages** and to process claims **against** other parties and claims **against** the agency. Therefore, administrative **costs** and claims paid out by the agency for property damage and **bodily** injury were available on a per-accident basis. **Legal costs** and **attorney** fees were **also** obtained from internal memos. **Data** from previous years was inflated to **1993** dollars based on the Consumer **Price** Index (U.S. Bureau of **the** Census, **1993**). Claims payouts by the agency were incurred **in** roughly **10** percent of **cases**, reflecting that the transit agency is rarely found legally liable in light rail collision accidents. **On the** contrary<sup>7</sup> the transit agency was able to partially or fully recoup **costs** from the other party in a substantial proportion of **cases**.

From a **societal** perspective, claims paid and received by the transit agency are transfer payments rather than actual **costs**. Therefore, in determining **social costs** claims paid by the agency are subtracted **from** non-agency **costs**, while claims paid to the agency are added to non-agency **costs**. Such transfer payments do not change the overall **cost** to **society**.

*6. Operator overtime.* When an accident occurs, SCCTA relieves the operator for **1-2** hours to impound the vehicle and **fill** out reports. The operator is replaced **from** a pool of "extraboard" operators waiting on standby. **Most** extraboard operators are **used** for purposes unrelated to collision accidents (such **as** sickness and no-shows) **so** it is doubtful that **this** pool could be reduced by reducing the number of collision accidents. While each operator is guaranteed a standard number of hours of pay, it is possible, given a shortage of extraboard operators, that an operator may need to work overtime. The **agency** **incurs** additional **expenses** for overtime, which is compensated at **1.5** times the hourly wage rate. Records of overtime on a per-accident basis were not available, but the agency estimates that no more than **two hours** are accrued **for** a typical accident.

*7. Supplemental service.* **If** both **tracks** are blocked for a long **period** of time, supplemental service such **as** a bus bridge **or** van shuttle must be provided to transport **passengers** to their destinations. To provide a bus bridge, an extraboard **operator** may be used, a deadhead may be available, or a **bus** **may** be diverted **from** an existing route. While the last option may incur additional **costs** **through** rider delay on other routes, actual examples are rare **so** **this** component **was** ignored. Provision of alternate **service** **was** infrequent (based on Unusual Occurrence Records, a bus bridge was provided in **4** **percent** of accidents, **and** some additional **cases** of van shuttles may not have been recorded). No good data existed on **the** length or nature of such **service**, **so** a crude estimate of **\$48** **per** **service** provision (one hour of operator time plus **overhead**) was **used**.

*8. Revenue loss from lost riders.* A loss of riders due to accident delay could **occur** either immediately or over the long term. **For** **this** study, the immediate loss of fare-paying riders was

assumed to be negligible; the vast majority of accidents caused system delays of 15-20 minutes or less, and it was assumed that this would not be enough time to drive a significant number of riders away. (Even if a significant number of riders found alternative transportation, the onetime revenue loss would be small compared to other accident costs.)

To look at long-term effects on ridership, a time-series regression model of ridership was constructed. A regression model was used to relate dependent variables which may impact ridership to monthly ridership levels from 1987 through 1993. Accidents were incorporated in a number of ways, including gross accidents per month, injury and non-injury accidents, and delay caused by accidents. No significant relationship between accidents and ridership was found; therefore, the cost of lost ridership was assumed to be zero for this study. A complete description of the regression modelling efforts is included in Appendix A

**9. Catastrophic insurance.** SCCTA is self-insured against everything but catastrophic claims (over \$5 million) and severe agency property damage (over \$200,000). Purchasing commercial insurance only for catastrophic situations is a practice common to most transit agencies (Cheaney et al., 1976). While SCCTA's light rail division has never had a claim approaching the \$5 million limit, insurance costs are still fairly significant: over \$500 when allocated on a per-accident basis. The extent to which costs could be reduced through a reduction in accidents, however, is not clear. Previous research (Cheaney et al., 1976) has found that there is some effort to account for risk when setting insurance rates, but in a highly intuitive, negotiated manner.

SCCTA purchases insurance with 10-12 other counties; light rail accidents, therefore, are a very small percentage of the total accidents which occur in this pool of transit agencies. Rates for the TA have declined in recent years due to a good safety record with no large losses. According to TA insurance staff the rate depends primarily on the past history and forecast probability of large accident claims, rather than the total number of accidents. While the likelihood of a severe accident occurring is certainly related to the total number of accidents, the insurance agency does not appear to explicitly evaluate this relationship when setting rates. Therefore, it is assumed for this study that a simple reduction in the number of light rail accidents would not lead to a corresponding reduction in insurance expenses, and insurance is not included in the per-accident cost tabulation.

### 3.4.2 Agency Staff Time

**10. Accident response, reporting, and investigation.** When an accident occurs, central control is called, and one or more supervisors respond to the scene; both a supervisor and the operator fill out an accident report. The supervisor then files the information, and reports are reviewed regularly by an accident review committee. In addition, a report must be filed with the California Public Utilities Commission. The light rail division estimates that a total of 2.5 to 3 hours of supervisor staff time is spent responding to accidents and processing reports. In addition, operators are paid 1/2 hour overtime for filling out a report. Reporting and investigation times appear to increase greatly in the event of a severe or fatal accident; a conservative estimate of 8

hours was used in **this** study. In order to monetize time **costs**, **annual** salaries were computed on an hourly basis and multiplied by **2.6** (based on standard agency practices) to account for fringe benefits and overhead.

**11. Training of replacement operators.** In rare **cases**, an operator **may** take permanent leave due to severe psychological trauma after an accident. This has happened once at **SCCTA**. **If so**, the operator must be replaced, and retraining **costs** are accrued. The light rail division **estimates** that **roughly 128** hours of **stafftime** and **5** weeks of **operator** time are involved in training the operator, for a total **time-cost** of **\$9700**. If no new operator is available, additional overtime expenses **would be** accrued instead. In addition, **after** severe or **fatal** accidents operators are given **1-2** days leave to recover **from** the psychological effects of an accident. **This** may **cause** a shortage of operators and **the** accrual of more overtime. Specific data was unavailable, **so this** absence was **valued at 1.5** days **at** the standard wage rate.

**12. Miscellaneous staff support.** The most significant additional portion of agency staff time was in the county's insurance division. Staff time spent on transit incidents was estimated at 90 percent of a full-time staff person plus **45** percent of a clerical support person. Ten percent of **this** time was estimated to involve light **rail** incidents, of which half were collision accidents. Total **cost** was estimated to **be \$248** per accident, based on the total number of accidents for **1991** through **1993**.

Other staff **costs** are relatively minor. The **TA** operates an Employee Assistance Program (**EAP**) which offers **counseling** or other aid to operators who have **suffered** stress. The program **costs \$16,180** annually; the transit agency estimates that 1 percent of program time is related to light rail collision accidents. Allocating **costs** to injury accidents only, the **cost** would **be \$22** per injury accident.

**SCCTA** has not incurred any exceptional public relations expenses due to light **rail** accidents, but the agency does have a Public Information Officer who may respond to inquiries about accidents. The agency estimates a 3 percent response time to accidents; given a **7.5** percent allocation of accidents to light **rail**, a negligible per-accident **cost** of **\$15** may **be** assumed. In the case of a catastrophic accident it may be necessary for a transit agency to **incur** additional public relations **costs**. **This** is an area for further investigation.

### **3.4.3 Other Societal Costs**

**13. Emergency response.** Emergency response **may** take the form of the local police department, fire department, or medical transport. In addition, **SCCTA** **contracts** with the sheriff's department to provide protective **services** for the division. Police, sheriff, and ambulance response were noted on the accident report forms. Fire department response was found in agency records.

Fire department and ambulance response **costs** were taken from *The Cost of Highway Crashes*. The average fire department response **cost \$550** in **1987** dollars (Miller et al., 1991); ambulance response averaged **\$221** for hospitalized **cases** and **\$167** for non-hospitalized **cases**, in **1992** dollars

(Miller, 1994). As the proportion of hospitalized vs. non-hospitalized cases was not known from accident records, a round figure of \$200 was used. Typical police and sheriff response costs were estimated using a total response/processing time of one hour for police and 1/2 hour for sheriff. Personnel costs of \$68 per hour were assumed, based on payroll size and employment figures for police departments, adjusted for California wage differentials and for fringe benefits and overhead (U.S. Bureau of the Census, 1993).

14. *Injury-related costs.* Due to the limited scope of the study and privacy concerns, no attempt was made to estimate actual accident- or injury-related costs to private parties. Instead, national estimates of per-injury costs according to KABCO injury severity were taken from *The Cost of Highway Crashes* (Table 3.2). While KABCO severity level was not given explicitly on accident reports, injuries were coded as apparent or claimed, and the occurrence of incapacitating or fatal injuries could be inferred from the text of the accident report.'

Injury-related cost categories include hospitalization and other medical expenses; vocational rehabilitation; household production; lost wages; insurance administration; "workplace" costs including lost productivity and retraining; emergency services; legal/court costs; and pain and suffering. On a case-by-case basis, actual costs will differ considerably from average cost estimates. The study assumes, however, that on the average costs according to injury level are the same as those estimated nationally from highway crash data.

Most categories were applied directly, based on the number and severity of injuries in each accident. However, some categories had to be adjusted due to the unique nature of the study. Emergency services were eliminated, having already been estimated on a per-response basis. Legal expenses were adjusted, as it appears that light rail accidents are less likely to involve court proceedings and legal expenses than the typical highway accident. The vast majority of attorneys are reimbursed as a percentage of the settlement won, 29.4 percent on the average. Court costs and fees average another 2 percent (All-Industry Advisory Council, 1988). Therefore, other-party legal expenses were estimated by taking 31 percent of compensation paid by the transit agency to other parties. This probably underestimates actual legal expenses, since in some cases parties may sue their own insurance company or contact an attorney without going to court. Insurance administration costs were not adjusted and may slightly overestimate actual costs, as the light rail agency's administration costs are already included. (Per-injury insurance administration estimates

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<sup>1</sup> "KABCO" is the injury coding scale most commonly used by police departments in accident reporting. The scale is K = killed; A = incapacitating injury; B = evident, non-incapacitating injury; C = claimed injury; O = no injury. The limitations of the KABCO system in describing injury severity and relating to actual cost are discussed elsewhere (6). However, a lack of better information about the nature and severity of injuries prevented the use of a more refined injury scale.

are based on the **costs** eligible for compensation—medical, lost wages and household production, and property damage—and published administrative **expense** ratios (Miller *et al.*, 1991.)

**Pain** and *suffering* are a large component of comprehensive injury **costs**. Estimates are based on numerous studies of **willingness** to pay to reduce risk (for example, the amount which automobile consumers are willing to pay for airbags or other safety-related features). **Pain** and suffering **costs** should not be ignored **as** part of the overall **cost** to **society**, even though their measurement is imprecise. Studies of willingness to invest in *safety* **at** a personal level should **be** directly applicable **to** the determination of **societal** levels of safety investment.

*15. Property damage to private vehicles.* Property damage to private vehicles was also taken from *The Cost of Highway Crashes*, with **cost estimates** on a per-vehicle basis according to injury level. Damage estimates of "**minimal**", "moderate", and "major" were available from accident reports but the correspondence of these levels to actual **cost** is **unknown**. However, an analysis of the correlation of injury level to reported damage level did show a significant positive relationship within the accident **data set**, **so** it *seems* reasonable to base property damage **costs** on injury level. Again, on a case-by-case **basis costs** **will** differ markedly. A property **damage cost of \$150** was assumed for bicycle accidents.

*16. Rider delay.* To estimate rider delay, train-minutes of delay were taken from agency records and multiplied by estimates of the number of riders affected, based on agency ridership surveys by time of day and location. Delay is probably overestimated, since the delay **of** two consecutive trains would actually result in many riders catching the first **train instead** of the second train. Nevertheless, the estimates of **29.1** passenger-hours for a non-injury accident and **80.3** passenger-hours for an injury accident should serve **as** a reasonable approximation. Delay time was valued for passengers at **67.5 percent** of the average national wage rate (Miller *et al.*, 1991), adjusted for California wage differentials, with wage information from (U.S. Bureau of the Census, 1993).

*17. Road travel delay.* *The Cost of Highway Crashes* gives crude figures for road travel delay, estimated from simulations of highway accidents. Estimates are provided for freeways, **arterials**, and collector **streets**. For this analysis, these delay **estimates** are applied based on the classification of the **cross-street** where the accident occurred. Delay is valued **at** 90 percent of the wage rate for drivers and **67.5 percent** for passengers (Miller *et al.*, 1991). (The differential between driver and passenger delay values reflects the greater disutility of time spent driving **as** compared to time spent riding in a vehicle.) **Again**, this should *only* be considered a **first** approximation and actual delay values may vary considerably depending on local **street** configurations and traffic volumes. Where **streets** are closely **spaced** and many alternate routes are available (such **as** the downtown **area**) delay is probably overstated.

## 3.5 RESULTS

### 3.5.1 Estimated Costs

A breakdown of average costs by agency and non-agency categories and by accident severity is given in Table 3.3. Costs by cost category are given in more detail in Table 3.4. Direct and indirect costs to the transit agency averaged \$2,568 overall, including \$1,872 for a non-injury accident and \$3,972 for an injury accident. Additional costs to society, including pain and suffering, totalled \$7,238 for each non-injury accident and \$202,439 for each injury accident.

Overall, the most substantial component of agency costs was vehicle damage (\$3,915 per accident), followed by claims administration (\$1,174) and legal costs (\$874). On average, however, \$4,311 of the agency's total costs were recouped from the other party involved in the accident. Legal costs and claims paid tended to be infrequent (less than 10 percent of all accidents) but relatively large, averaging \$9,161 and \$2,969 respectively, in cases where they did occur. Catastrophic insurance was also a relatively substantial cost when calculated on a per-accident basis (\$660 in 1993), but it is not clear that a reduction in accidents would lead to a near-term reduction in insurance costs, so this was not included in the total cost estimate. Agency stafftime and driver overtime costs were smaller but still substantial, at \$593 per accident. Costs were not substantially greater for minor injury than for non-injury accidents. Also, no measurable long-term impact on ridership was found.

For costs not borne by the agency, emergency response, rider delay, and road user delay costs were a relatively minor component except in property damage only accidents. Emergency response costs averaged \$154 per accident; rider delay averaged 46 passenger-hours or \$397. Again, a few cases of unusually high delay skewed the average somewhat.

### 3.5.2 Reliability of Estimates

Detailed agency cost data were available for 53 non-injury and 23 injury accidents. The costs for non-injury accidents were relatively consistent, and therefore the estimates for property damage only accidents may be considered fairly reliable. The cost per injury accident, however, could be highly influenced by just one or two large claims, on the order of hundreds of thousands or even millions of dollars, which may occur once every few years. No claims over \$16,000 were paid by the agency in the 3 1/2 year time period for which records were available, but one \$300,000 claim (not included in the data set) was recorded in the first three years of the system's operation. If this \$300,000 claim payment had occurred in the period covered by the data set, average agency costs would have increased from \$2,870 to \$6,544 per accident. Claims payments would have comprised 40 percent of agency costs rather than 6 percent. Therefore, the cost estimates for injury accidents should be regarded as less reliable due to the more variable nature of the data. It should also be noted that claims cases can sometimes take many years to resolve, so it is possible

that **costs** have been underestimated for the existing data *set*. **As** of this writing, at least one accident from the period analyzed was **still** in the legal process and claims had not been resolved.

### 3.5.3 Costs by Accident Type

**Costs** were also broken down by accident type (Table 3.5). Accidents were classified as "left-turn" (parallel-running vehicle turns left in **front** of the LRV); "right-angle" (motor vehicle pulls out **from** a side **street**); "motor vehicle-other" (including mostly right-turn and anti-parallel left-turn accidents) and "pedestrian/bicycle." Differences by agency **cost** category, including LRV damage, **claims** administration, claims payments, and legal **expenses**, were tested for significance using a Tukey studentized range test on the variable means. LRV damage and total itemized **costs** were significantly greater for right-angle accidents than for other **types**, while claims processing and legal **expenses** were significantly greater for pedestrian and bicycle accidents, due to the greater probability of injury in such accidents.

Costs for most other categories were defined based on injury severity, and differences in **costs** among accident **types** should be *caused* primarily by differences in the proportion of injuries sustained for each **type**. A significance test on total non-agency **costs** showed that **costs** were substantially higher for pedestrian and bicycle accidents, **again** due to the greater probability of injury. Differences between accident **types** involving motor vehicles were insignificant.

### 3.5.4 Transferability of Results

While the **cost** methodology developed is generally applicable, the **usefulness** of the actual numbers is limited *since* actual data was taken from only one transit property. When considering **costs** to other light rail transit properties, both geographical differences in wage rates, legal **costs**, etc. and differences in operating procedures, equipment, and system characteristics may lead to different **costs** among properties.

In general, highway accident **costs** tend to be slightly higher in California than for the nation as a whole; **costs** in Santa Clara County *seem* to be close to the statewide average. **The** statewide **cost** per claim in 1989 was \$8,187 for **bodily** injury **claims** and \$1,638 for property *damage* claims, compared to a nationwide average of \$7,950 and \$1,380, respectively (**this** average excludes states with no-fault **insurate**) (Insurance Research Council, 1990). **Pain** and suffering--the greatest component of full **societal** cost--accounted for 27 percent of bodily injury awards in Santa Clara County, also roughly the statewide average. While the propensity to award compensation for pain and *suffering* varies **across** regions, in general it is treated as a multiple of tangible **costs** and therefore increases proportionally **as** **medical** and other **costs** increase (California Department of Insurance, 1993).

Overall, **costs** in Santa Clara **County** would be expected to be higher than average due to a number of factors. Compared to the **national** average, wage **costs** are 11 percent greater **in** California and



22 percent greater in Santa Clara County (U.S. Bureau of the Census, 1993). Differences in the **insured** vehicle fleet, such as a greater proportion of small and **urban-garaged** vehicles, **also** lead to higher-than-average claims **losses** (Highway Loss Data Institute, 1988). Therefore, agency-related **costs** for the SCCTA should be higher **than for** a light rail system located in an area of average wage rates and accident claim **costs**. **Note that most** non-agency **costs** are already based on **national** averages.

**Costs** to the TA could **also** be **affected by the** proportion of uninsured motorists in the region, which would affect the agency's ability to recover **costs** from the motorist. In 1990 the proportion of **uninsured** motorists was *estimated* to be **20-25** percent for **the** state as a whole and **15-20** percent for the San Francisco Bay area (**Marowitz, 1991**). In urban areas **where** the proportion of **uninsured** motorists is higher, the TA would be expected to **recover** a **smaller** portion of **its costs**.

Another **source** of **cost** variation **between** properties would be differences in the proportions of accidents **involving** injuries, severe injuries, and deaths. System characteristics--particularly **operating** speed—are a primary determinant of accident severity. A logit severity model, based on **data** from the light rail systems in Santa Clara County and San Francisco, showed (~~as expected~~) that the probability of an accident resulting in **injury** increased **significantly** as the **speed** of the light rail vehicle increased. "Left turn" accidents were also found to have a higher probability of injury **than** other accident **types**, as did accidents which *occurred* during the morning and evening **peak** hours. (Left turn accidents were not significantly more severe for the Santa Clara **data set** alone.) Therefore, **systems** which operate at **speeds** upwards of **40** or **45** mph through grade crossings would tend to have more frequent and severe injuries, and therefore higher accident **costs**, than the Santa Clara **system** which operates at a **maximum** of **35** mph. Severity may **also** depend on other **system** characteristics, such as the configuration of grade **crossings**.

### 3.6. POLICY IMPLICATIONS

#### 3.6.1 The significance of severity

**As** demonstrated in the crash **cost** literature referenced in this paper, total **societal costs** are highly dependent upon the severity of injuries in **the** accident. A **fatality** **can** have **costs** an order of magnitude greater than an incapacitating **injury**, which may in turn have **costs** an order of magnitude greater than a minor injury. In the **case** of a transit agency's **costs**, another dimension enters the picture: the probability that the **agency** will be found **partially** or **fully** responsible for an accident. Due to a widespread **emphasis** on safe **system** design and **operating** procedures and the limited potential for driver error on a **rail transit system**, this probability *seems* quite low for the new light rail transit properties. It is certainly **non-negligible**, however, and even a single severe or fatal accident **can** result in liability claims in **the** hundreds of thousands of dollars, ten to one-hundred times the **cost** for a "**typical**" accident. The fact that **the** agency **has** "deep pockets" **may** add to the likelihood that it is sued in the event of a severe accident. Transit agencies realize **this**

and **set** aside a substantial pool of money for self-insurance purposes in addition to **carrying** outside catastrophic insurance. Overall, the implication **is** that any measures a transit agency **can** take to protect itself from **liability** could have potentially significant payoffs.

Qualitative evidence also shows that other **costs increase** substantially in the **case** of a severe accident. Agency staff **spend many** hours responding to the accident and conducting follow-up investigations. A lengthy police report is filled out and, in the **case** of a fatality, the **California PUC** sends **an** investigator to the scene of the crash. In extreme **cases**, **an** operator may need to take extended leave, resulting in personnel shortages or retraining **costs**. Finally, severe accidents **can also** have disproportionate effects on public perceptions of **safety**. Cheaney, **et al** (Cheaney et al., **1976**) note that **society** displays a degree of tolerance for noncatastrophic accidents but may react strongly to accidents they perceive **as** "catastrophic."

Overall, reducing the severity of accidents may be even more productive *than* reducing the absolute number of accidents. For example, earlier detection of a potential accident could allow a greater reduction in **LRV speed** before impact, thereby reducing the probability of injury. The expected **cost** reduction could then be calculated. The results of the **cost** severity analysis may also be useful in narrowing the focus of countermeasure implementation. While the total number **of** pedestrian and bicycle accidents was **small** (10 percent of **all** accidents), **this** category was particularly expensive; the probability of the accident resulting in injury was **almost** 60 percent, and all three fatalities were in **this** category. Therefore, efforts to reduce pedestrian accidents may have significantly larger payoffs on a per-accident basis *than* efforts to reduce vehicle accidents. Conversely, right-turn accidents on the downtown pedestrian mall, where **operating speeds** are low, rarely resulted in injury or substantial property damage and may deserve relatively little attention.

### 3.6.2 Implications for safety investment

A transit agency **acting** in its own economic self-interest may be expected to invest in **safety** improvements up to the **point** where the **costs** of such improvements **equal** the benefits to the agency. **However**, investment beyond **this** point **can still** achieve significant **societal** benefits that do not **accrue** to the transit agency. **This** becomes more true **as** the severity of the accident increases, **as most** injury-related **costs** (by far the **largest** component of injury accident **costs**) are not borne by the transit agency. For the data **set** analyzed the **net cost** paid by the transit agency was a very small proportion of the total accident **cost**.

While the potential for liability is **an** incentive for transit agencies to make larger **safety** investments, it does not **increase** the monetary **risk** to the level of **full societal costs**, particularly since the light rail agency is **rarely** found at fault. The disparity between **costs** to the transit agency and **costs** to **society suggests** that **safety** investment decisions should be made at the **societal** level rather than at the level of **one** particular agency. Legislators, for example, may wish to fund **safety** investment programs independently of the transportation agency's operating budget. **As** mentioned earlier, the

full societal cost of an accident represents the maximum rational public expenditure to prevent such an accident (Miller et al., 1991). In the likely event that safety programs are funded at a lower level, legislatures might conduct an explicit comparison of the cost-effectiveness of various safety improvement programs across both transportation and non-transportation areas. This would help society achieve the maximum benefit (in terms of accidents, injuries, and deaths prevented) per dollar spent.

Table 3.1 \* Summary of Cost Categories

<i>cost category</i>	Description	Payer	Source of information
<b>Agency property damage</b>	Damage to LRVs and other agency property	Transit Agency	Agency records
<b>Claims administration</b>	<b>Damage adjustment; processing of claims for and against agency</b>	<b>Transit agency</b>	<b>Agency records</b>
<b>Claims payments</b>	Claims for bodily injury and property <b>damage paid out by agency</b>	Transit <b>agency*</b>	Agency records
<b>Claims received</b>	<b>Claims payments received by agency</b> from individuals	<b>Society**</b>	Agency records
<b>Legal &amp; court expenses</b>	Legal counsel and court fees paid by the agency	Transit agency	Agency records
Operator overtime	Overtime paid by agency to LRV operators	Transit agency	Estimated by light rail division <b>staff</b>
<b>Supplementary service</b>	Bus bridge or van shuttle around accident scene	Transit agency	Occurrences <b>from</b> agency records; service costs estimated
Revenue loss	Immediate or long-term revenue loss due to lost ridership	Transit agency	Time-series analysis of ridership
Catastrophic Insurance	Agency insurance against catastrophic liability or <b>property damage</b>	Transit agency	Agency records
Accident response	Staff time spent responding to <b>scene</b> , filling out <b>reports</b> , and investigating accident	Transit agency- <b>-time cost</b>	Estimates by agency <b>staff</b>
Replacement operator training	Training for <b>new</b> operators to <b>replace</b> operators <b>who have taken</b> permanent leave as result of accident	Transit agency- <b>-time cost</b>	Estimates by agency <b>staff</b>
Misc staff support	Other <b>staff</b> time: employee assistance program, requests for information <b>from</b> public	Transit agency- <b>-time cost</b>	Estimates by agency <b>staff</b>
Emergency response	<b>Response</b> to accident by police, fire, and medical transport	<b>society (local government)</b>	<b>Response from</b> agency records; <b>response</b> costs from <b>(6)</b> or <i>estimated</i>
Injury costs	<b>Costs</b> associated <b>with</b> injuries incurred	Society	Injury level <b>from</b> accident records; <b>costs per injury from (6)</b>
Property damage	Vehicle & other property damage to other party	Society	<b>Costs</b> per vehicle, <b>by</b> injury level, <b>from (6)</b>
Rider delay	Delay to light rail <b>system users</b> due to accident	Society	Agency <b>records of system</b> delay <b>and</b> ridership
Road travel delay	Delay to road <b>users</b>	Society	From <b>(6)</b> , according to cross-street classification

\* Subtracted **from** societal costs

\*\* Subtracted **from** agency costs

Table 3.2 - Costs Per Injury by KABCO Severity (1988 dollars)

Injury Level	Hosp/ Med	voc Rehab	Household Production	Wages	Insurance Admin	Workplace	Pain & Suffering
K	\$5,859	\$0	\$92,014	\$428,316	\$43,751	\$6,186	\$1,743,917
A	\$9,660	\$69	\$3,250	\$11,728	\$2,470	\$961	\$133,925
B	\$1,742	\$24	\$845	\$2,946	\$721	\$333	\$22,858
C	\$1,017	\$19	\$522	\$1,782	\$484	\$223	\$9,927
0-Per Vehicl	\$73	\$1	\$71	\$135	\$155	\$45	\$369

Source: Miller et al, 1988

**Table 3.3a - Average Cost Per Accident**

<b>Transit Agency</b>	<b>\$2,568</b>
<b>Non-Agency</b>	
<b>Direct</b>	<b>\$22,817</b>
<b>Pain &amp; Suffering</b>	<b>\$49,096</b>
<b>Total Societal</b>	<b>\$74,481</b>

**Table 3.3b - Average Cost by Accident Severity**

<u><b>Injury/Fatality</b></u>		<u><b>Property Damage Only</b></u>	
<b>Transit Agency</b>	<b>\$3,972</b>	<b>Transit Agency</b>	<b>\$1,872</b>
<b>Non-Agency</b>		<b>Non-Agency</b>	
<b>Direct</b>	<b>\$55,171</b>	<b>Direct</b>	<b>\$6,786</b>
<b>Pain &amp; Suffering</b>	<b>\$147,268</b>	<b>Pain &amp; Suffering</b>	<b>\$452</b>
<b>Total Societal</b>	<b>\$206,411</b>	<b>Total Societal</b>	<b>\$9,111</b>

Table 3.4 - Average Cost by Cost Category and Accident Severity

<b>Cost Category</b>	<b>All Accidents</b>	<b>Injury/ Fatality</b>	<b>PDO</b>
<b>Total Accidents</b>	<b>166</b>	<b>55</b>	<b>111</b>
<b>Transit Agency</b>			
<b>Direct--Per Accident</b>			
Property Damage	\$3,915	\$2,657	\$4,538
Claims Processing	\$1,174	\$1,609	\$959
Claims Payments	\$320	\$800	\$83
Claims Received*	(\$4,311)	(\$4,311)	(\$4,311)
Legal & Court Expenses	\$874	\$2,428	\$104
Operator Overtime	\$75	\$89	\$69
Supplementary Service	\$2	\$4	\$0
Revenue Loss	\$0	\$0	\$0
<b>Direct--Annual</b>			
Catastrophic Insurance**	\$0	\$0	\$0
<b>Indirect--Staff Time</b>			
Accident Response, Reporting & Investiga Replacement Operator Tr	\$191	\$215	\$179
Misc. Staff support	\$58	\$176	\$0
	\$269	\$284	\$262
<b>Non-Agency</b>			
Emergency Response	\$154	\$241	\$111
Property Damage	\$1,780	\$2,463	\$1,442
<b>Injury-Related Costs</b>			
Medical, Lost Production Pain & Suffering	\$16,368	\$48,161	\$614
	\$49,096	\$147,268	\$452
<b>Delay</b>			
Rider Delay	\$397	\$692	\$251
Road Travel Delay	\$128	\$123	\$130
<b>Transfer Payments</b>			
Claims to TA *	\$4,311	\$4,311	\$4,311
Claims received from TA	(\$320)	(\$800)	(\$83)
<b>Total Societal Cost</b>	<b>\$74,481</b>	<b>\$206,411</b>	<b>\$9,111</b>

\* Breakdown by injury vs. non-injury not available

\*\* Cost not allocated on a per-accident basis

Table 3.5 - Cost by Accident Type

	1. Left-Turn	2. Right-Angle	3. Other M. V.	4. Ped/Bicycle	Total Motor Vehicle	Total All Accidents		
Total Number	106	14	27	16	147	163		
Total W/Itemized Costs	44	8	16	8	68	76		
<b>Transit Agency - Itemized</b>								
property Damage	\$3,017	\$16,995	\$1,094	\$408	\$4,472	\$3,915	**	2 sdt 1,3,4 <sup>a</sup>
Claims Processing	\$1,016	\$1,259	\$987	\$2,191	\$1,038	\$1,174	**	4 sdt 1,3
Claims Payments	\$210	\$0	\$0	\$2,016	\$136	\$320	•	4 sdt 1,2,3 at 0.
Legal & Court Expenses	\$309	\$771	\$381	\$5,201	\$380	\$874	**	4 sdt 1,3
<b>Total Itemized</b>	<b>\$4,552</b>	<b>\$19,025</b>	<b>\$2,462</b>	<b>\$9,816</b>	<b>\$6,026</b>	<b>\$6,283</b>	<b>**</b>	2 sdt 1,3
<b>Non-Agency</b>								
Direct	\$10,138	\$13,227	\$8,990	\$142,034	\$10,221	\$22,817	**	4 sdt 1,2,3
Pain & Suffering	\$9,561	\$18,626	\$6,305	\$419,006	\$9,827	\$49,096	**	4 sdt 1,2,3
<b>Total Societal</b>	<b>\$21,558</b>	<b>\$40,677</b>	<b>\$16,065</b>	<b>\$565,839</b>	<b>\$22,370</b>	<b>\$74,481</b>	<b>**</b>	4 sdt 1,2,3

\* = F-test for difference of means significant at 0.10 level

\*\* = F-test for difference of means significant at 0.05 level

<sup>a</sup> read as "cost for type 2 (right-angle) accident is significantly different than for type 1, 3, or 4"



## 4. KINEMATIC ANALYSIS

### 4.1 INTRODUCTION

Analysis of the kinematics of vehicles involved in light rail vehicle collisions **has** been performed to provide guidance in formulation and evaluation of countermeasures. This analysis examined the movement of both the light rail vehicles (LRV's) and rubber tired-vehicles (RTV's) in the seconds preceding a potential collision. Realistic ranges were established for all relevant parameters, such **as** initial velocities and **acceleratiodeceleration** rates for the vehicles. Analysis cases were chosen to define the envelope of **all** possible cases rather than to depict a particular collision. The focus of the analysis is on vehicle movement, although other factors such **as** human reaction time and sensor performance characteristics are also considered.

The kinematics analysis is **used** primarily in support **of** the active and reactive countermeasures, although it can also provide usefbl insight into some of the passive countermeasures.

### 4.2 OBJECTIVES

The kinematics analysis lays the foundation for formulation and evaluation of countermeasures, subject to the performance characteristics of the vehicles involved. The initial results indicate what approaches are most likely to result in significant improvements to system safety. Additional analysis provides fbrther detail regarding the candidate countermeasures, including the structure, system specifications, and component specifications for the countermeasure. Depending on the countermeasure being considered, it may be possible to develop a reasonably detailed warning algorithm.

#### 4.2.1 Determine Countermeasure Approach

The first results of the kinematics analysis provide general guidance as to feasible countermeasures. For example, the instant at which a particular vehicle must **start** braking in order to avoid a collision can be determined for any **set** of initial conditions and **acceleratiodeceleration** profiles. Determining which vehicle must brake (and at what moment) allows the countermeasure approach to be formulated. For instance, it may be possible to avoid a certain number of collisions if the Light **Rail** Vehicle were to automatically apply the brakes when a rubber-tired vehicle (RTV) passes beyond a specified point at a specified velocity. Another approach would be to have the driver of the RTV apply the brakes, perhaps in conjunction with a steering maneuver, to avoid a collision.

#### 4.2.2 Determine System Structure and Requirements

Once the approach has been defined for each candidate countermeasure, more detailed analysis is performed to further specify the countermeasure, including the structure and system requirements. The structure of the countermeasure defines the data required **as** well as how they are used. For instance, one system might require the precise position and velocity of the RTV and only general position for the LRV. A warning (to the **RTV**) could be issued if it were determined that the rubber-tired vehicle would cross the tracks and that the LRV would cross through the intersection at some time within the next five seconds. For such a warning to be effective, it would have to be issued far enough in advance of the collision that the driver could react in time to avoid **a** collision. This condition creates a system level requirement such **as** the system must be able to detect that a RTV is likely to enter the path of an oncoming LRV at least **2.5** seconds before the collision would take place. Furthermore, the warning must be extreme enough that it attracts the drivers attention and alerts them to the nature of the danger i.e., make the driver realize that a LRV is overtaking the RTV and making a **left turn** into the path of the LRV is likely to cause a collision.

#### 4.2.3 Determine Component Requirements

The system requirements are used to generate component requirements, such as sensor update rate and accuracy, computational time delays, communications range and time delays, and warning device characteristics. The component requirements are used to determine the cost and availability of the components. Component costs **will** be used later in the study to help determine the overall cost and cost-effectiveness **of** the various countermeasures.

#### 4.2.4 Define Warning Algorithms

Warning algorithms play a key role in all of the active countermeasures. If warnings are issued unnecessarily, i.e., when there is in fact no danger, they become a nuisance, particularly to occupants of the buildings near the light rail system. The issuing of numerous false alarms might even make motorists tend to ignore the **warnings** when there is a real danger. On the other hand, if warnings are issued too late, there **may** not be adequate time to recognize the danger and react appropriately, avoiding a collision. Obviously, there is a tradeoff between these two types of occurrences which needs to be examined.

Issuing an appropriate alarm is tied directly to the quality **of** information available. Quality of information includes the type of information available (position, velocity, and acceleration rates), the accuracy **of** the information (error in position and velocity data) and the timeliness of the information (are sensor outputs available once a second or ten times a second, or continuously).

### 4.3 METHODOLOGY

The kinematics analysis involves examining dozens of cases of RTV and LRV trajectories. These trajectories are carefully chosen to determine the limiting cases, or envelope of system operations. Over a dozen parameters are required to completely describe some of the trajectories. For instance a creep-up maneuver by a car in the left turn pocket is defined as follows:

- 1) Car initially stopped at a certain position (LRV at a specified velocity and location),
- 2) At a particular time, car starts accelerating at a specified rate,
- 3) At a particular time, car transitions to travel at constant velocity,
- 4) At a particular time, car decelerates to a stop,

When all the parameters are specified, this generates one possible trajectory for the RTV. Other categories of trajectories for the RTV's include,

- 1) From a standing start, proceeding through the intersection, (acceleration followed by constant velocity)
- 2) Approaching the intersection at some velocity and braking to a stop,
- 3) Approaching an intersection at some velocity and proceeding through the intersection,
- 4) Approaching an intersection, slowing, and then proceeding through the intersection.

For any of these scenarios, either the LRV or RTV could start braking (from gently to emergency braking) any time, due to sensing of danger by the driver, operator or a collision warning system. For each of these cases, it is possible to determine when (if at all) the vehicle traverses the collision zone (the area where the paths of the RTV and LRV cross). If both vehicles occupy the collision zone simultaneously, then a collision occurs. The analysis is performed to determine the limits of conditions under which collisions can be prevented.

#### 4.3.1 Definition of Important Terms

Through out the analysis, certain terms are used, with very specific meanings. Definitions for the two most important, collision zone and critical range are presented here.

#### 4.3.1.1 Collision Zone

In the previous section the term *Collision Zone* was introduced, referring to the area where the paths of the RTV and LRV crossed. If both vehicles are in this zone simultaneously, a collision occurs. Figure 4.1a shows the geometry of a typical intersection where median running is used. The collision zone is defined by cross-hatched area. The location of this zone is a function of how tightly the RTV turns, as shown in Figure 4.1b, with Figure 4.1c showing the geometry of an intersection where a multi-lane street crosses the light rail tracks.

The actual size of the collision zone is dependent of the width of both vehicles and the angle at which they cross. For simplicity's sake, we have taken the collision zone to be 2.5 meters by 2.5 meters. Making the length and width equal simplifies plotting of data, allowing the longitudinal and lateral dimensions to be reduced to one dimension, the distance from the beginning of the collision zone. This definition makes plotting of data from the computer runs relatively simple. That definition does complicate the transition from a position on the pavement to a point on a graph, as the distance from a location such as the stop line to the collision zone depends on how sharply the driver of the RTV turns. The ambiguity of this distance takes on less importance by attempting to ensure that all RTV's stop before the stop line, with the distance from the stop line to the collision zone providing an extra margin of safety.

Typical acceleration, velocity, and position trajectories for a RTV are shown in Figure 4.2. These particular profiles are for a car creeping up approximately one car length in the left turn pocket. The profiles are not jerk-limited (i.e. acceleration rate is allowed to change instantaneously), as jerk limiting has very little effect on total time to travel a given distance. Additionally, it is possible to compensate for jerk-limiting by choosing slightly different values of acceleration.

#### 4.3.1.2 LRV Critical Range

For any given parameter set (initial positions, velocities, and acceleration profiles), there exists a certain set of LRV initial locations which will result in a collision. If the LRV is very near the intersection and moving rapidly, it will clear the collision zone before the RTV enters it. Similarly, if the LRV is far away, the RTV will pass through the collision zone prior to the arrival of the LRV. For some set of intermediate initial positions of the LRV, there will be a collision if the RTV enters the collision zone. The set of LRV initial positions which result in collisions is called the *Critical Range*, or more properly, *Critical Range Interval*. These two terms are used interchangeably. The upper end of the critical range is defined as the initial position of the LRV which results in the LRV entering the collision zone just as the RTV is exiting it, i.e., the left front of the LRV hits the left rear of the RTV. The lower end of the critical range is determined by the RTV entering the collision zone just prior to the LRV exiting it. As a practical matter, RTV's rarely if ever hit the rear of an LRV in a left-turn type

collision. This is because it takes at least two seconds (a single unit train is approximately 30 meters (100 feet) long, and at 15 m/sec (35 mph) it takes two seconds to pass). for an LRV train to pass a given point, and in that time the driver of the RTV generally notices the train and takes evasive action such as braking or changing path. The analysis **used** in this report examines the sensitivity of critical range to various changes in vehicle actions, such as braking rate or the instant at which brakes are applied.

#### 4.3.2 Approach to Analysis

The critical range for the LRV gives the relative degree of **safety** for the system. The smaller the critical range interval, the less likely a collision **will** occur. If the critical range can be reduced to zero, than no collision **will** occur. Assume that the **critical** range in the baseline system for a specific maneuver by an RTV is 30-90 meters (100-300 feet). This means that a collision occurs if the LRV is anywhere from 30 to 90 meters from the collision zone when the RTV starts moving. If a specific countermeasure could decrease the size of the critical range by a factor of four (say is becomes 75-90 meters), the probability of a collision has been reduced to **25%** of what it had initially been.

The entire analysis is aimed at examining the critical range **as** a function of **all** other system parameters. Effective countermeasures **shrink** the size of the critical range, increasing system **safety**. If countermeasures can be implemented which reduce the size of the critical range to zero, a complete class of collisions could be eliminated. In practice this is not thought to be achievable in all cases, at least not with existing technology. This indicates that the goal of this project must be limited to reducing the number, severity, and impact of collisions rather than eliminating them completely.

Reducing the size of the critical range interval is completely equivalent to reducing the number of accidents. It is in fact possible to dramatically reduce the critical range interval. It should be noted that this does not necessarily imply that the velocity profile of the LRV is changed. Quite the contrary, the most effective way of eliminating collisions is generally to alter the RTV's trajectory, preventing it **from** entering the collision zone (against a red light) as an LRV **is** approaching.

#### 4.3.3 Sensitivity of Critical Range to System Parameters

The critical range varies depending on the other system parameters. These in **turn** are influenced by the countermeasures. Assume **for** example that a RTV was on a trajectory which would **carry** it through the collision zone, resulting in a crash with the LRV (or a case which would have a large critical range for the LRV). If a collision warning/avoidance system detected this situation and alerted the driver of the RTV, he could take evasive/corrective action. This adjustment to the RTV's trajectory might prevent it **from** entering the collision

zone at all, collapsing the critical range to zero size, i.e., there wouldn't be a collision regardless of where the LRV was. The amount by which the RTV's trajectory is altered depends on parameters such as when the alarm/warning is initiated, the driver's perception and reaction time, and the RTV's braking rate. All of these parameters, as well as many others, are examined in the analysis in an attempt to determine possible countermeasures and their relative effectiveness.

## 4.4 ANALYSIS

### 4.4.1 Analysis Assumptions and Parameters

The accuracy of the analysis is limited by the reasonableness of the underlying parameter values and assumptions. Table 4.1 presents the parameter values used for the kinematics analysis. In addition to the nominal value, maximum and minimum values are presented. The nominal values were chosen to represent a slightly conservative estimate of real world performance figures.

One of the critical and more uncertain parameters in this analysis is driver reaction time. A number of researchers have studied such times. Reaction times vary widely from study to study, depending on response measured, alerted versus surprised, driver workload and other factors. In general, reaction time appears to be faster for audible alarms than for visual alarms, on the order of 100-200 ms (e.g., Postman and Egan, 1949; Matson, et al, 1955; Goldstone, 1968). Other studies have found that reaction time increases as expectancy decreases (e.g., Warrick, et al, 1965; Krinchik, 1969)

Sivak, et al (1981) examines driver response time to novel rear brake signal signals. The study involved trapping an unsuspecting motorist between a vehicle equipped with a novel rear brake light system and an observer car. The brake lights of the lead vehicle were activated (without actual braking) and the interval until an observed deceleration of the subject vehicle was measured. The data was collected on busy urban streets and the stop signals were presented at times when there was no obvious need for deceleration. Mean observed response time was 1.21 seconds with a standard deviation of 0.63. It is important to note that a few reaction times were as long as three seconds.

Similarly, Wortman and Matthias (1983) examined the mean perception-response times for drivers confronted with the onset of a yellow phase at a traffic signal. Approximately 800 drivers were observed at six locations and had a mean response time of 1.30 seconds, standard deviation of 0.60 and the 85th percentile time of 1.8 seconds.

Olson, et al (1984) measured alerted and surprise reaction times of 64 drivers to an obstacle in the roadway. Specifically, they measured the time from first sighting the obstacle until the driver's foot contacted the brake pedal. The mean and 85th percentile surprise reaction times

were **1.1** and **1.4** seconds respectively. While the mean and 85th percentile alerted reaction times were **0.7** and **0.9** seconds respectively.

In terms of light rail accident countermeasures, it would be impossible to predict driver reaction times without field testing. The three preceding reports suggest an approximate range for driver reaction times to visual alarms.

Johansson and Rumar (**1965** and **1971**) examined drivers' response time to an audible signal. Drivers were stopped and asked if they would tap their brakes **as quickly as possible** after hearing a noise sometime in the next **10 km**, **321** subjects were observed. A klaxon horn, hidden in a mailbox approximately **5 km** down the road, **was** sounded **as** the car passed. Brake response time was measured, including observer response time. The mean subject response time less the mean observer response time, **was** on the order of **0.5** seconds. Note that this value is about **200 ms** faster than the alerted response time to a visual stimulus found by Olson, et al. The authors estimated a median brake reaction time under a surprise condition of **0.9** seconds.

Because the subjects were alerted to the experiment, it is **difficult** to generalize Johansson and Rumar's work to the proposed audible alarms. The mean reaction time appears to be in line with other works comparing audible and visual stimuli response time. The earlier works found that audible stimuli tend to have a slightly quicker response time. Drivers' surprise response time to an audible alarm is probably on the order of **1** second. Further work will be necessary to establish this value.

Olson (**1989**) summarizes a number of articles on driver reaction time. The author notes that it is impossible to make an exact prediction of perception-response time; however, "given a reasonably clear stimulus and a fairly straight forward situation, a great deal of data suggest that most drivers (i.e., about **85%**) should begin to respond by about **1.5** seconds after the first possible visibility **of** the object or condition of concern." We therefore use **1.5** seconds as the baseline value.

The LRV initial velocity is taken as **15 ~~ctc~~** (**33.6** mph) which is nearly equal to the **35** mph maximum speed allowed while median-running in the Santa Clara County system. The LRV braking rates **of 1.5** and **2.25 m/sec/sec** are within about **1%** of the service and maximum braking rates for the SCCTA system. The RTV braking rates used vary from **1.5** to **6 m/sec/sec**. Table **4.2** characterizes the braking rates **used**.

#### **4.4.2 Baseline System**

The next step in the analysis is to set **up a** baseline *case*. **This** is **used** for comparison during the rest of the analysis, allowing various approaches and sensitivities to be judged against a well defined case.

Figure 4.3 presents several possible movements for a vehicle stopped in the left **turn** pocket. The first, represented by the solid lines, portrays a vehicle acceleration at **1.5 meters/sec/sec** for four seconds (up to a velocity of **6 m/sec** or about 13.4mph) and proceeding through the intersection at constant velocity (called ‘run light, fast’). The second trajectory, represented by alternating long and short dashes, also involves running the light and proceeding through the intersection, although at a slower velocity. The acceleration period lasts only two seconds, resulting in a velocity of **3 m/sec** or about **7 mph**. **This** case is labeled “run light, slow”. The third case, represented by dots, is identical to the second profile for the first four seconds, at which point the vehicle **starts** to decelerate at **1.5 m/sec/sec**, coming to a stop at time  $t = 6.0$  seconds. **This** “long creep-up” maneuver covers **12 meters** or about 40 feet. The next case is a somewhat shorter creep-up maneuver. The alternating short dash/dot curves show that after one second, acceleration stops, and the vehicle maintains a constant **1.5 m/sec** until 4.0 seconds, at which time it brakes to a stop. In this ‘medium creep-up’ trajectory, **6 meters** (about **20 feet**) are covered in five seconds.

One should note that even though the final results are very different, all four cases are identical for the first second. The second and third cases are interesting to examine because of their similarities and differences. They are identical for the first four seconds, yet are completely different from a safety point of view, **as** the long creep-up maneuver never enters the collision zone and therefore cannot result in a collision. The challenge for a collision warning/avoidance system is to be able to distinguish between safe and unsafe maneuvers by the rubber-tired vehicle soon enough to issue an effective warning i.e. a warning which can trigger evasive action resulting in no collision.

The next step in the analysis is to examine what happens when there is an LRV present as well as a rubber-tired vehicle. Figure 4.4a presents such a case, with the horizontal **axis** representing time and the vertical **axis** the distance from the collision zone. Each vehicle moves forward (up on the graph) approaching the collision zone. They then enter this zone, traverse it, and continue along their way. Note that the front and rear ends of each vehicle are shown. We have taken the collision zone to be **2.5 meters** by **2.5 meters** (just over eight feet square). This represents approximate width of the LRV **as well as** the width of the RTV as it angles across the tracks. Selecting the length and width of the collision zone to be the same allows the far edge of the zone to be represented by a single line at **2.5 meters** beyond the near edge of the CZ (the dotted line **2.5 m** above the horizontal **axis**).

The exact distance of the collision zone from the stop line depends on the path of the RTV through the intersection. In general, the graphs will show the collision zone (and not the stop line). However, countermeasures will attempt to ensure that RTV’s halt before the stop line, using the distance between the stop line and the near edge of the **CZ** **as** an extra margin of safety.



A collision occurs if both vehicles occupy the collision zone at the same instant. This means from the time the front bumper of the RTV crosses the near edge of the collision zone until the rear bumper passes the far edge, the vehicle is in danger. The RTV is assumed to be 4.7 meters (15.4 feet) long, meaning that it is in danger for 7.2 meters (23.6 feet) along its path (2.5 m plus 4.7 m). Traveling at 6 ~~0sec~~ this exposure interval is 1.2 second. Similarly, the LRV is assumed to be 30.5 m long, resulting in a 33 meter exposure to collision. At 15 ~~0sec~~ this is 2.2 seconds. **As** the vehicle velocity decreases, the time interval required to cross the collision zone increases.

Zooming in on the upper right of Figure 4.4a results in Figure 4.4b, which has the collision zone entry and exit times marked for both vehicles. For this particular case, the LRV is far enough from the intersection that the RTV clears the collision zone ( $t=6.2$  seconds) prior to the LRV's entry (at  $t= 6.5$  sec).

Figure 4.5a is a repeat of 4.4a, except that the LRV is 15 meters closer, with an initial position 82.5 meters from the collision zone when the RTV starts moving. The RTV enters the collision zone first, but the LRV enters the CZ at  $t=5.5$  seconds, prior to the RTV's departure. This scenario results in a collision where the LRV runs into the side of the RTV. In Figure 4.5b the LRV is another 15 meters closer initially, **so** it enters the collision zone one second earlier, at 4.5 seconds. In this case when the RTV enters the collision zone at time  $t=5.0$ , it strikes the side of the LRV.

Figure 4.6 shows what happens when the LRV is even closer to the intersection as the RTV starts its maneuver. The Light Rail Vehicle passes through the intersection before the RTV enters the **CZ**, and no collision occurs. **As** a practical matter, cars generally don't run into the rear portion of the LRV's. The collisions usually involve the LRV's running into RTV's, or RTV's striking the front portion of the LRV's. Once the LRV is in the field of view of the RTV driver, the drivers generally recognize the danger and take evasive action, and therefore do not strike the back half of the LRV's. This evasive action *can* involve braking, steering, or some combination of both.

Figures 4.4 - 4.6 show the three possible results when an RTV crosses through the collision zone **as** an LRV is approaching:

Condition 1) - RTV passes safely in front of LRV,

Condition 2) - Collision, LRV strikes RTV (Fig 3.3a) or RTV runs into LRV (Fig 3.3b)

Condition 3) - LRV passes in front of RTV.

Another possible result when an RTV is about to traverse through the collision zone is that the RTV changes trajectory, and does not enter the collision zone. Enhancing the probability of this is the basis of a large class of countermeasures.

It is important to determine the dividing lines between the first three cases. To distinguish between the first and second conditions, one must determine how close an LRV **can** be before it hits a RTV attempting to cross in front of it. This distance is called the LRV Minimum Collision Distance. Similarly, distinguishing between conditions 2 and 3 results in the LRV Maximum Collision Distance. Since the critical range is **defined as** the range of LRV positions which result in collisions, it is the range **between** the Minimum and Maximum Collision Distances.

**An** example, using the data from Figures 4.4, 4.5, and 4.6, may help clarify these definitions and concepts. **In** Figure 4.4, the time difference between when the RTV clears the collision zone (6.2 seconds) and when the LRV enters it (6.5 seconds) is 0.3 seconds. With the LRV traveling at 15 m/sec, this corresponds to 4.5 meters. Thus **if** the LRV **started** 4.5 m closer at time  $t=0$  (i.e. **at** a position 93 m from the collision zone) it would just barely hit or **miss** the RTV, thus this is the Maximum Collision Position for the velocity profiles **used** in this figure. Similar analysis of Figure 4.5 or 4.6 reveals that the Minimum Collision Position for these velocity profiles is 46.5 m. These two positions **define** the critical range. The next step is to determine the sensitivity of the critical range to various system characteristics, such as braking by one or both of the vehicles. The key parameters describing braking are the time at which the brakes are applied and the braking rate that they are able to achieve.

#### 4.4.3 Countermeasures

There **are** a large number of possible collision countermeasures. First we will present various ways of categorizing the countermeasures. This is followed by descriptions of representative candidates.

##### 4.4.3.1 Category Characteristics

The countermeasures can be categorized in any of several manners. Some of the ways discussed include:

- 1) Location of the new equipment (wayside, onboard, or combined),
- 2) Technical sophistication (new technology/old technology)
- 3) Method of operation (Active vs. passive)
- 4) Control method (automatic vs. manual)
- 5) Evasive action (LRV or RTV braking, RTV steering change)

For each countermeasure considered, one must judge both the cost and the effectiveness of the countermeasure. For some this is done analytically, while for others the evaluation is based on engineering judgment. For instance, one of the proven standards for protecting at-

grade crossings is with the use of two quadrant crossing gates. This is an effective method of preventing collisions, although to stop left-turning vehicles, four quadrant gates would probably be more effective. Logistic constraints prevent the **use of** physical barriers such as crossing gates at many intersections in the San **Jose** System.

Given the wide variety of possible countermeasures, we **will** present some **of** the more promising ones, including at least one or **two** from each category, followed by a discussion **of** the characteristics of each grouping.

#### **4.4.3.2 Candidate Countermeasures**

**This** section presents a brief description of each of the countermeasures given consideration. Some of these are only part of a complete solution, such **as** the mechanism for detecting a likely collision, or the method for countering a hazard condition once it is detected. The solutions are generally presented from least to most expensive and lowest to highest technical risk.

Knock Down Strips (passive barrier)- These would be plastic 'posts' placed at the far edge **of** crosswalks. They would collapse when run over, and pop back up again immediately, presumably with no damage to either the RTV or the strip. They would help stop RTV's from cutting the turn too tight.

Passive Warning Signs - This would consist of additional signage to make RTV drivers aware that the LRV system is operating on the median of a particular street. This is one of the least costly countermeasures.

Signal Timing Changes - The first step is signal pre-emption, creating red signals for cross traffic and parallel traffic left turn pockets when an LRV is approaching. The next step, which is currently being implemented by the TA, involves delaying the straight through green by 3-5 seconds. This reduces the probability that drivers in the left **turn** pocket (who are **used** to leading left turn timing) would run the red left turn arrow when the straight through signal turns green.

Active Barriers - This includes several **types** of equipment which would move into place, **blocking** RTV's from entering the collision zone when an LRV is approaching. **All** of these would block access to the collision zone, such **as** conventional crossing gates. The cheapest is probably pop-up plastic posts which a visual rather than physical barrier. **As** with the passive knock-down strips, these would **suffer** no damage if a RTV ran over them. Crossing gates, as mentioned above, fall into this group, **as** do structural pop-up posts.

Automatic Audio Warnings - These are warnings which would be sounded automatically. They could consist of bells, horns, a synthesized voice, or some combination **of** the above elements. The alarms could be mounted either on the wayside or on the LRV's. Ones

mounted on the LRV's could be intended to warn either the RTV driver or the LRV operator. Any of these could be sounded every time an LRV travels through an intersection, only when traffic is present in the left turn pocket, or only when sensors detect moving (hazardous) traffic in the **left turn** pocket. These could also be progressive, increasing in intensity **as** the danger level increases, (assuming the sensors are sophisticated enough to provide this information).

Automatic Visual Warnings - This would be a supplement to the existing 'Trolley Coming' signs, such as a flashing red border or a strobe light. **As** with the audio warnings, these could be progressive, such **as** changing the flashing rate with increased danger.

Conventional Sensors - The system currently **has** sensors which detect the presence of both RTV's and LRV's, **although** only at discrete points. Never the less, these could be used to trigger either of the two preceding warning systems, much as they trigger the existing 'Trolley Coming' signs.

Advanced Sensors - There are many sensors which could provide better quality information on the presence/movement **of** traffic in the left turn pockets. Some would provide position on a continuous or high frequency, while others measure velocity as well **as** position directly. This category includes several technologies such as radar, IR laser, ultra-sound, and video signal processing. The cost of most of these sensors is dropping rapidly, and even if they are not economically competitive today, they probably will be soon.

Automated Evasive Action - The simplest, most near-term form **of** this would be automatic activation of the LRV brakes when a likely collision is detected. Automated evasive active by the RTV is obviously very far in the future, when some percentage **of** RTV's are equipped with computer controlled brakes and/or steering as well as a communications system. By the time cars are available with these capabilities, they may to be smart enough to prevent foolish actions (like **running** red lights) which would put them into a hazardous situation in the first place.

Countermeasures, are discussed in greater detail Chapter 5.

#### **4.4.4 Determine LRV Performance Limits**

The first analysis performed examined the limits of what can be achieved by deceleration **of** the LRV when a collision is possible or likely. This is done by examining the *critical range* for a variety of *cases*. Initially, the critical range is determined for a typical maneuver by the RTV. Then the sensitivity of the critical range to LRV braking parameters is examined to determine the effectiveness of this **as** a possible countermeasure.

#### 4.4.4.1 Sensitivity to LRV Braking

The first parameter to be examined is the time at which the brakes are applied. This is done without regard to method **used** to apply the brakes (automatic vs. manual), although obviously to apply the brakes at the instant that the RTV starts moving (time  $t=0$ ) would be faster than humanly possible. It would also result in numerous instances of unnecessary braking at a high rate (service braking or maximum braking). This would probably occur when riders are not expecting a severe deceleration, and might cause injuries, especially to standees on the LRV.

##### 4.4.4.1.1 LRV Braking Initiation Time

LRV trajectories for several braking initiation times are shown in Figure 4.7, along with the RTV movement from the previous. There is one curve for each of the four braking initiation times selected (**0.5**, 1.5, 2.5, and 3.5 seconds), as well as the baseline where the brakes are not applied at all. A braking rate of 1.5 m/sec/sec is used, which is nearly equal to the system specification of 1.56 m/sec/sec (3.5 mph/sec, or coming to a complete stop from 35 mph in 10 seconds). The LRV initial position is -67.5 meters, the same as in Figure 4.5b. The LRV curve for no braking is identical to Figure 4.5b which results in a collision at 4.5 seconds. However, even initiating braking at 0.5 seconds, well before it is possible to determine whether or not the RTV is going to run the light and enter the Collision Zone, is insufficient to prevent a collision.

The effect of braking initiation time on the critical range is presented in Figure 4.8. With no braking, the critical range is from 42 to **93** meters. With braking, both the upper and lower boundary of the critical range are reduced. For instance, if the LRV is 80 meters from the collision zone when the RTV starts moving (time  $t=0$ ), it collides with the RTV unless it starts braking before time  $t=2.0$  seconds. **As** the upper bound of the critical range decreases, it is more likely that the RTV can pass safely in front of the LRV. On the other hand, the lower limit of the Critical Range also decreases. Starting 40 m from the collision zone and without any braking, the LRV will pass safely in front of the RTV. However if it applies the brakes before 3.5 seconds, the LRV will slow down enough that the RTV will strike the rear portion of the LRV. The right hand boundary **of** the Critical Range slants more than the left boundary, indicating that with earlier braking, the size of the Critical Range decreases slightly. (The **two** curves are closer together when braking starts at 0.5 seconds than when braking starts at 4.5 seconds.) Clearly, if the LRV is going to beat the RTV through the Collision Zone, it is better not to brake at **all**. *Also*, based on experience of the TA personnel, **cars** rarely, if ever, strike the rear of an LRV; once the LRV starts overtaking the RTV, the driver of the car realizes that they shouldn't **turn** left and alters **course** to avoid a collision. This means that the left edge of the Collision Zone **is** somewhat fuzzy, and the right edge **of** the CZ is probably the area that deserves most attention. One final observation is that even if the LRV starts braking at time  $t=0$ , the instant that the RTV starts to move, the Critical Range Interval can not be reduced to zero. Simply put, at certain initial positions of the LRV, if the RTV starts moving,

there is nothing that the LRV operator can do to avoid a collision. This is not to say that LRV should never apply the brakes. Some collisions can be avoided, and many other instances the LRV's velocity at the time of impact is reduced. This may reduce the severity of the collision to some extent, although given the **mass** of an LRV even if the velocity is **reduced from 15 m/sec to 10 m/sec**, the collision is still likely to be reasonably severe.

#### 4.4.4.1.2 LRV Braking Rate

The braking rate is the other parameter which directly contributes to the effectiveness of LRV braking. As with the previous analysis, a braking rate of **1.5 m/sec/sec** is assumed as the baseline. Variations are taken at **50%** higher and lower, **2.25** and **0.75 m/sec/sec**. The actual maximum braking rate for the Santa Clara County system is **2.24 m/sec/sec (5 mph/sec)**. The system also has an emergency braking mode, which provides open-loop (uncontrolled) braking at a rate which can vary at least  $\pm 10\%$  from the maximum braking rate, with the down side being even greater under some circumstances, such as wet track. The emergency braking mode is only used when the motor controller is not functioning properly, and is roughly equivalent to locking the wheels and skidding to a stop in a rubber-tired vehicle.

Figure 4.9 presents results for these variations in braking rate. This figure, like Figure 4.7, uses Figure 4.5 as a baseline. The LRV brakes are applied at **1.5** seconds (note, this is before the Long Creep-up Maneuver and Run Light, Fast profiles can be distinguished from each other). In addition to the three braking rates mentioned above, a fourth curve with no braking is presented. Even with a braking rate of **2.25 m/sec/sec**, starting at an unrealistically early time (**1.5** seconds), the LRV still hits the RTV (the LRV enters the collision zone at **6.0** seconds and the RTV doesn't clear the CZ until **6.2** seconds). As with variations in LRV braking initiation time, improving the LRV braking rate is still relatively ineffective in eliminating collisions.

Earlier application of the brakes would eliminate some number of collisions. On the other hand, applying the brakes at maximum (**2.25 m/sec/sec**) whenever a car in the left turn pocket moves even slightly would most likely result in a much larger number of injuries to standees in the LRV's.

The Critical Range Interval for various braking rates is shown in Figure 4.10. This is similar to Figure 4.8 in that, the right hand edge of the Critical Range curves to the left (decreases) with improved braking performance of the LRV (earlier or higher braking rate). As in Figure 4.8, the left edge of the Critical Range Interval would also curve left if the LRV applied the brakes in cases where it would safely pass in front of the RTV. In this figure, it is assumed that the LRV only applies the brakes in cases where it would hit or pass behind the RTV, causing the left edge of the Critical Range Interval to be a vertical line.

#### 4.4.4.2 Discussion of LRV Braking

The preceding analysis has shown that LRV braking can eliminate a small percentage of the collisions and reduce the severity of some others. However, braking by the LRV's is physically not able to eliminate most left-turn collisions. This is due to both the high speed and limited braking rates of LRV's. Braking of the LRV's is limited by the coefficient of friction of a steel wheel on steel rail, which is much lower than rubber tires on either concrete or asphalt. The occupants of an RTV are all seated and presumably belted in, eliminating the dangers present for standees when LRV's brake even at **2.25 m/sec/sec**. For these reasons, RTV's can generally out brake LRV's by a factor of three or four. The limited braking capability of the LRV's, combined with their higher approach speed to an intersection, rules out LRV braking as a viable solution to the left turn collisions. There is no realistic set of parameter values for which LRV braking can cause the size of the Critical Range Interval to decrease to **zero** i.e., to avoid a collision regardless of the LRV's position when an RTV starts to run a red light.

#### 4.4.5 Determine RTV Performance Limits

The analysis in the previous section indicated that LRV braking is only marginally effective in eliminating left turn collisions. The next set of actions to be examined involve evasive maneuvers by the rubber-tired vehicle. For the moment, we will not concern ourselves with what instigates these actions, but rather how effective they can be in eliminating collisions.

The LRV's evasive actions are limited strictly to braking. We ~~will~~ focus the analysis on RTV braking, although steering maneuvers are also possible and will be examined.

##### 4.4.5.1 Sensitivity of RTV Braking

RTV braking is much more promising as a method for avoiding collisions due to two basic facts. First, an RTV in the left turn pocket is approaching the intersection a much lower speed than the LRV, generally by a factor between two and four. Second, the RTV is capable of much greater deceleration rates than an LRV. This is due to both a better coefficient of friction (rubber tire on pavement is close to **1.0** as opposed to perhaps **0.25** for steel wheel on steel rail) and better passenger restraint. This results in braking distances which are at least an order of magnitude lower for the RTV compared to the LRV.

##### 4.4.5.1.1 RTV Braking Initiation Time

Due to the very short stopping distances for slow-moving RTV's, braking can be initiated much nearer the moment of impact and still be an effective collision-avoidance maneuver. Figure 4.11 shows trajectories for braking initiation times of **3.0, 3.5, 4.0, and 4.5** seconds, as well as with no braking. Note that in Figure 4.7, the corresponding figure for LRV braking,

the braking initiation times varied from **0.5** to **3.5** seconds, and none of them were adequate to prevent a collision. The braking rate used is **1.5 m/sec/sec**, which is very gentle for a rubber tired vehicle. A value of two, three, or even four times this is more realistic for braking in an emergency situation. For comparison, braking rates of **7.5** to **9.0 m/sec/sec** are recorded for new vehicles on *dry* pavement, operated by professional drivers. When brakes are applied at **3.0** seconds, the RTV stops about four meters prior to entering the collision zone. When braking is started at **3.5** seconds, the RTV just enters the CZ, while braking at **4.0** and **4.5** seconds results in the RTV proceeding through the Collision Zone and stopping beyond the far edge. The key observation in this figure is that if the RTV can be stopped prior to entering the CZ, no collision occurs, regardless of location of the LRV. The Critical Range has collapsed to zero **size** when the RTV stops short of the CZ.

Figure **4.12** shows the Critical Range Interval as a function of braking initiation time. The left edge of the Critical Range Interval curves very sharply to the right at approximately **3.5** seconds. If braking starts any time before **3.45** seconds, even at this low braking rate of **1.5 m/sec/sec**, the RTV does not enter the collision zone and no collision occurs. This really amounts to the same thing as a normal stop at a LRV pre-empted left **turn** pocket.

One final item to note on Figure **4.12** is that the right boundary of the Critical Range Interval is a vertical line. This is a result of the assumption that if a RTV is going to beat the LRV through the intersection, the RTV will not apply its brakes, and slow down or stop on the tracks. This assumption is not always valid. For instance looking at the trajectory for braking at **3.5** seconds in Figure **4.11** shows the RTV coming to rest on the tracks. For this case, the Critical Range extends to infinity to the right. This means that if the RTV stops on the tracks and never moves, eventually a LRV **will** hit it, even if the LRV started a kilometer away.

#### **4.4.5.1.2 RTV Braking Rate**

The analysis in the previous section used a very modest RTV braking rate of **1.5 m/sec/sec**. As was mentioned previously, most **vehicles** are capable of braking rates of **7.5 m/sec/sec** or greater, even if drivers are unwilling to brake at this high a rate. In this section we examine the effects of higher, more reasonable braking rates. Figure **4.13** shows vehicle trajectories with braking rates of **1.5, 3.0, 4.5, and 6.0 m/sec/sec**. Braking for all **cases** starts at **4.5** seconds, just **0.5** seconds before the RTV enters the Collision Zone. With a braking rate of **6.0 m/sec/sec**, the RTV is able to stop right at the edge of the Collision Zone, while with more modest braking rates, it enters the CZ prior to **coming** to a complete stop.

The sensitivity of the Critical Range to braking rate is shown in Figure **4.14**. The shape of **3.12** is similar to **3.10**. The left edge of the critical range starts out nearly vertical, and then curves sharply to the right, and eventually meeting the vertical right edge of the Critical Range Interval. For braking performance above a certain value (earlier braking initiation time or higher deceleration rate) the RTV stops prior to entering the Collision Zone and no collision



occurs, regardless of the LRV's initial position. In these cases, the size of the Critical Range Interval has decreased to zero.

#### 4.4.5.1.3 Simultaneous Variation of Braking Rate and Initiation Time

Figures 4.11 and 4.12 use a very gentle braking rate (1.5 m/sec/sec) therefore a early braking initiation time (over 1.5 seconds prior to entering the Collision Zone) is required to stop the vehicle short of the CZ. Figures 4.13 and 4.14 use a late braking initiation time (0.5 seconds prior to entering the CZ), and require a high braking rate (6.0m/sec/sec) to eliminate all collisions. There is an obvious tradeoff between braking initiation time and the required braking rate.

Closer examination of this tradeoff gives significant insight into possible collision warning/collision avoidance methods. Figure 4.15 presents the Critical Range Interval for several combinations of braking rate and braking initiation time. Each of the curves represents a different braking initiation time. The highest curve (dashed) is just a repeat of Figure 4.12, representing a braking initiation time of 4.5 seconds, or just 0.5 seconds prior to the RTV entering the Collision Zone. The lower curves represent 4.0, 3.5, and 3.0 second braking initiation times (1.0, 1.5, and 2.0 seconds prior to Collision Zone entry respectively). Although the time intervals between these four curves is equal, their spacing is clearly not even. As one moves from one curve to another, a change of 0.5 seconds in the braking initiation time results in a factor of two change in the braking rate required to reduce to size of the Critical Range Interval to zero. This indicates that although it is possible to prevent collisions with very late, severe braking, an additional 0.5 to 1.0 seconds or warning time reduces the required braking rate dramatically, and would undoubtedly eliminate a certain number of collisions. The objective of a collision warning system should then be to warn the driver of the RTV as soon as possible, although late warnings (with correspondingly late braking) are clearly better than no warning at all.

One can examine the trade-off between braking initiation time and the braking rate required to prevent entry into the collision zone. Figure 4.16 characterizes this trade-off. It has been prepared using the "Run light, Fast" RTV trajectory of Figures 4.11 through 4.15. Clearly putting on the brakes even slightly earlier allows much lower braking rates while still stopping before entering the Collision Zone. Note the second vertical time scale on the right, presenting the braking initiation time with respect to the moment the RTV would enter the CZ rather than with respect to when the RTV starts moving. This redefinition of the time scale may seem unimportant, but it is critical when considering other possible RTV velocity profiles (of which there are infinitely many). For instance, if a vehicle is 12 meters from entering the Collision Zone and traveling at 6 meters per second, the previous history is irrelevant - the braking distance will be dependent only on the braking rate and the RTV's velocity at the instant that braking starts.

The only value of previous history may be for warning algorithms, when trying to predict what the velocity of a vehicle is likely to be one or two seconds in the future. For instance, if two vehicles are at the same location and same velocity, but one is decelerating and the other is accelerating, the one that is braking presents much less of a danger. If they were both to start braking at the same instant and rate, they would both have the same stopping distance. If both waited for one second and then started braking, obviously the one which had been accelerating would be closer to the **CZ** and traveling at a higher velocity, and would travel further before **coming** to a complete stop.

#### 4.4.5.2 RTV Steering Actions

**To** this point, we have assumed that both vehicles follow a **pre-determined** path along the ground, with speed being the only variable. **This** is clearly a **correct** assumption for the LRV, **as** it follows the tracks. RTVs, in contrast, may avoid collisions by steering as well as braking. However, the literature suggests that, at least in automobile-automobile accidents, drivers tend to brake rather than steer, even when post accident analysis reveals that steering would have been a safer action. Edwards and Malone (1982) examined evasive actions based on self reported behavior of drivers involved in approximately 4,000 accidents between 1979 and 1981. Their findings are summarized in Table 4.3.

Adams (1994) summarizes a number of articles on collision avoidance maneuvers. From this review, the author concludes that drivers are more likely to brake than to steer, while the optimal maneuver would more frequently be steering alone, or steering in combination with braking rather than braking alone.

On the other hand, it may not be appropriate to extrapolate the conclusions of this work to the case of LRV left-turn collisions. In the LRV case, the RTV driver is planning to turn, and the steering action to avoid a collision would be to proceed straight (in conjunction with braking). In sum, it is unclear what reaction a reactive alarm **would** elicit from drivers during a turning maneuver. Further field work **would** be necessary to establish drivers' reactions to a reactive alarm.

In **all** the figures with RTV braking, the curve of position vs time becomes a horizontal line when the vehicle comes to stop (toward the right hand side of the graph). Sometimes the RTV stops prior to entering the **CZ**, while other times it comes completely to rest after it has entered the collision zone. For **cases** where the RTV just enters the **CZ** by a couple of meters, it would be possible to avoid a collision simply by not turning i.e., continue braking while proceeding straight, stopping within the intersection, but not on the light rail tracks (not in the **CZ**). The RTV could then finish its left turn **after** the LRV is past. While this is clearly possible, and perhaps even likely, to be conservative in this analysis, it is assumed that the RTV does not change its path track along the ground.

#### 4.4.5.3 RTV Avoidance Maneuvers

Kinematically speaking, RTV avoidance maneuvers are the most effective way to eliminate collisions. This is due to three factors:

- 1) Low speeds while approaching an intersection (in left-turn pocket).
- 2) High maximum braking rates are possible
- 3) The RTV **can** change its path along the ground, unlike the LRV.

The down side to RTV evasive action is that it may be difficult to cause the driver of the RTV to initiate braking or change the planned steering profile. Given that an RTV driver must be in the **process** of running a red light to create a dangerous situation in the first place, they are probably not paying close attention to the surroundings and may not observe, recognize, or heed warnings. The problem of getting the drivers attention seems to be the weak **link** if any scenario involving RTV evasive action. This is discussed in more detail in Chapter 5.

#### 4.4.6 Determine Last Possible Braking Moment

The analysis from the previous section starts answering the question of when the RTV must start braking in order to avoid entering the Collision Zone. Figure 4.16 presented those results for a single vehicle velocity profile, one where the vehicle starts from a standstill, accelerates at **1.5 m/sec/sec** for four seconds, and then travels at constant speed. This analysis must be generalized, as various vehicles will be traveling at different speeds. Figure 4.17 is similar to Figure 4.16, but presents required braking initiation times for several RTV approach speeds. (For each curve, the RTV is approaching the intersection at a constant speed, rather than accelerating from a stop as in the previous cases.) The curve for **6 m/sec** is very similar to the curve in Figure 4.16, where the vehicle was moving at **6.0 m/sec** at times **4.0** seconds and above. With the higher approach speed of **9 m/sec** (**20 mph**) the vehicle must brake much earlier for the same braking rate. If one assumes a moderate braking rate of **3.0 m/sec/sec** (**6.7 mph/sec** or about **0.3 Gs**), the RTV must start braking **1.5** seconds prior to entering the Collision Zone. The braking initiation time (required to prevent entry to the CZ) varies inversely with braking rate, **so** cutting the braking rate in half (to **1.5 m/sec/sec**) doubles the braking initiation time to **3.0** seconds. The braking initiation time varies linearly velocity, **so** cutting the velocity by a factor of three (to **3 m/sec**) drops the braking initiation time **1.5** seconds down to **0.5** (prior to collision zone entry).

The position at which the RTV must start braking varies with the velocity squared. This is because in addition to the braking time increasing, the average velocity during the deceleration period also increases linearly with initial velocity. Figure 4.18 shows variations of both braking time and braking position with RTV approach velocity. A deceleration rate of **3.0 m/sec/sec** is used for both curves.

The position curve basically provides the **nearest** that an RTV should be (at any particular velocity) before applying the brakes. This assumes that the vehicle will brake at a moderate rate (**3.0 m/sec/sec**). This is exactly the **type** of information needed to define a warning algorithm, as will be done in subsequent **sections**.

#### 4.4.7 Determine Appropriate Warning Moment

The previous analysis provides useful insight into the relationship between vehicle velocity, position, and braking initiation time. Translating that knowledge into a workable warning moment equation or algorithm involves both **engineering** judgment **as well as** analytical work. In doing *so*, it is desirable to make reasonably conservative assumptions, tending to error on the side of giving **unnecessary** warnings rather than delaying a warning when it is needed. This philosophy obviously breaks down if taken to an extreme, **as** false alarms would be issued frequently. This would reduce the alarms' effectiveness in two ways. First, the public would get used to the alarms and tend to ignore **them** (the boy who cried wolf). Second, if the alarms were going off frequently, occupants **of** nearby buildings would undoubtedly complain, and the intensity of the alarms would be reduced to a lower level than would be tolerated if the alarm sounded only occasionally when a hazard truly existed.

##### 4.4.7.1 Baseline System

The first step in the process of determining **the most** effective warning moment is to take the data from Figure 4.17 and replot it in a **manner** which could be used to trigger a warning. Figure 4.18 presents the data for braking at **3 m/sec/sec**. The lower portion of the figure shows the braking initiation time **from** Figure 4.17, plotted **as** a function of the RTV approach velocity. The upper portion of the figure shows the corresponding positions at the moment deceleration starts. This curve of position vs. speed presents the nearest that the vehicle should be before the brakes are applied for **any** given speed. For instance, at a speed of **9** dsec, the vehicle should start braking at or **Wore** it reaches a position of **13.5** meters from the Collision Zone.

The next item to consider is the response **time** of the RTV driver. This includes recognizing the alarm and taking action. **Human** response times vary quite a bit, both from one person to another, and even for a particular individual, depending on the time **of** day, their mood, etc. We have chosen **1.5** seconds **as** a reasonably conservative response time. This response time is added to the braking time to determine the warning moment, **as** shown in Figure 4.19. **As** with Figure 4.18, time is shown on the bottom and position on the top of the graph. Figure 4.19 assumes that the RTV is approaching **the** intersection at a constant velocity, allowing the drivers reaction time to be converted into **a** distance simply by multiplying by the velocity. For instance, at **6 dsec**, a reaction time of **1.5** seconds corresponds to a vehicle movement of 9 meters. Note that both the braking distance **and** the reaction distance (distance the vehicle

moves during the drivers reaction time) go to zero at zero velocity, even though the reaction time remains constant at **1.5** seconds. The warning position curve in Figure **4.19** is used as the baseline for comparisons in the following section.

#### **4.4.7.2 System Variations**

The braking rate is the first parameter to be varied. Figure 4.20 shows the warning distance (position of the RTV when the warning is to be issued) for various braking rates. In addition to the curve for a braking rate of **3.0 m/sec/sec** (identical to Figure **4.19**) data for **1.5** and **4.5 m/sec/sec** have been added. Obviously reducing the braking rate to **1.5 m/sec/sec** dramatically increases the distance at which the warning should be given. This might be appropriate for the first alarm in a system which uses a progressive warnings. If the vehicle passes the second curve (for instance is still going at **6 dsec** at a distance of **15** meters, a second, more intense **alarm** would be issued. The braking distance increases with approach velocity squared, **so** the separation between the curves increases rapidly toward the right side of the graph.

The second parameter to be varied is the driver's response time, as seen in Figure **4.21**. In addition to the (conservative) baseline value of **1.5** seconds, curves are shown for **2.0** (rather slow) and **1.0** seconds (reasonably quick). Figure **4.21** is similar to **4.20**, but the curves are closer together, indicating that the warning position is less sensitive to the drivers reaction time than the braking rate.

Acceleration of the RTV during the time interval between the warning and the initiation of braking is the last item to be examined analytically. Figure 4.22a presents three RTV trajectories. The solid curve is the baseline, representing an approach to the intersection at constant velocity. At **2.5** seconds, with the RTV **15** meters from the Collision Zone, a warning is issued. At **4.0** seconds (after the **1.5** second reaction time interval), the vehicle starts braking at a rate of **3.0 m/sec/sec**. this results in the vehicle coming to a complete stop at the edge of the collision zone at time  $t=6.0$  seconds. starting points of the other two trajectories have been adjusted **so** that they also pass through **15** meters at a velocity of **6 dsec** at **2.5** seconds. After a **1.5** second reaction time, both start braking at a rate of **3.0 m/sec**. The dashed curve represents a vehicle which is already decelerating at **1.5 m/sec/sec**, by **4.0** seconds, it **has** already slowed to **3.75 m/sec**. From this reduced velocity, the vehicle stops more quickly, coming to a stop at **5.25** seconds, **5.34** meters (**17.5** feet) prior to entering the CZ. The other case (dotted curves) represents **a** vehicle accelerating at a rate of **1.5 dsec**. When the driver hits the brakes (**4.0** seconds), the vehicle is moving at **8.25 dsec** rather than the **6 dsec** when the warning was issued. It is also about **1.5** meters (**5** feet) closer to the CZ the baseline 'constant approach velocity' case. The extra speed increases the stopping distance, and the vehicle doesn't come to a stop until **6.75** seconds, at a position of **7** meters beyond the beginning of the Collision Zone. This would result in a collision for certain initial positions of the LRV, i.e., the warning was issued too late for this particular case.

Two vehicles can be at the identical *speed* and position at one instant, receive the same warning, and have identical response times, but have significantly different trajectories resulting **as** the result of modest differences in **acceleratiodeceleration** lasting only a second or two. **This can** clearly be seen in Figure 4.22a. The way to counteract these variations in warning effectiveness is to compensate for the RTV's acceleration. Although obviously this **can not be** predicted exactly, for most **cases** assuming that the acceleration level **will** remain constant for the next second or two **is** reasonable. **Making** this assumption changes the trajectories in Figure 4.22a to those in 4.22b. A warning is given to the accelerating vehicle earlier, at **1.9** seconds instead of 2.5 seconds. It **starts** braking at 3.4 seconds and comes to a stop at the edge of the CZ at time  $t=5.85$  seconds. The baseline curve is unchanged, while for the decelerating vehicle, no warning is given, **as** this vehicle stops safely on its own.

These cases indicate that knowledge of the RTV's acceleration can be useful in both eliminating false alarms and issuing more effective warnings in some cases.

#### 4.4.8 Determine Warning Algorithm

Analysis in the previous section made a strong case for a warning algorithm which uses position, velocity, and acceleration. The key parameters assumed are a **1.5** second driver reaction time and a 3 m/sec/sec braking rate (approximately 0.3 **G s**). The algorithm assumes that when a warning is issued, the RTV will maintain its current rate of acceleration the reaction interval and then decelerate to **a** stop at a moderate rate. **An** alarm would be issued when the RTV transition from a safe to **an** unsafe trajectory following these assumptions.

The analysis and discussion **up to this** point was based on the presumption of stopping the RTV prior to its entry into the Collision Zone. **An** added margin of safety can be achieved by warning the vehicle when the assumed profile would result in the RTV crossing the stop line rather than entering the CZ. **This has the** added benefit that the stop line is uniquely defined, where the location of the CZ **will** vary, depending on the RTV's path through the intersection. **As** was mentioned previously, the distance from the stop line to the entry of the CZ will vary depending on the intersection geometry and the RTV's steering actions. While this can be up to **15** meters (50 feet) it can also be **just** a couple meters. Regardless of the exact value, this distance **has** now become an extra margin of safety, **as** warnings would be issued in sufficient time to **stop** the RTV at or short of the stop line.

#### 4.4.9 Collision Warning System Description

The system which evolves from this analysis effort is one that senses a rubber-tired vehicles movements in the left turn pocket and continually examines the likelihood of the vehicle failing to halt prior to the stop line. When the collision warning system detects a likely occurrence of over-running the stop line, it issued a warning to the driver of the RTV. The exact nature of

this warning **has** not been determined, **but** would probably consist of some sort **of** audio alarm, perhaps supplemented by a visual warning. The audio warning would attempt to cause the RTV driver to realize that there was imminent danger from a light rail vehicle. The alarm would probably consist of a train horn **or** bells, perhaps with a synthesized voice with a warning such as “Danger, Train **Coming**”. The visual portion **of** the warning, assuming it **is** included, would have some sort of **flashing** lights (which are more pronounced than the existing “Train **Coming**” signs).

The intent **of** the warning would be to **alert** the RTV driver to the existence **of** the LRV. It would be up to the driver to determine **the** most effective evasive action available to **him/her**. **This** philosophy would limit legal liability and probably be least **as** effective **as** a system which attempted to **instruct** the driver **as** to **the most** effective evasive action. **Part** of the difficulty **as** to recommending an evasive action **is** that the most effective action depends to some extent on how quickly the driver reacts, **and this** would not be **known** by the collision warning system.

#### **4.4.10 Determine System and Component Requirements**

There are several types **of** requirements and specifications which go into the design **of** a collision warning system. The highest **level** of requirements are on system performance, such **as** the number **of** accidents that the system would be expected to eliminate.

The next level down would consist **of** sub-system requirements, such as the sensing sub-system or the alarm sub-system. The **alarm** system could have a requirement that a certain percentage of the drivers would recognize or react appropriately to an warning when it is issued.

The **final** level of requirements get down **to** component specification, and might include items such as the accuracy and frequency **with** which the sensors measure the vehicle’s position or velocity. Similarly, an audio alarm **might** be required to produce a certain sound level at a specified distance.

The example requirements listed above **are** reasonable items to specify, and are intended to show the type of requirements which would be placed on a system prior to prototyping **or** deployment.

Detailed specifications would in fact **be part** of the next phase of this project. Under the current funding the requirements were examined a bit less rigorously. The depth is sufficient to determine basic feasibility of the **concept**, although most of the values presented represent engineering judgments rather than the **results of** rigorous analysis.

#### 4.4.10.1 System Requirements

They system level requirements might take a form such as “The collision warning system should reduce **left** turn accidents throughout the entire light rail system by 50%.” It would **also** be reasonable to expect the system to be cost-effective, such as requiring that the life-cycle benefits exceed the total **system** costs (capital and maintenance). The cost effectiveness analysis is highly dependent **on** the assumptions used. Specifically, should benefits be measured as savings to the TA **or to** society **as** a whole (the difference being costs borne by RTV drivers/owners when they **are** at fault in a collision). Similarly, how should funding by outside sources (state or federal) **be** considered when calculating the costs. There are really two cost-effectiveness calculations **to** be performed, one regarding the TA exclusively, and the other looking at society **as** a whole.

#### 4.4.10.2 Sensor Requirements

The warning algorithm defined in section 3.8 requires knowledge of the RTV’s position, velocity, and acceleration. Numerous technologies exist to measure position, and some can measure velocity directly, but **no** ground-based sensors can measure acceleration directly. That can only be determined by taking a numerical derivative of the velocity signal. Taking one derivative numerically is not terribly troubling (determining speed by taking differences of position readings), but taking a second one to get acceleration is likely to be much more difficult for a couple of reasons. First, when taking a derivative, noise tends to get amplified. Additionally, data must be taken over a finite time interval to get meaningful results, and the required time interval increases significantly if a second derivative is required. For these reasons, it seems reasonable to **measure** velocity directly, (which can be done with a Doppler-type radar) unless a the position sensor has both very high update rates and excellent accuracy.

Regardless of how the primary sensors function, the output from the signal processing software should be updated at least 10-20 times per second and perform well in **all** ambient conditions. The position signal should have an uncertainty of no greater than  $\pm 1.0$  m. The velocity signal accuracy should be approximately  $\pm 0.5$  ~~deg~~ with the acceleration signal at  $\pm 0.5$  m/sec/sec. Obviously, if the position signal is **used** as the basis for the velocity reading, its accuracy (and update rate) **would** have to be much better than specified here. There are also some tradeoffs between the **accuracies** of the various signals i.e., if the velocity and acceleration signals are more **accurate** than specified above, the tolerance on the position signal can be loosened a bit. **This** might allow a technology such as video signal processing to be used for position, which would open up the possibility of recording intersection activity on a continuous tape loop. **This would** be valuable in reducing system down time and litigation costs after a collision.



The performance specifications presented here can be met by existing sensors. the cost of these sensors in on the order of **several** thousand dollars each in production quantities.

#### 4.4.10.3 Alarm Requirements

The alarming equipment ~~will~~ probably consist of a combination of visual and audio alarms. The combination should have performance such that **98%** of the time the warned drivers would be aware of the alarm, and **80%** of the time the driver would recognize the nature of the danger and take appropriate ~~evasive~~ action.

#### 4.4.10.4 Communications/Signal Processing Equipment

This type of equipment is both very accurate and very fast, with the performance constantly improving. Additionally, the cost of these items is dropping rapidly. It is not expected that the computers or communications equipment ~~will~~ present difficult technical problems or prove to be a cost driver for the system. Keeping with the time scales presented previously, a response time of 0.05 to 0.10 ~~seconds is~~ both reasonable and achievable.

### 4.5 RESULTS AND CONCLUSIONS

The kinematic analysis presented here demonstrates that in many situations, it is impossible for the LRV to stop to avoid a collision. **This** is due to a number of factors, including the limited coefficient of friction of a steel wheel on steel rail. Following the philosophy of the original safety plans, namely keeping rubber-tired vehicles off the tracks as a LRV approaches the intersection, is much better. Rubber tired vehicles tend to be traveling much slower than LRV's as they approach an intersection in the left-turn pocket and ~~can~~ stop much more rapidly (as well as having steering ~~options~~). Stopping times for RTV's are on the order of a second or two, as opposed to approximately ten seconds for the LRV's.

In most instances it is possible to provide a warning to the RTV driver which would, even after allowing for a moderate reaction time of **1.5** seconds, allow the RTV to stop out of harm's way. The sensors, communications, and computer technologies do not seem present terribly difficult challenges. The ~~largest~~ uncertainty about such a collision warning system is in the nature of the alarm. The ~~collision~~ warning system envisioned relies on the driver of the RTV (which is about to make a ~~left or~~ U-turn by running a red light) to recognize and react to an alarm. Since this alarm ~~would~~ only be given infrequently (when a likely collision is ~~sensed~~), it could be more intense than an alarm which would be sounded every time an LRV traversed an intersection. This would increase the probability that the alarm would be capable of attracting the RTV driver's attention, although it remains to be seen if the driver would respond to the alarm appropriately. **This seems** to be the only missing item requiring further research prior to prototyping and testing of the proposed system.



## Appendix A – Terminology

Car - conventional automobile, **used as** a synonym for RTV

Collision Zone or CZ - The area where the volumes swept out by the RTV and LRV coincide. It is assumed to be a square **2.5** meters on a side.

Critical Range - The range **of** LRV initial positions which result in collisions for a given set **of** RTV and LRV velocity profiles and RTV initial position.

Driver - person who drives a rubber-tired vehicle

Intersection - same as generic meaning, **so** it includes not only the collision zone but the surrounding area as well.

LRV - Light Rail Vehicle

(LRV) Maximum Collision Distance - The largest distance away that the LRV can be (at time  $t=0$ ) which still results in the RTV hitting the LRV before it safely passes in front of the RTV.

(LRV) **Minimum** Collision Distance - The minimum distance away that the LRV can be (at time  $t=0$ ) which still results in the LRV hitting the RTV before it safely passes in front of the LRV.

Operator - person who operates the LRV

RTV - Rubber-Tired Vehicle, also referred to as car or automobile, although it could also be a truck, van, bus, etc.

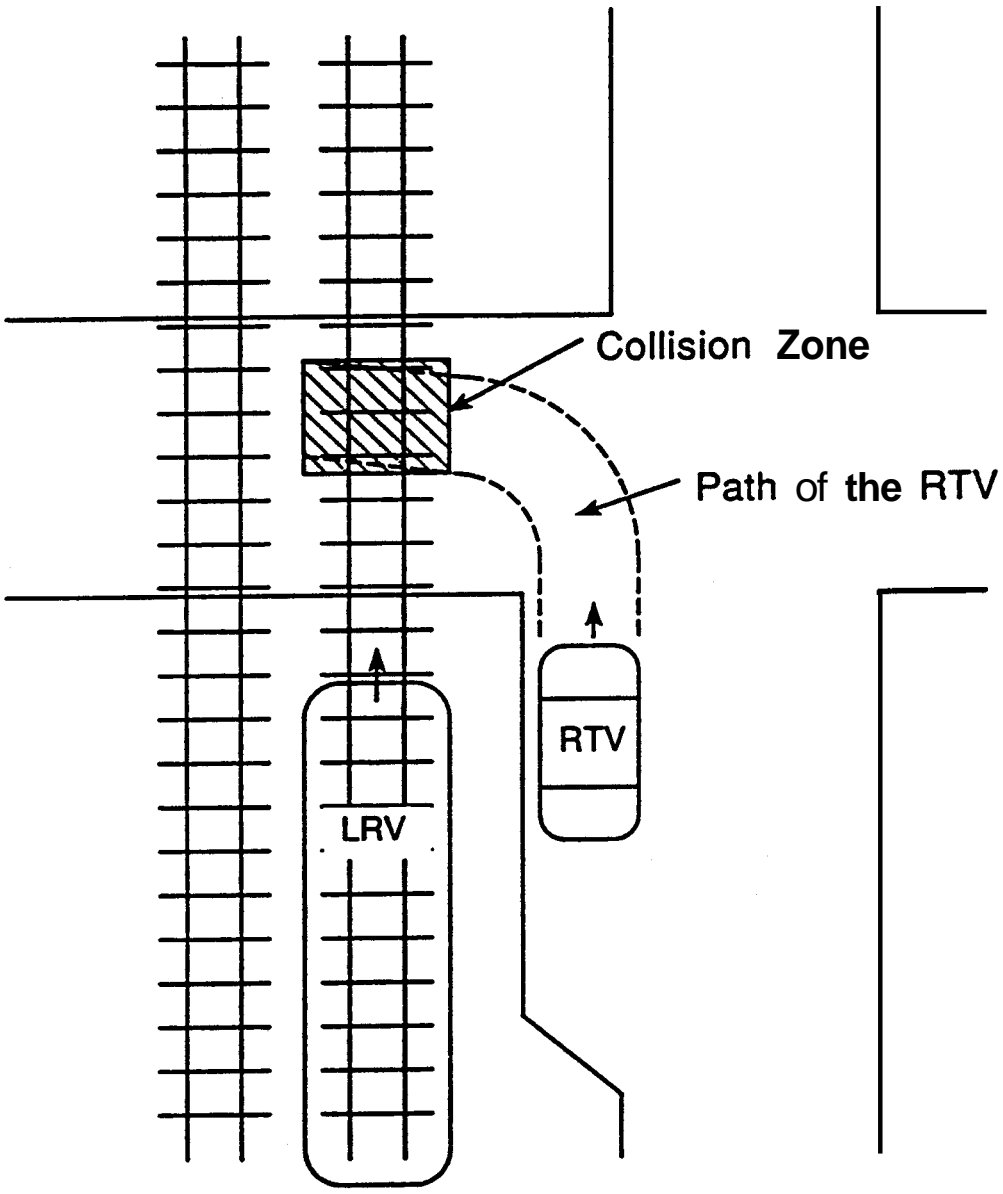


Figure 4.1a - An illustration of the Collision Zone (CZ)

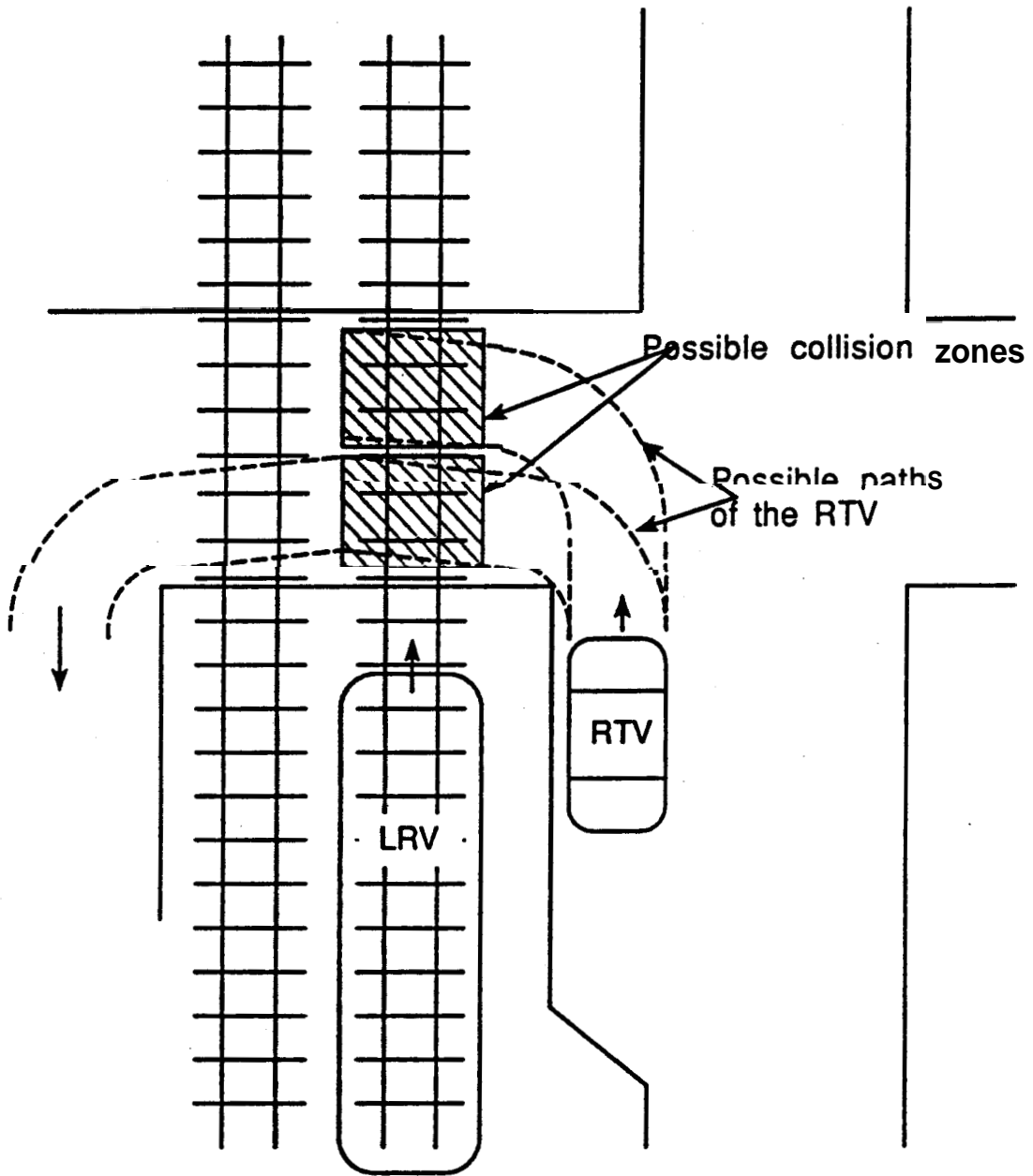


Figure 4.1b - Effects of RTV Turning Radius on the Collision Zone

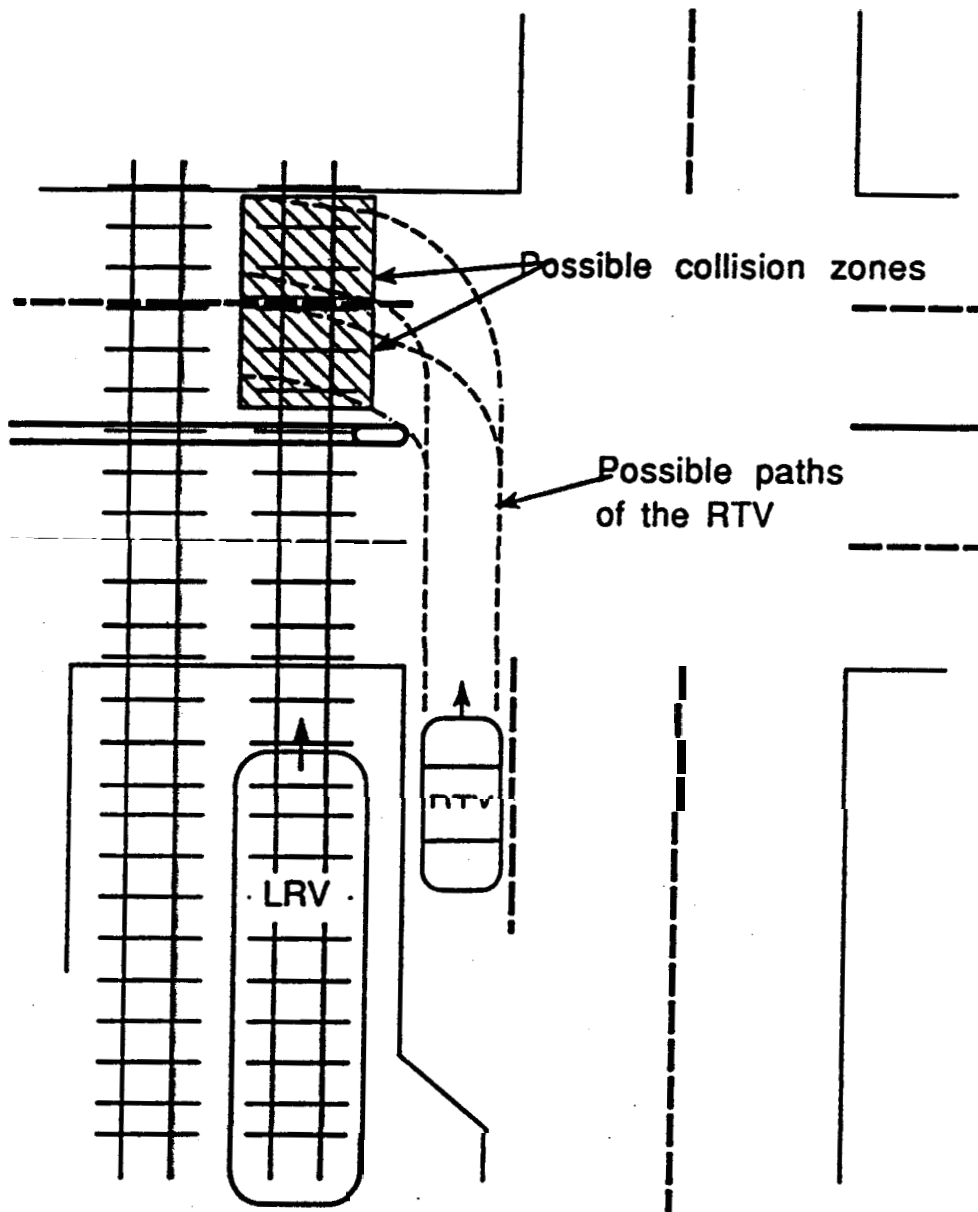


Figure 4.1c - Collision Zone in a Multi-lane Intersection

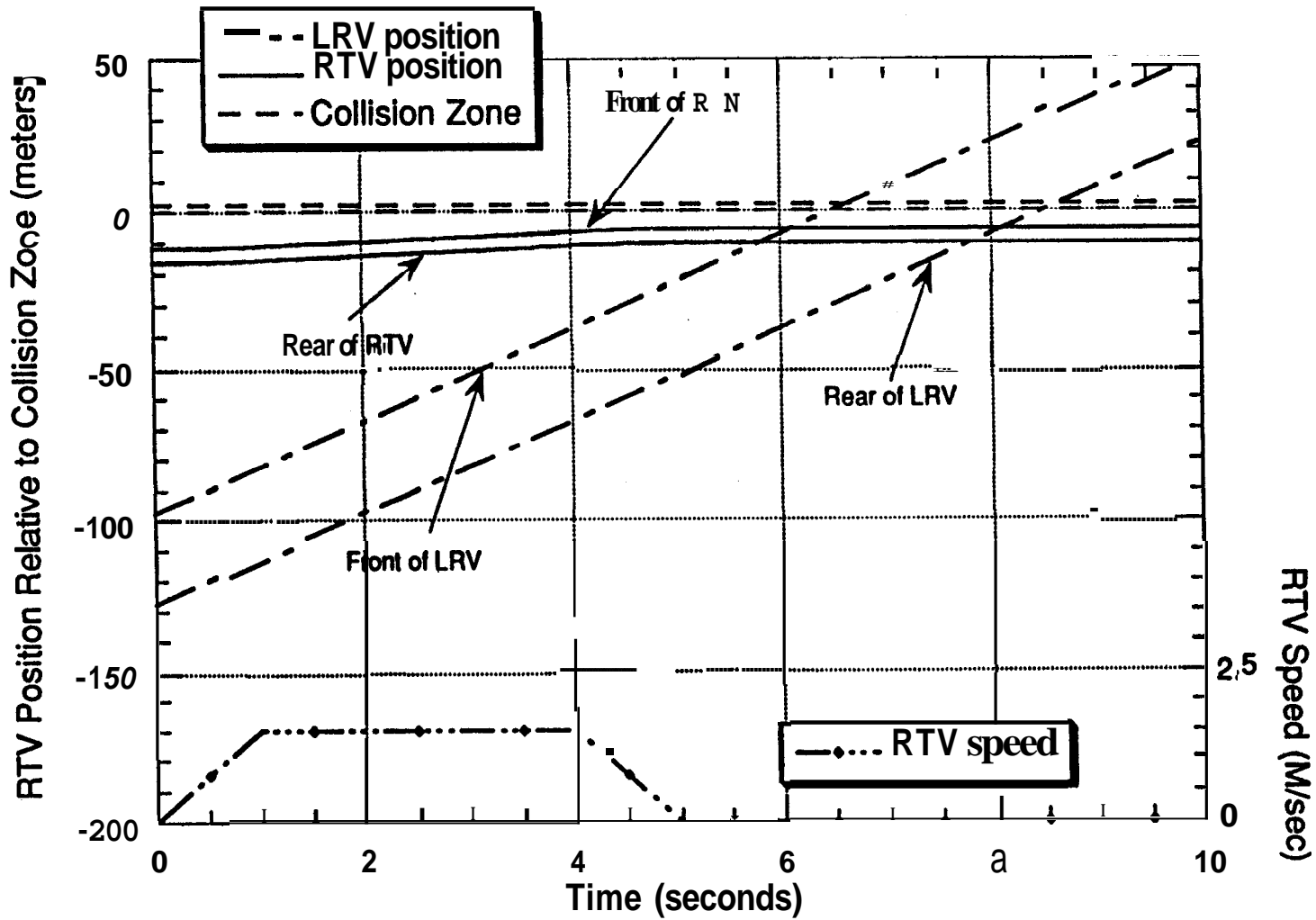


Figure 4.2 - Short Creep-up

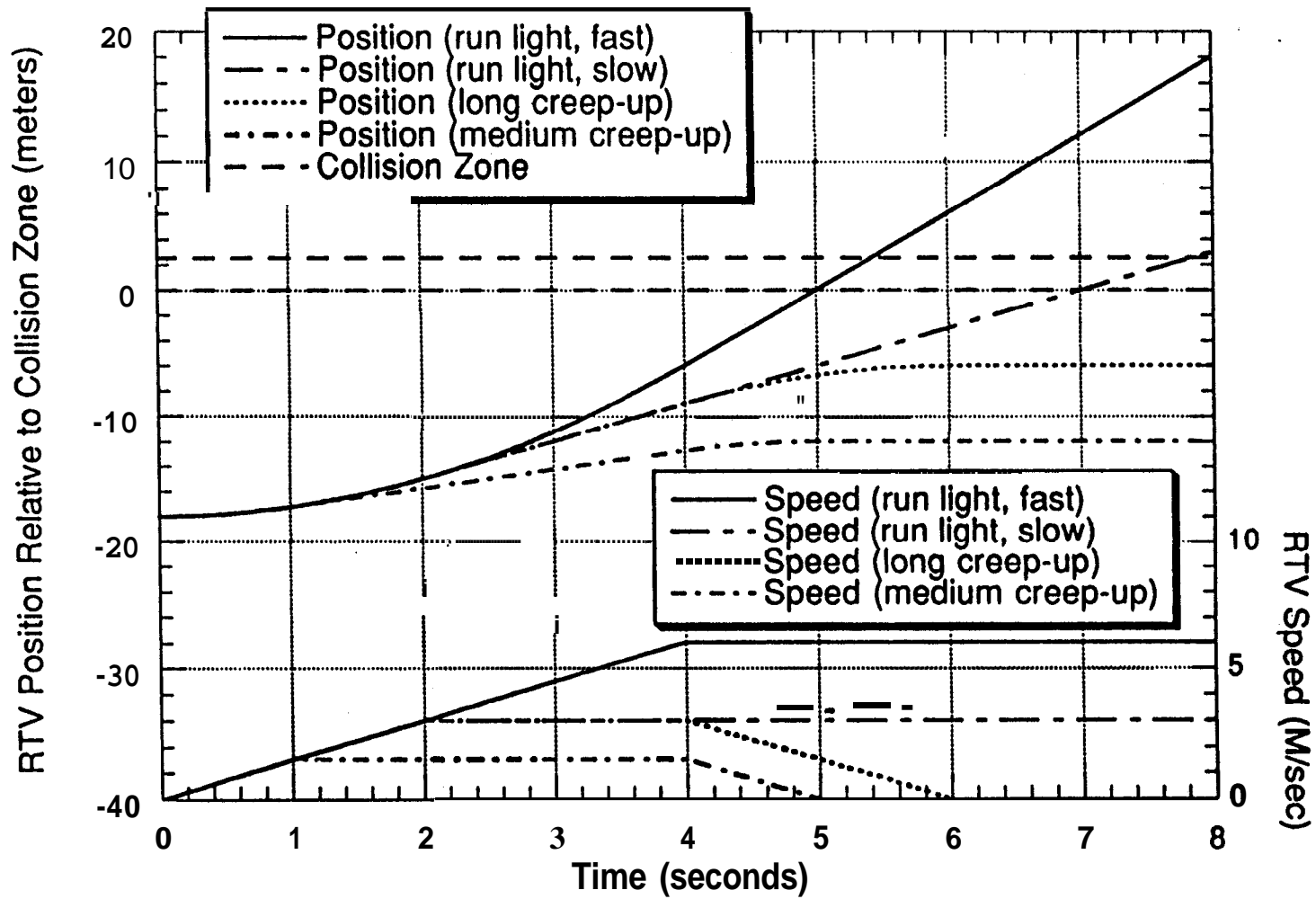


Figure 4.3 - Various Trajectories



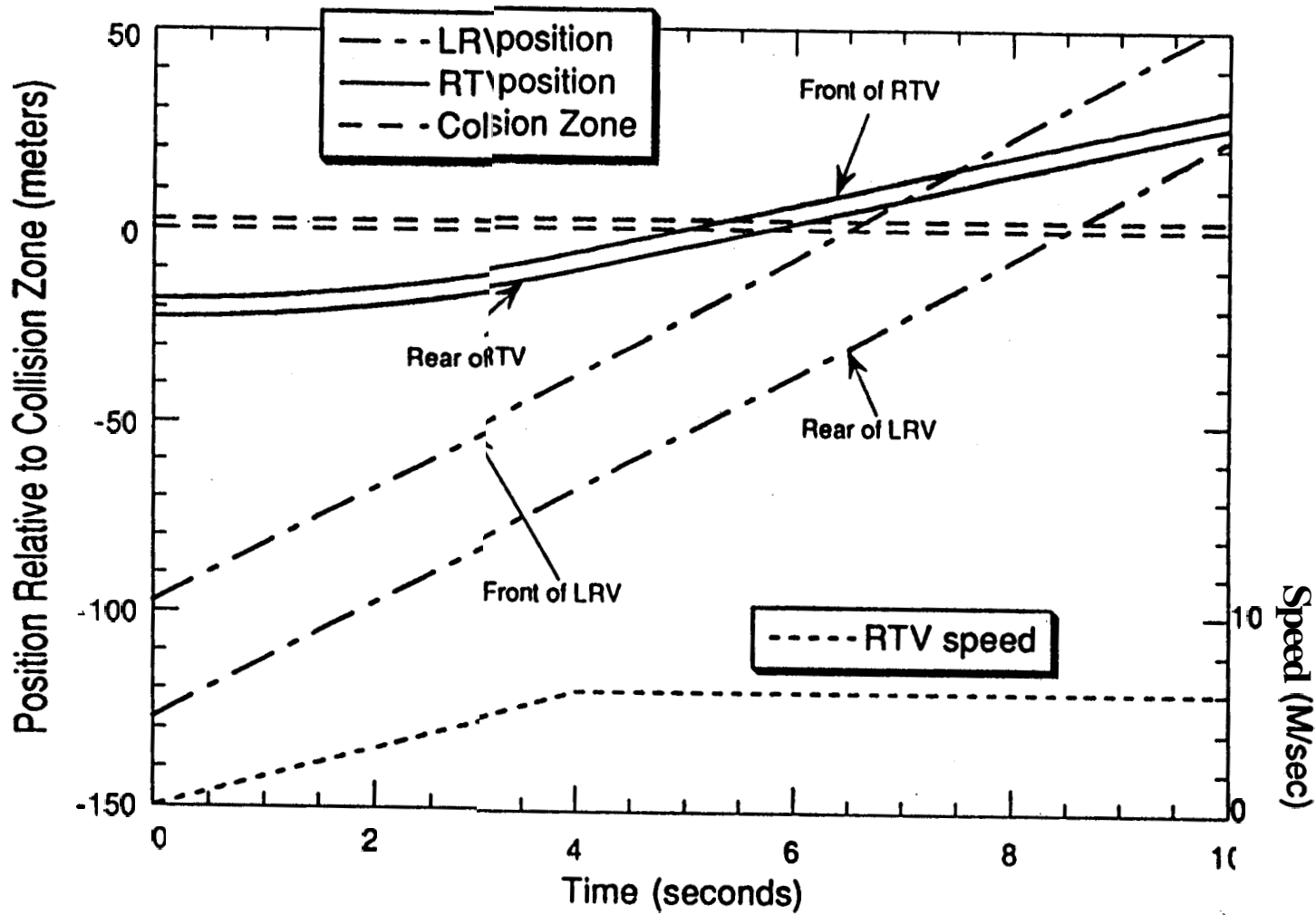


Figure 4.4a - LRV Passing Safely Behind RTV

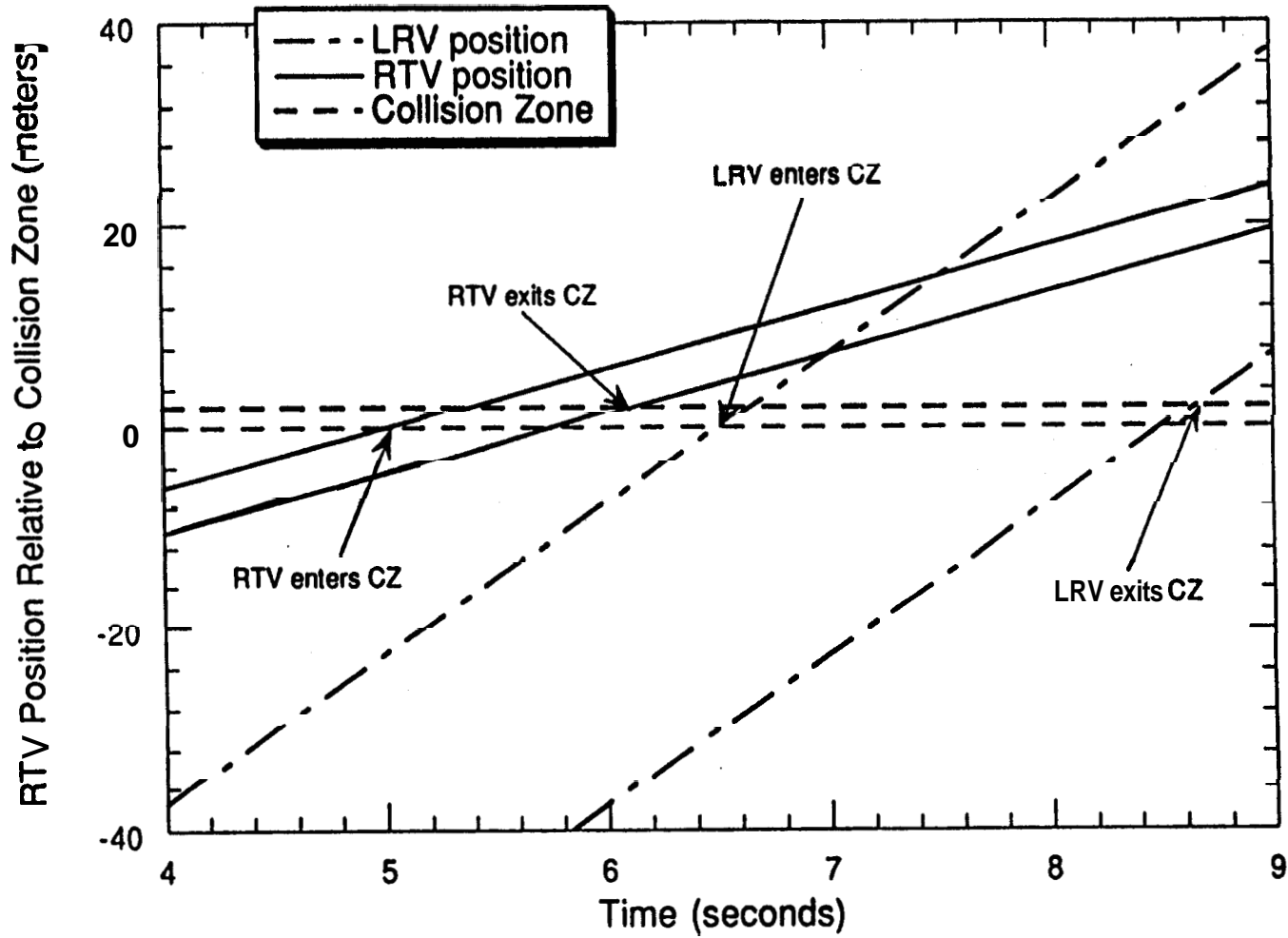


Figure 4.4b - Enlargement of Upper Right of Figure 4.4a

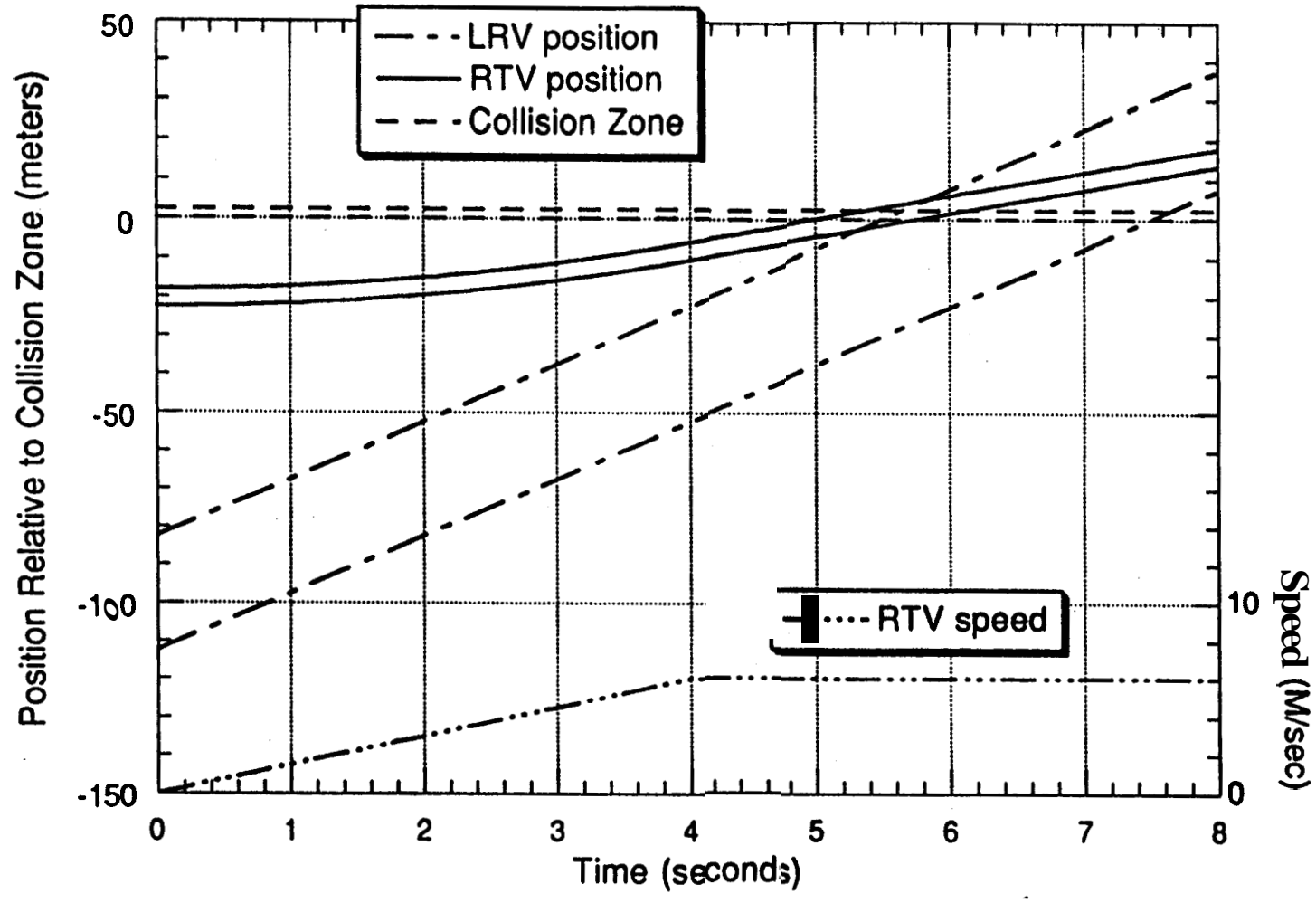


Figure 4.5a - Collision, LRV Runs into the Side of RTV

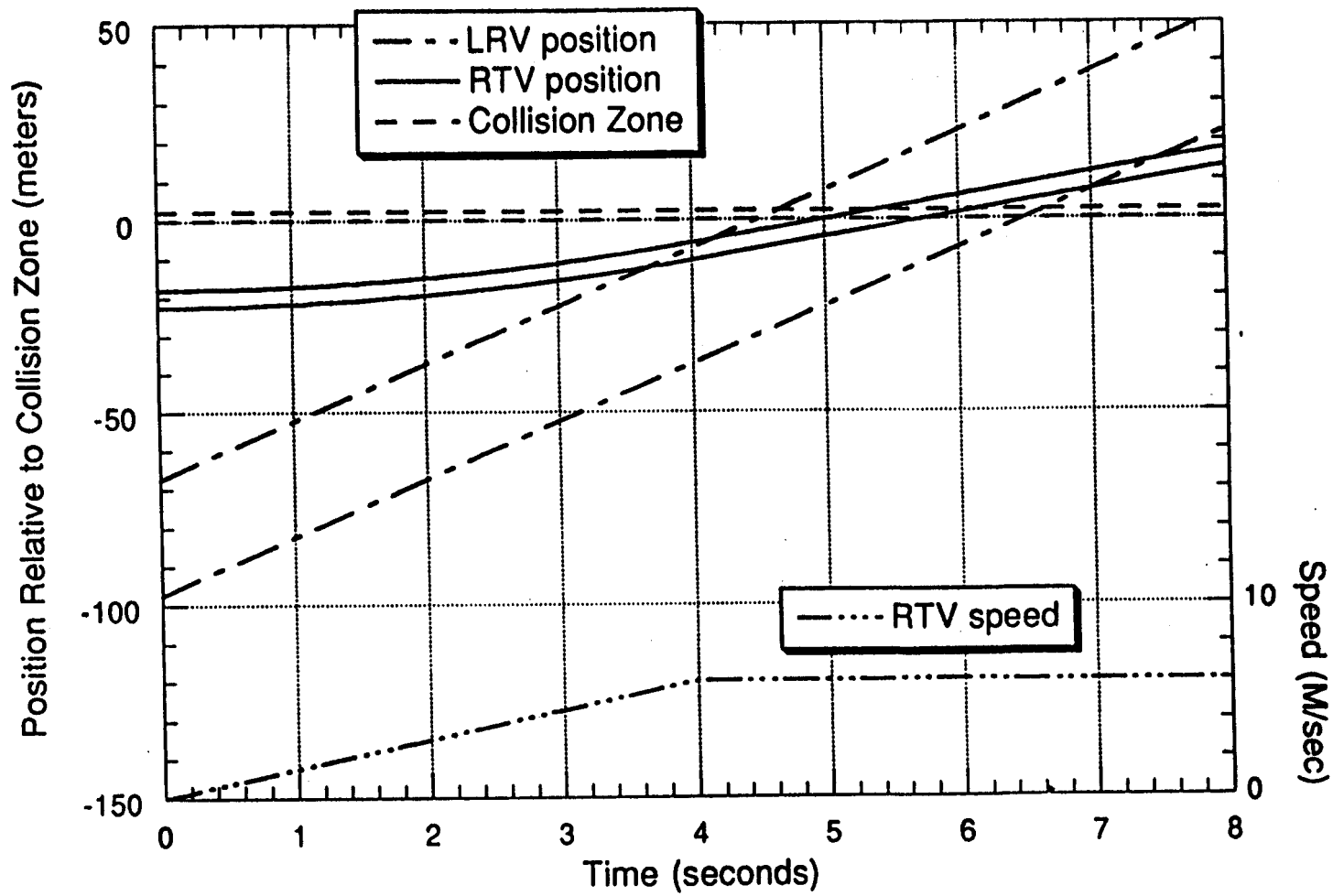


Figure 4.5b - Collision, RTV Runs into the Side of LRV

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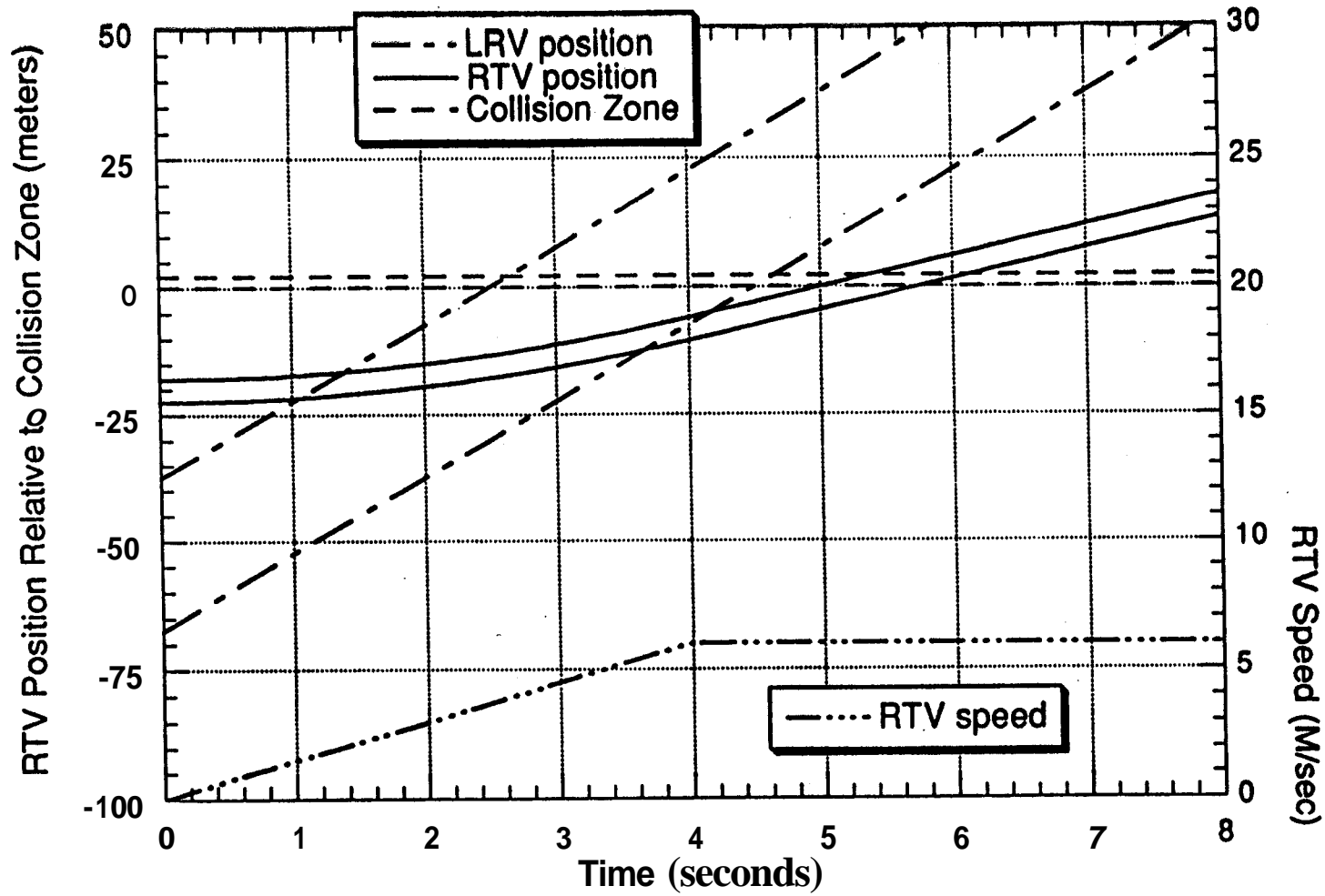


Figure 4.6 - LRV Passes Safely in Front of RTV

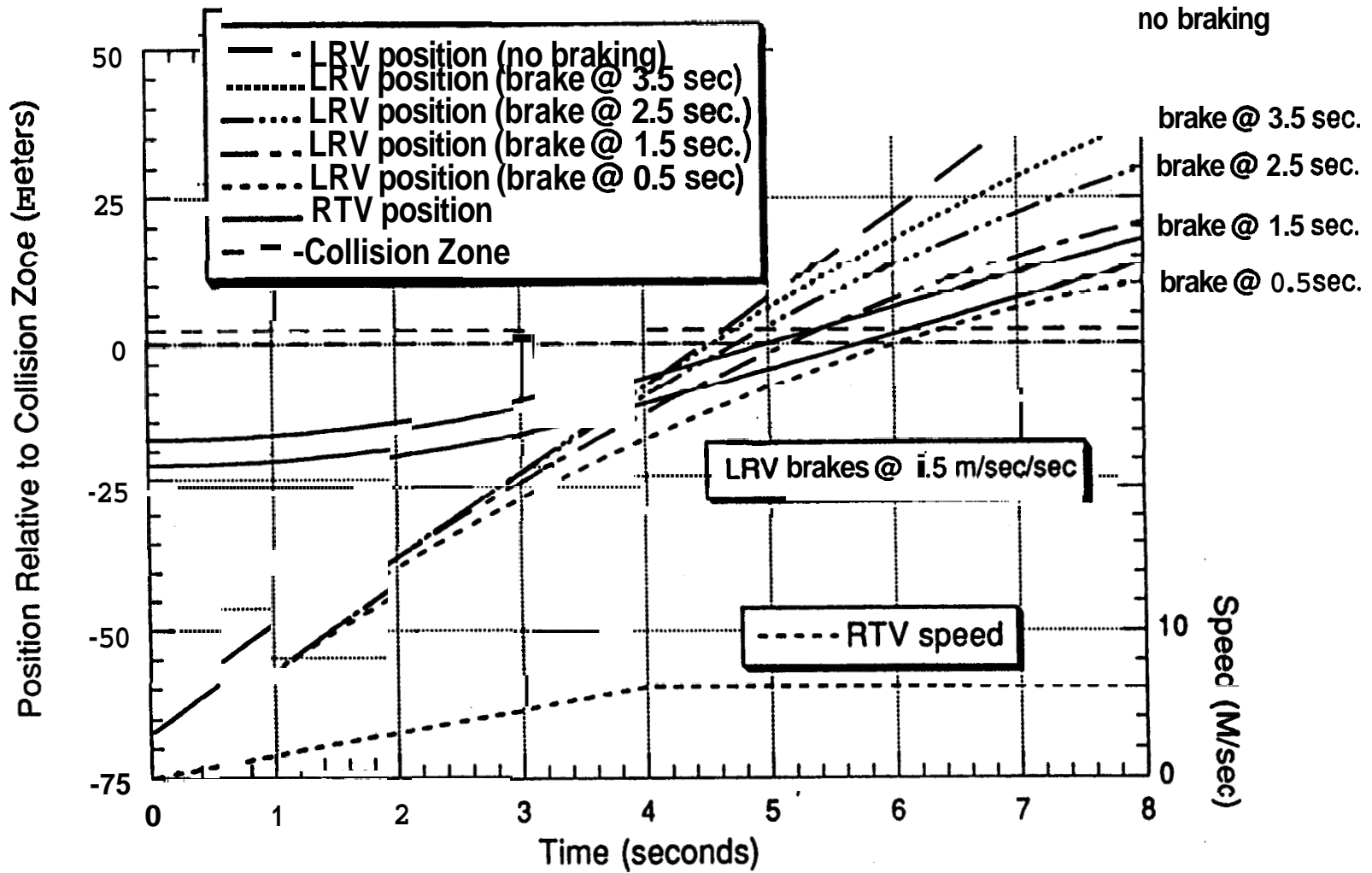


Figure 4.7 - Braking Initiation Point

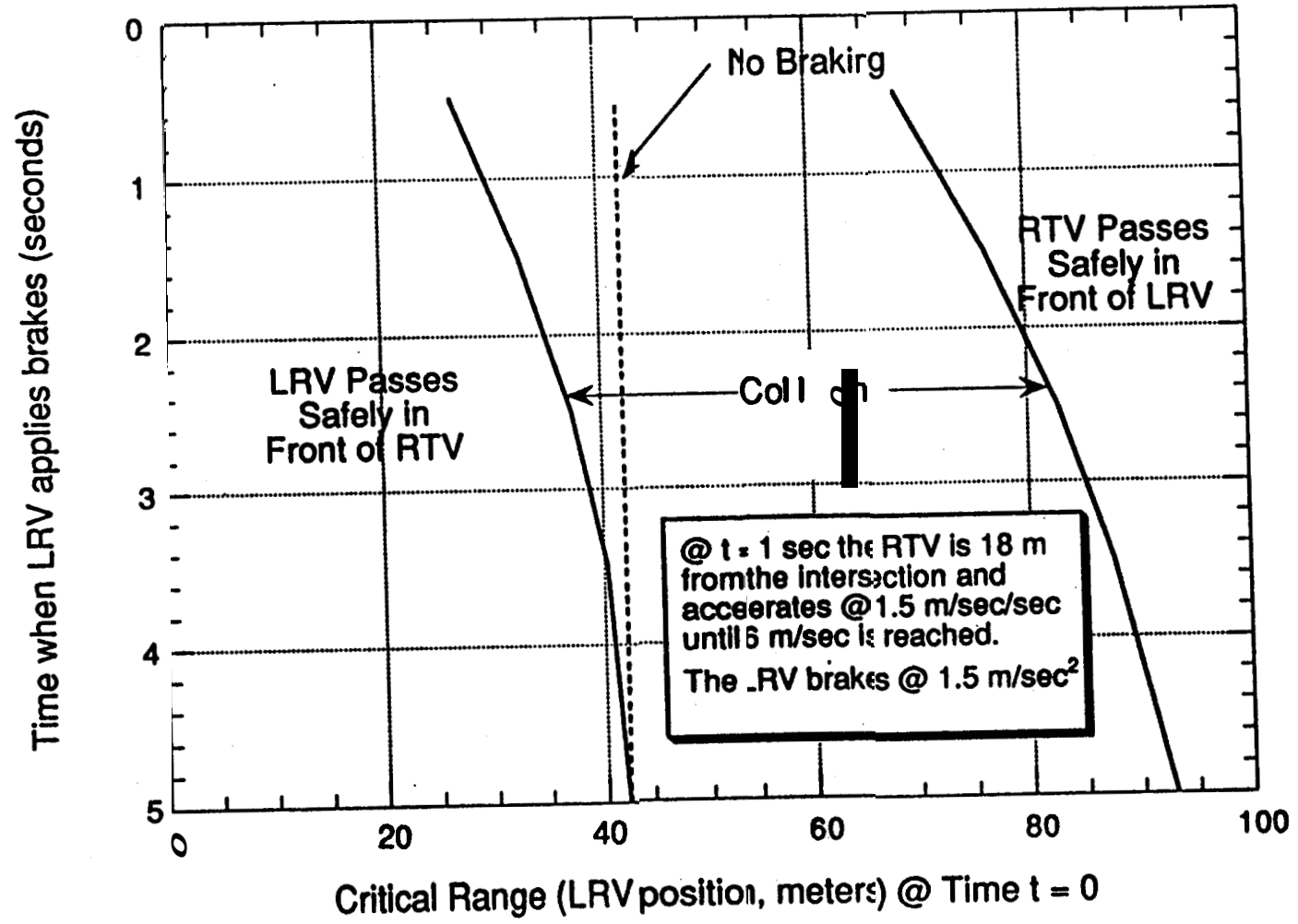


Figure 4.8 - Critical Range vs. LRV Brake Initiation Time

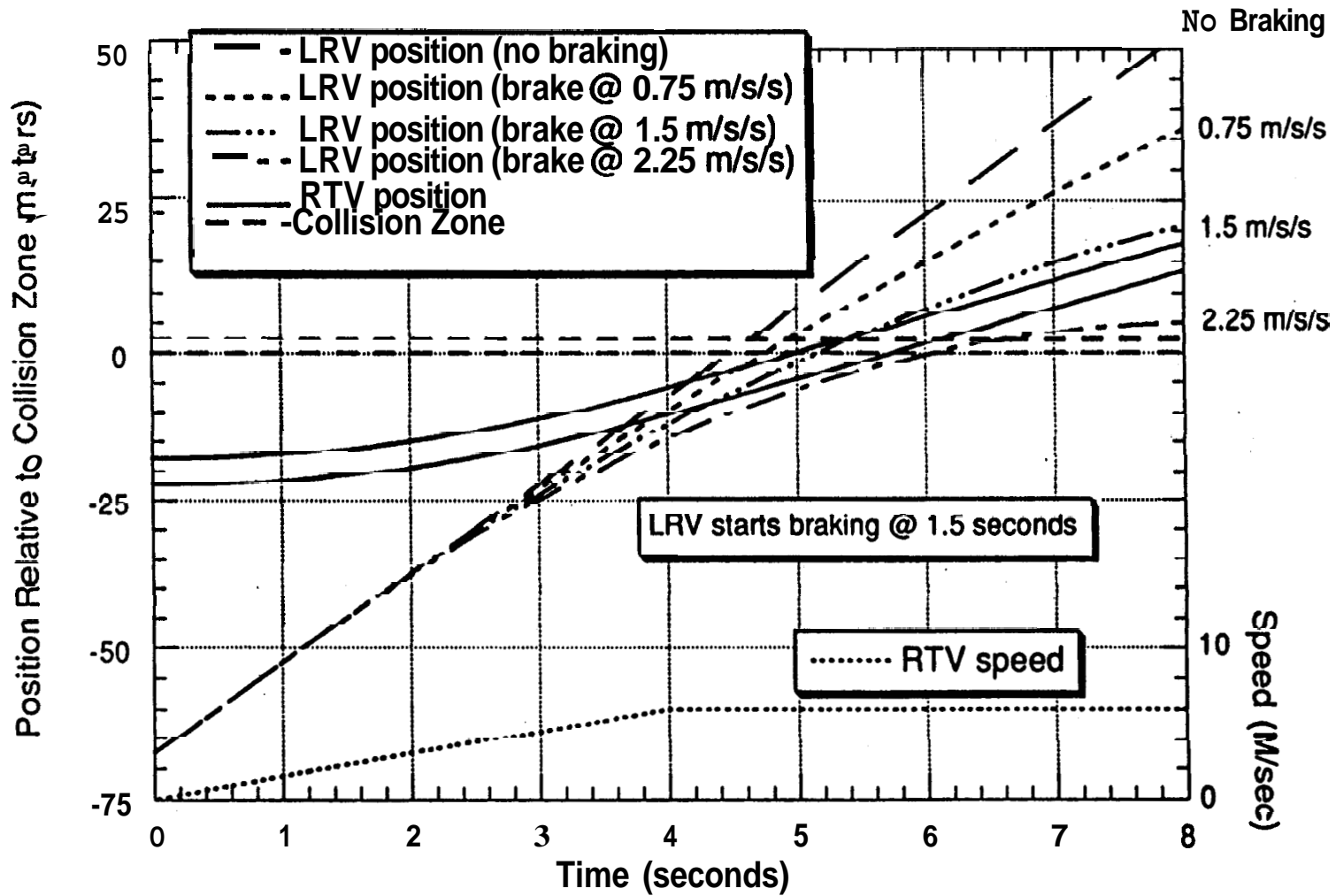


Figure 4.9 - LRV Braking Rates



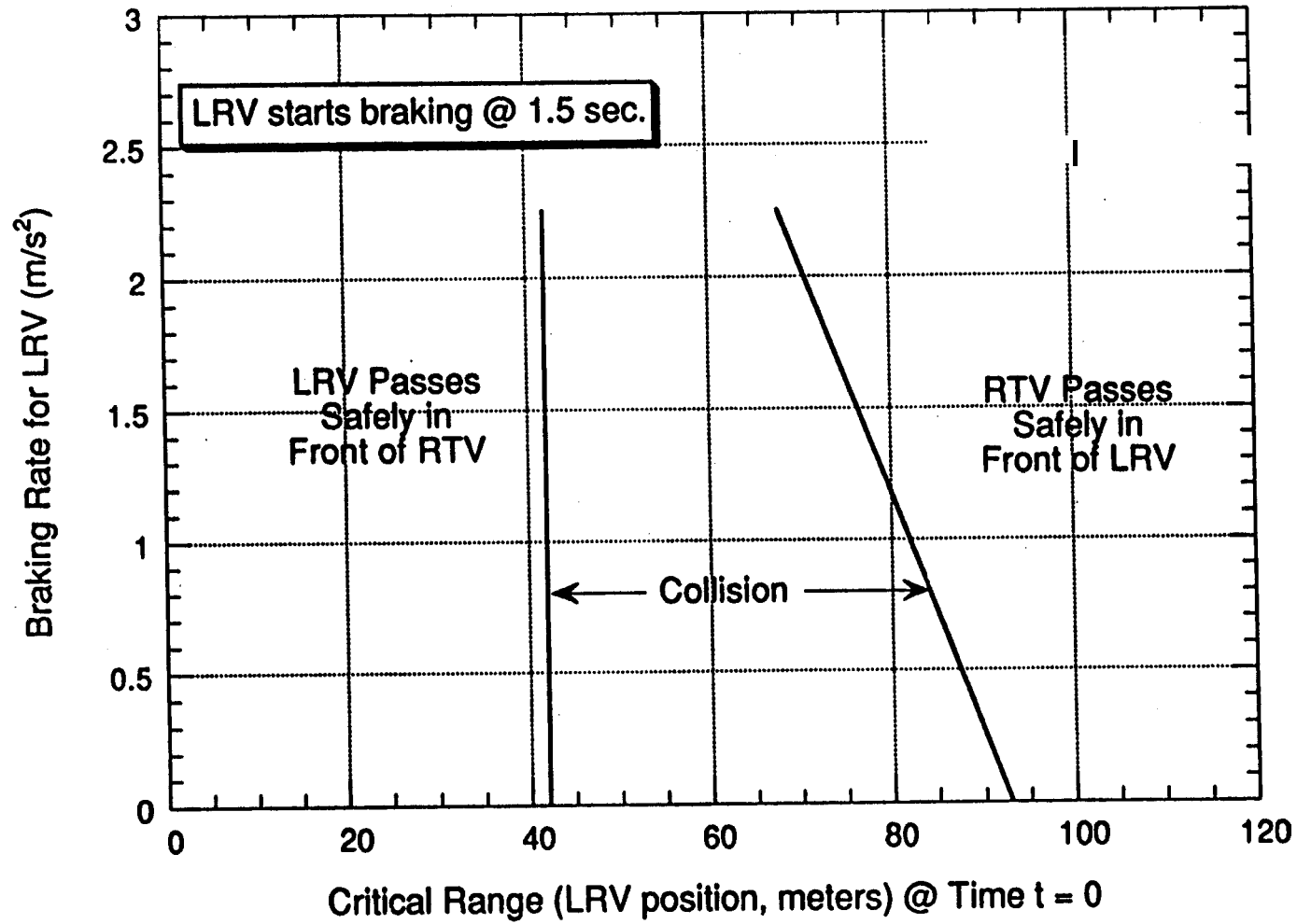


Figure 4.10 - Critical Range vs. LRV Braking Rates

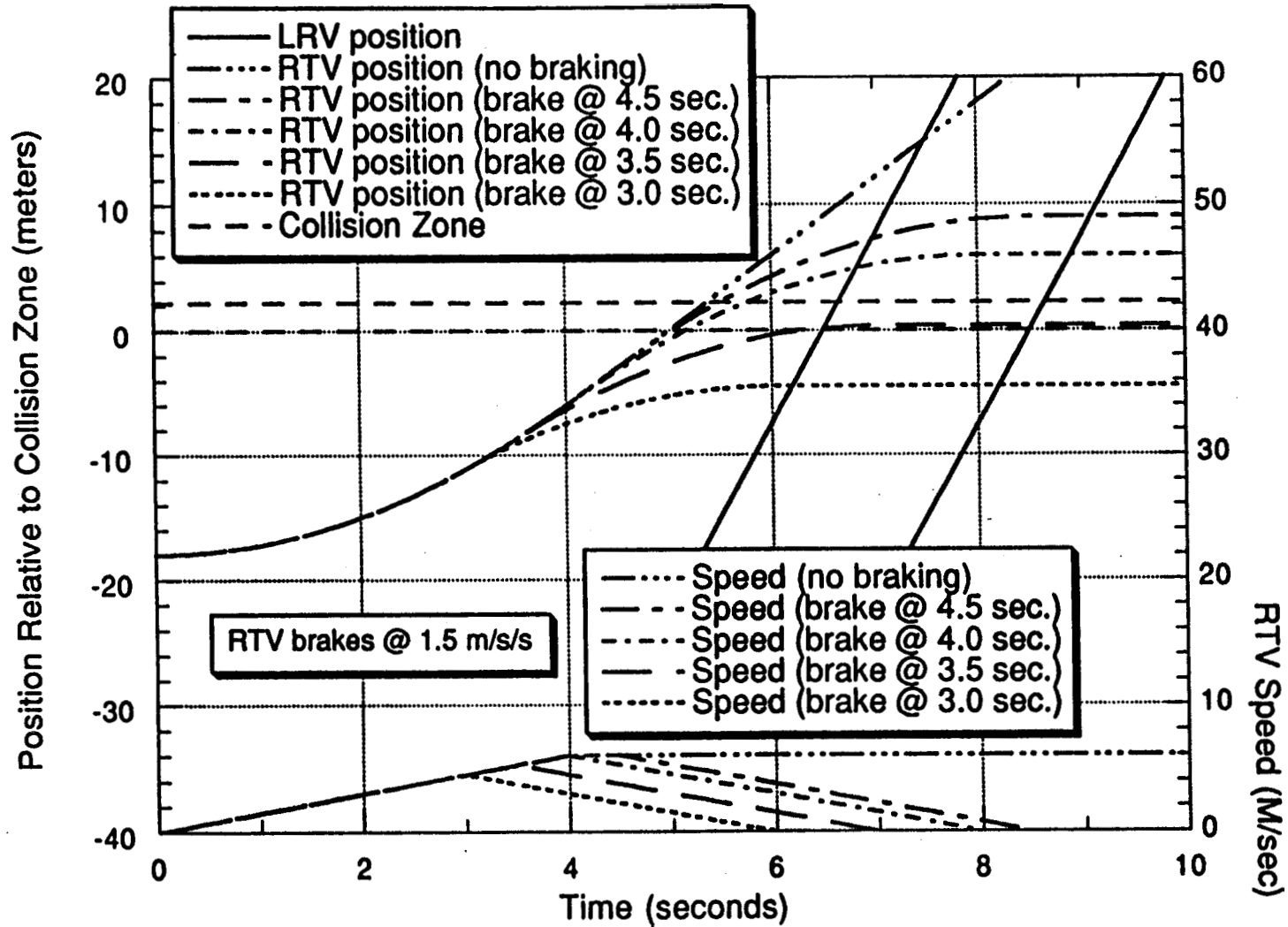


Figure 4.1 1 - Trajectories with Various RTV Braking Initiation Times

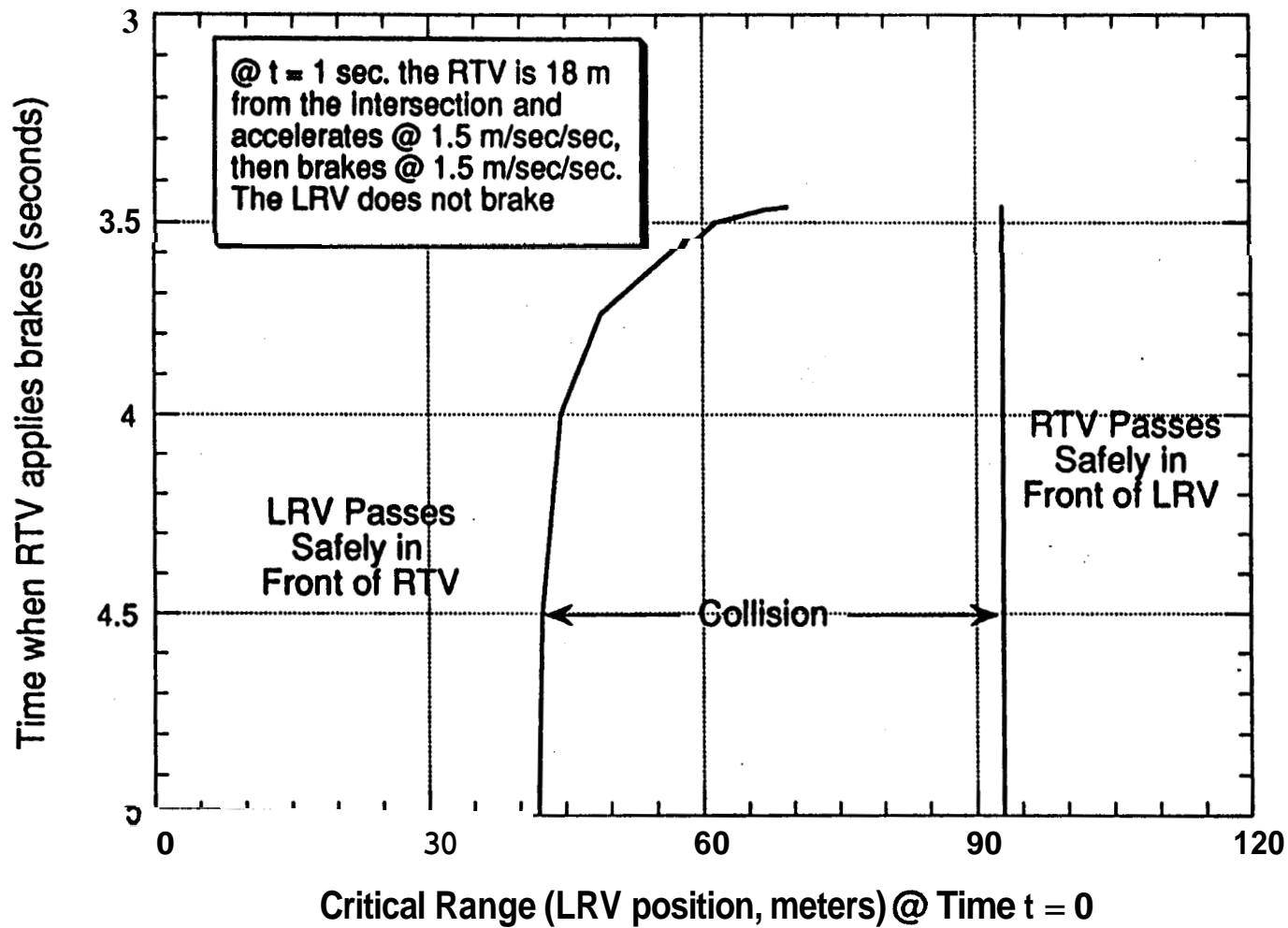


Figure 4.12 - Critical Range vs. RTV Brake Initiation Time

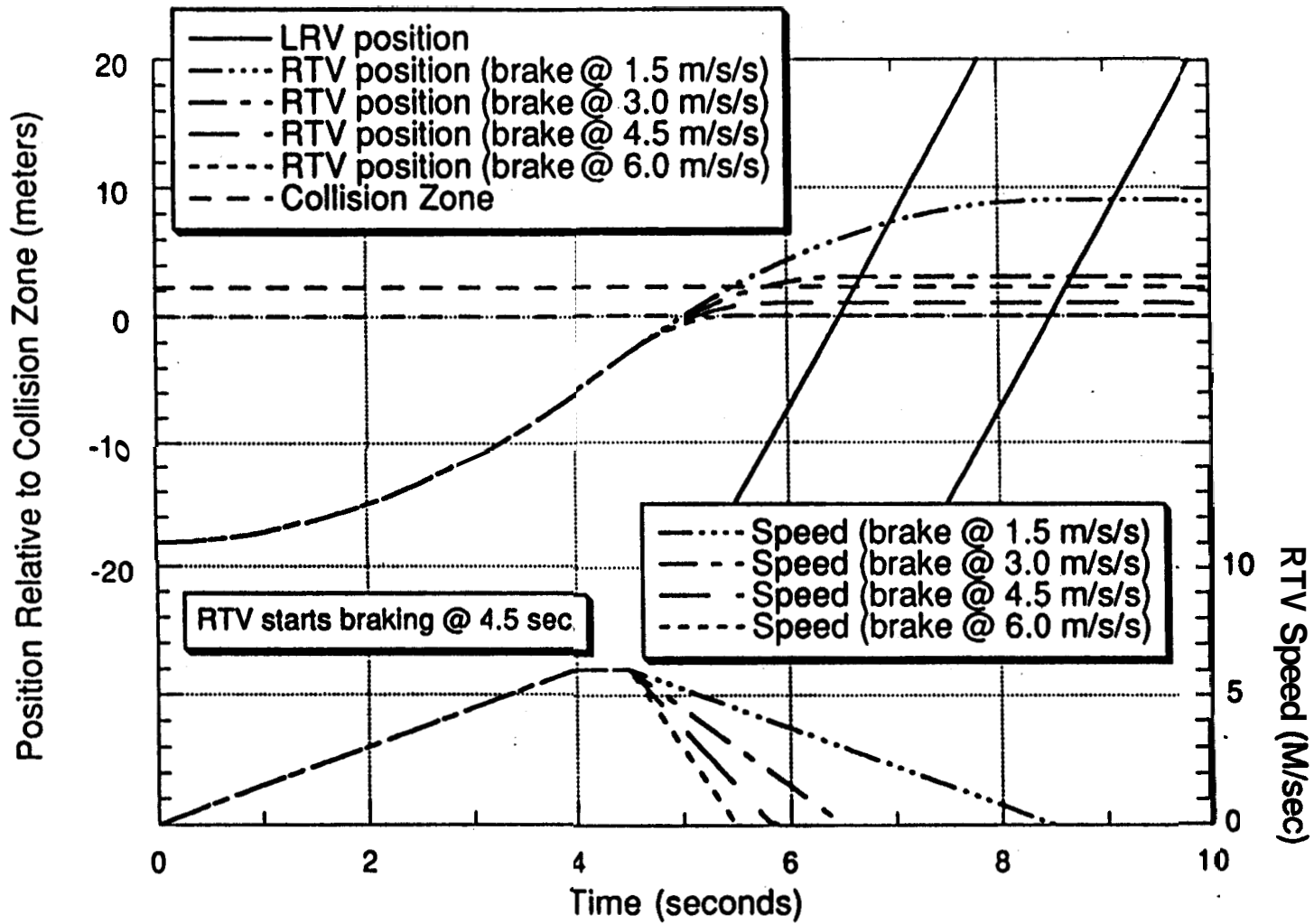


Figure 4.13 - Trajectories with Various RTV Braking Rates

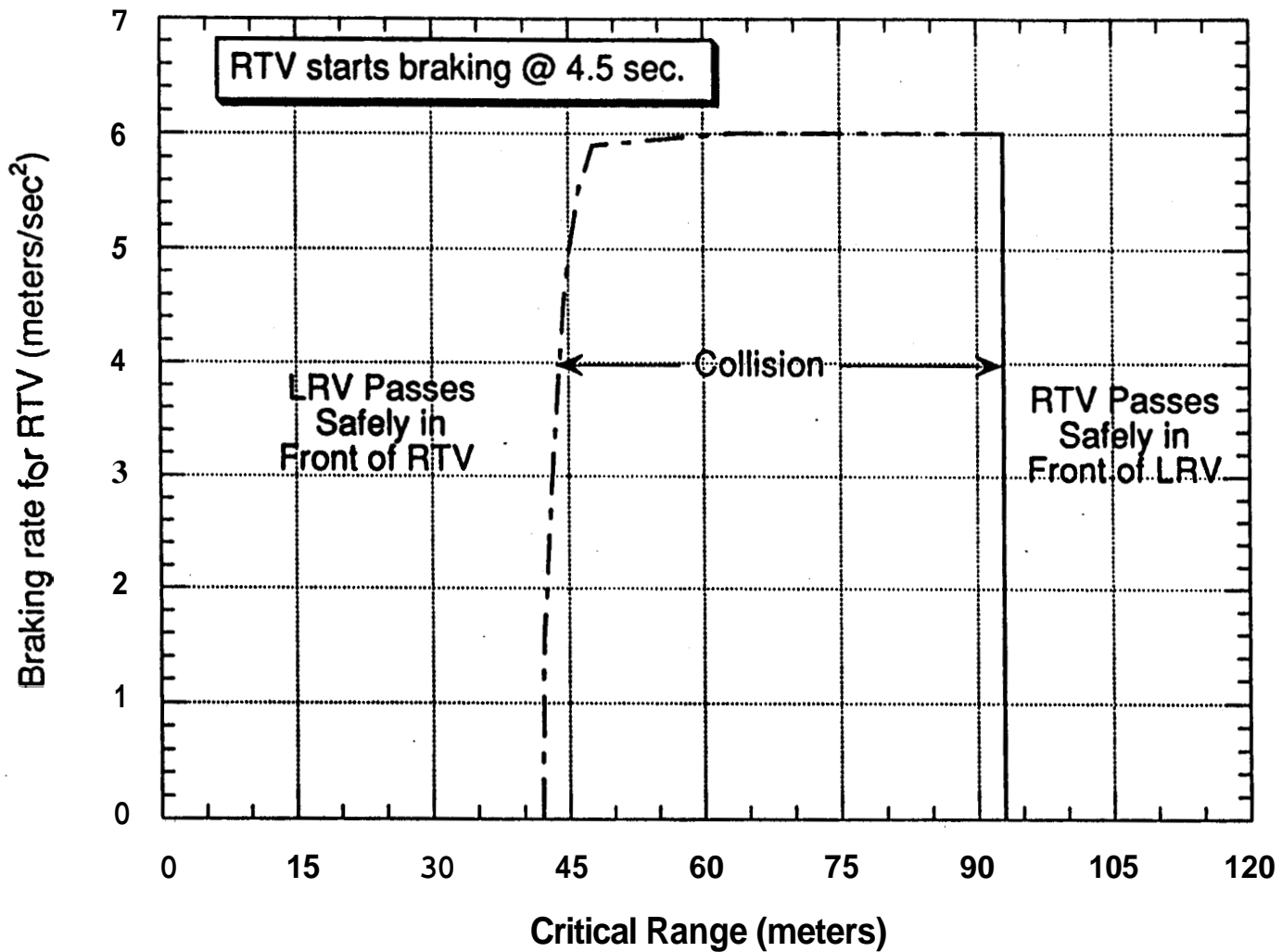


Figure 4.14 - Critical Range as a Function of Braking Rate

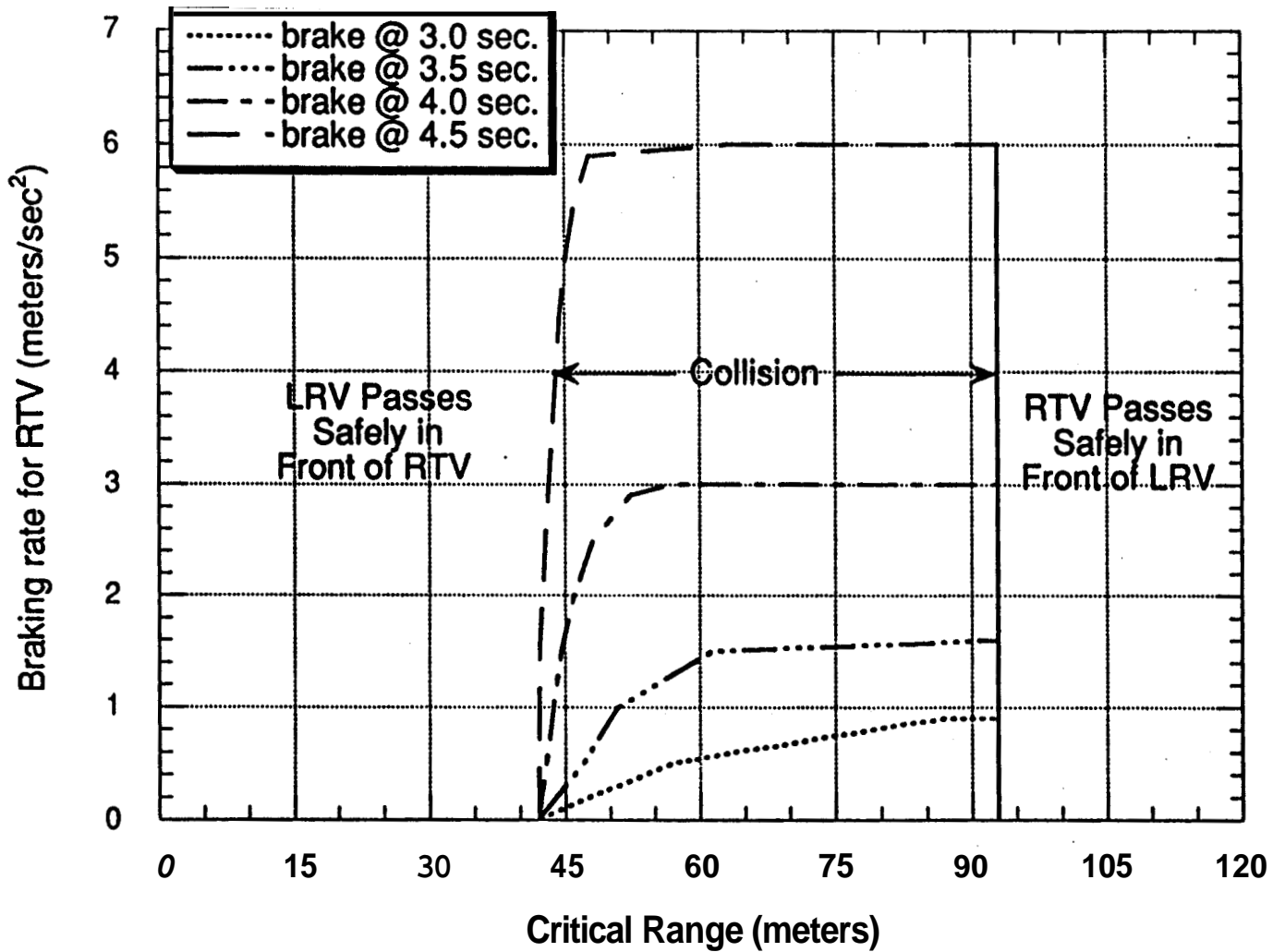


Figure 4.15 - Critical Range as a Function of Braking Rate and Brake Initiation Time

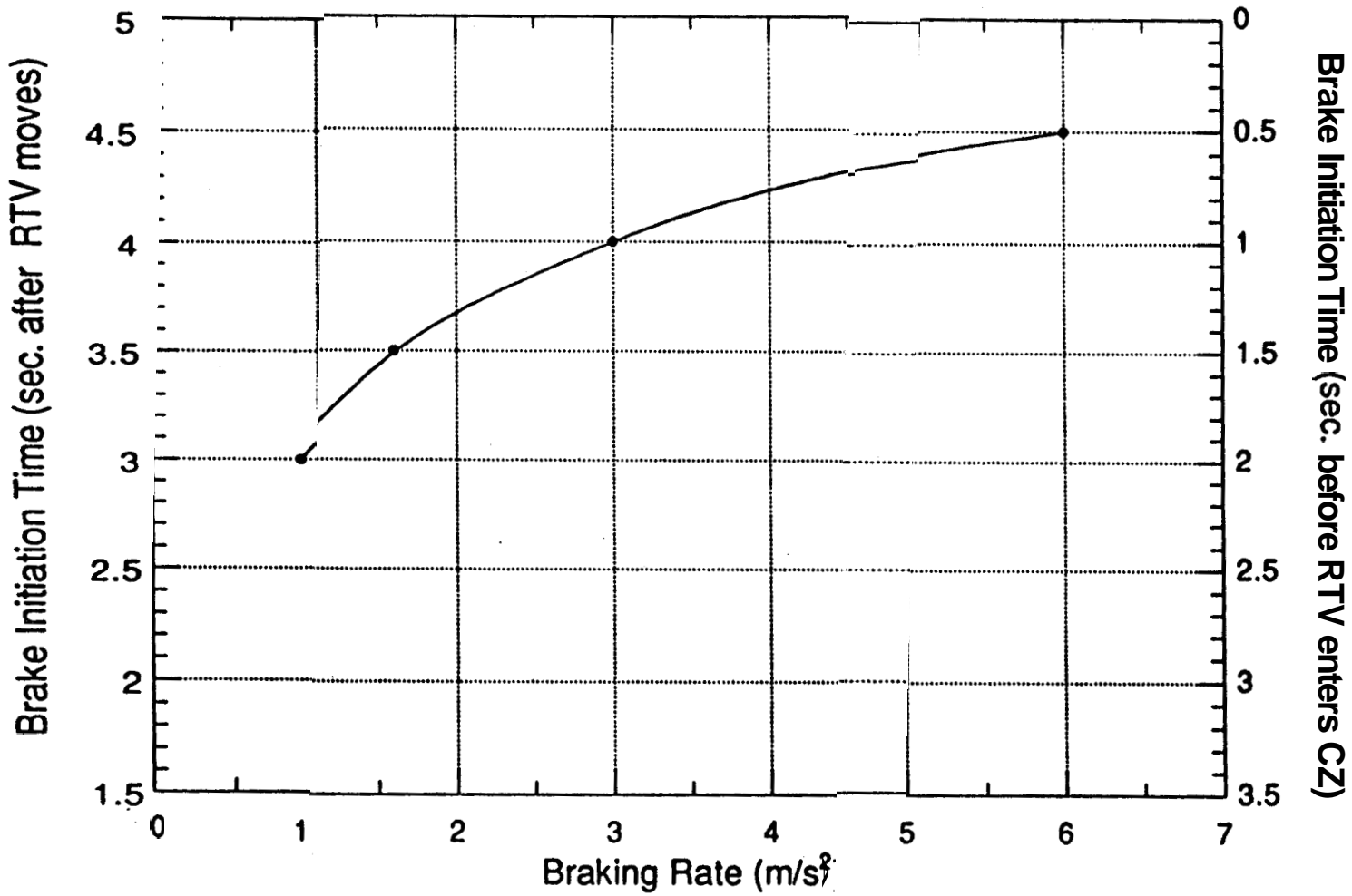


Figure 4.16 - Intercepts from Figure 4.15

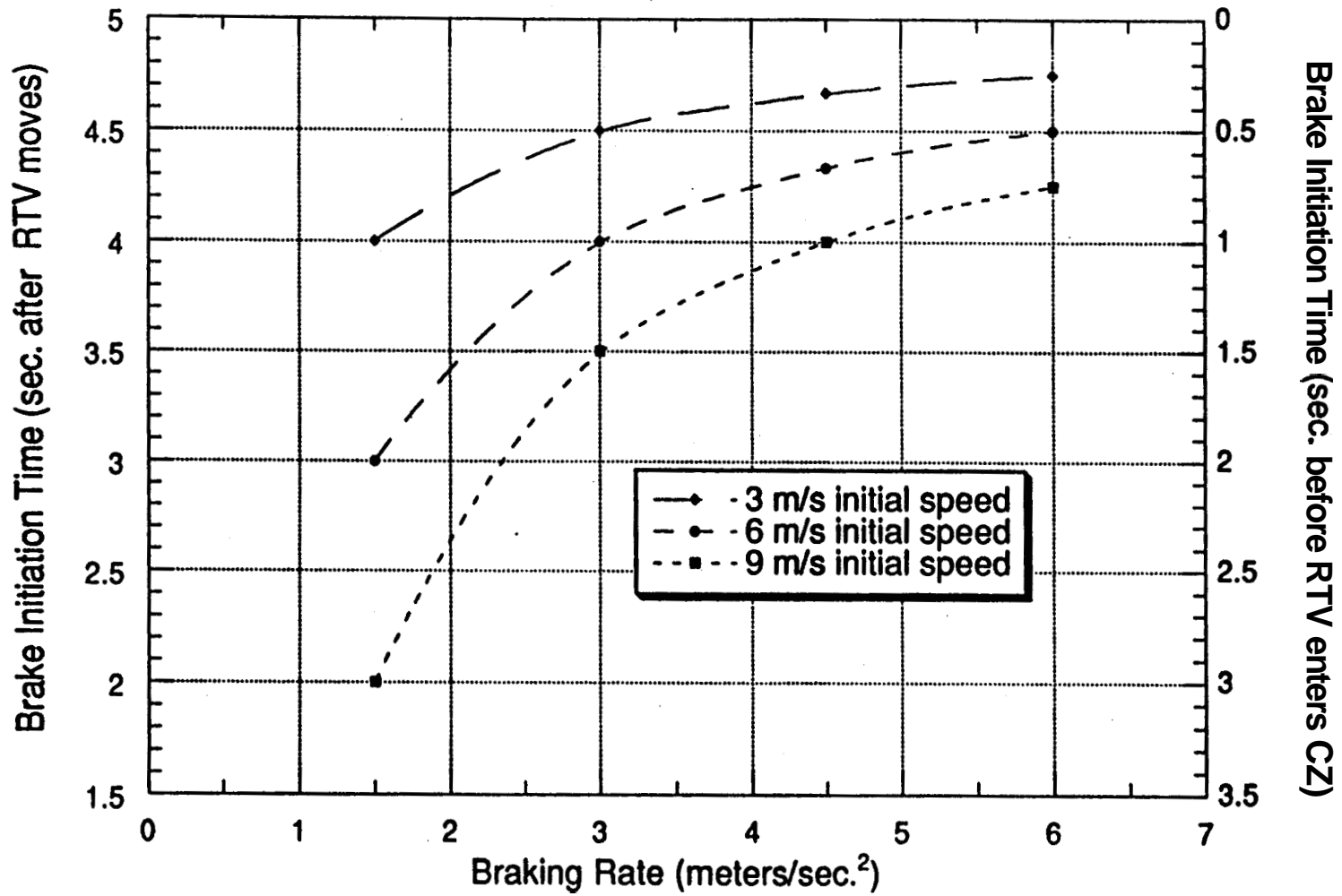


Figure 4.17 - Required RTV Braking Rates to Avoid a Collision



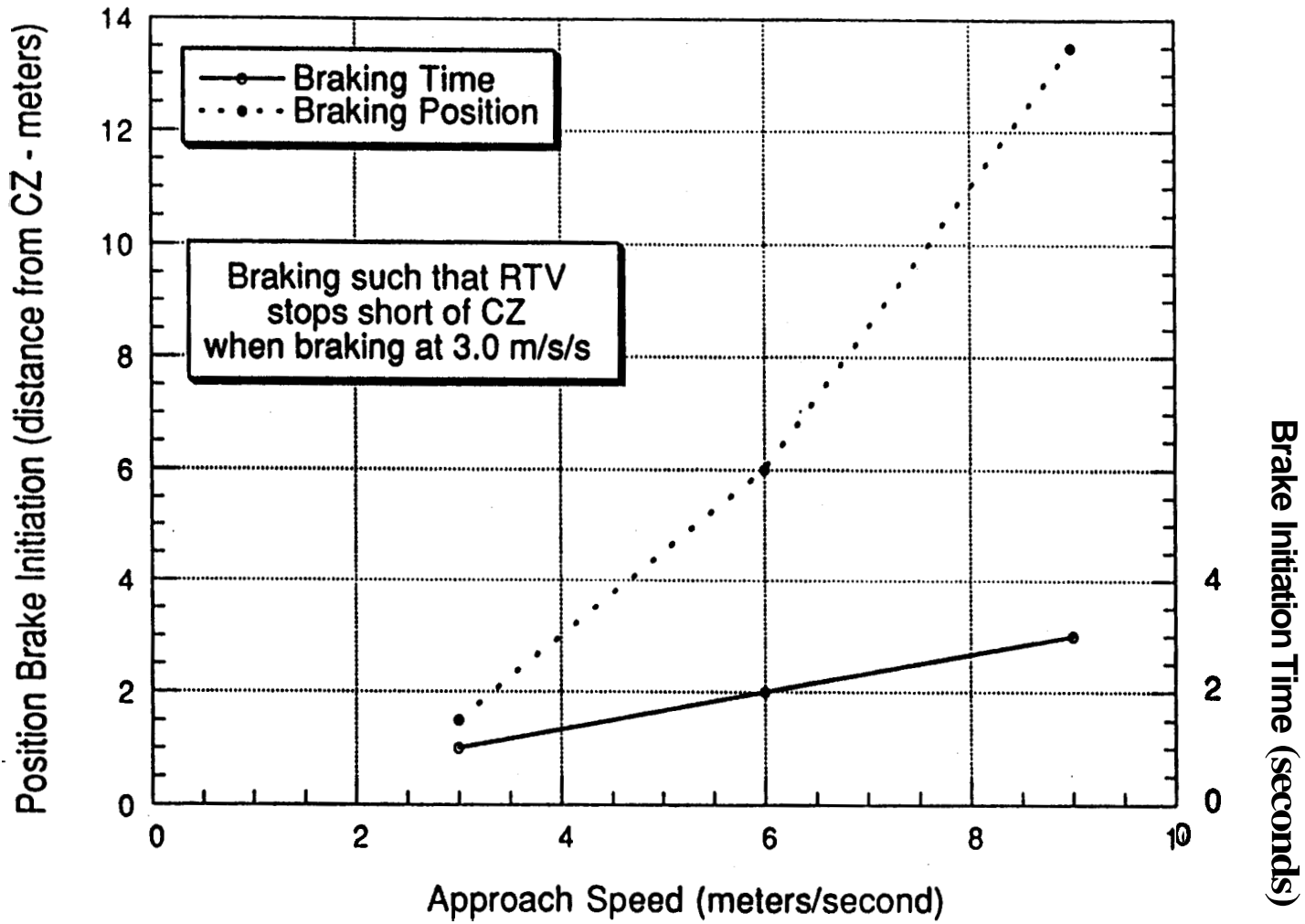


Figure 4.18 - Brake Initiation Parameters vs. Approach Speed

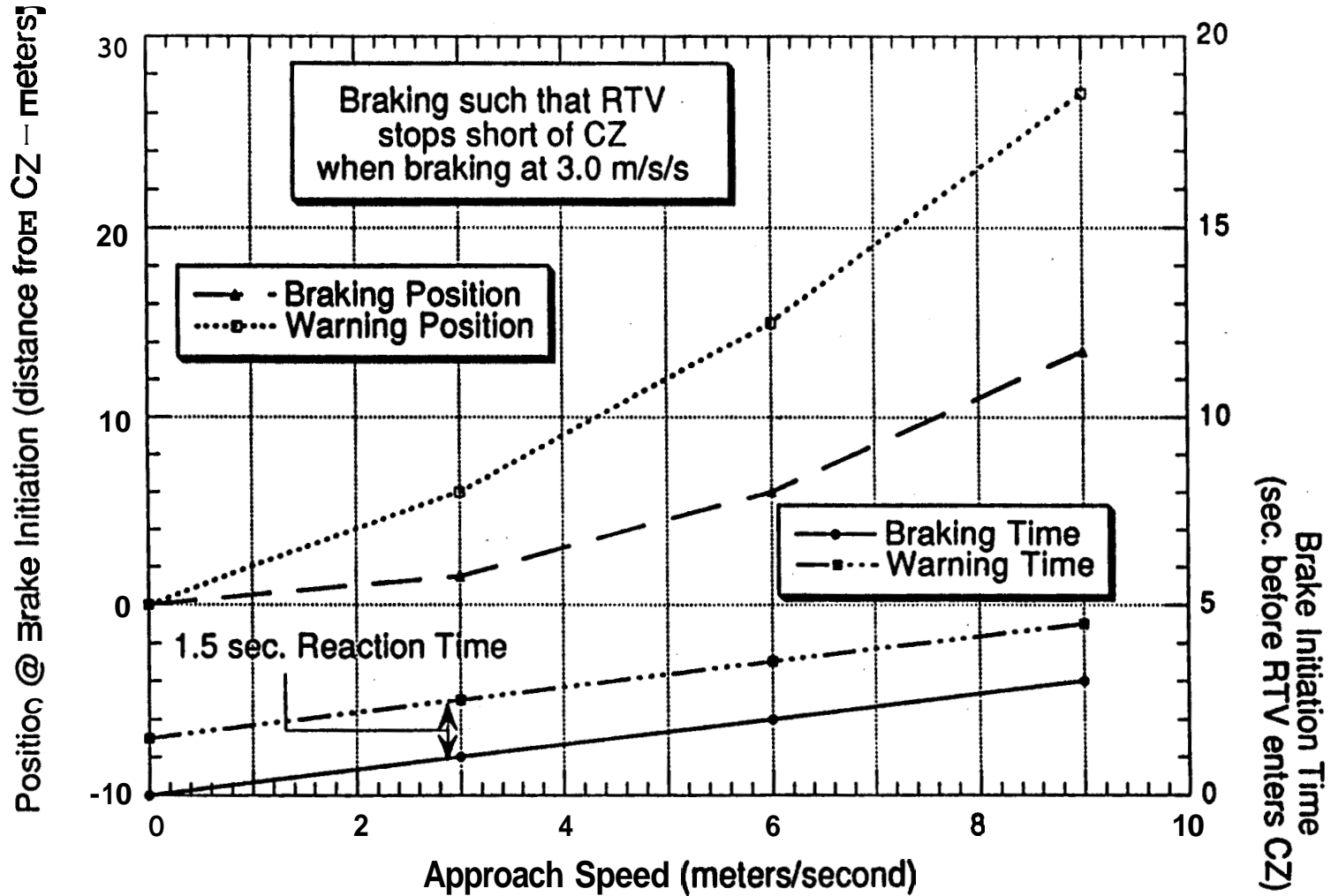


Figure 4.19 - Warning Moment Time and Position

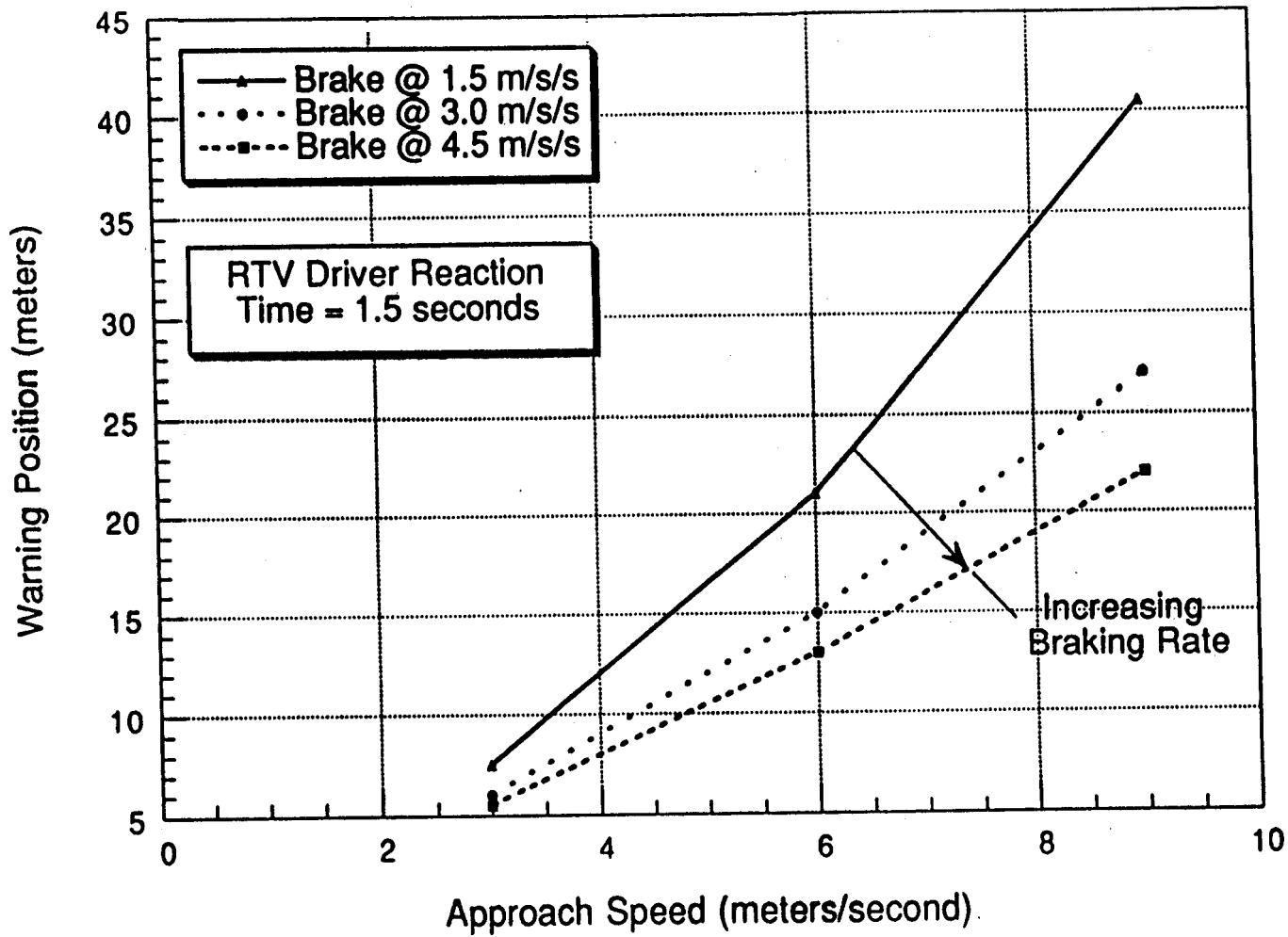


Figure 4.20 - Sensitivity of Warning Position to Braking Rate

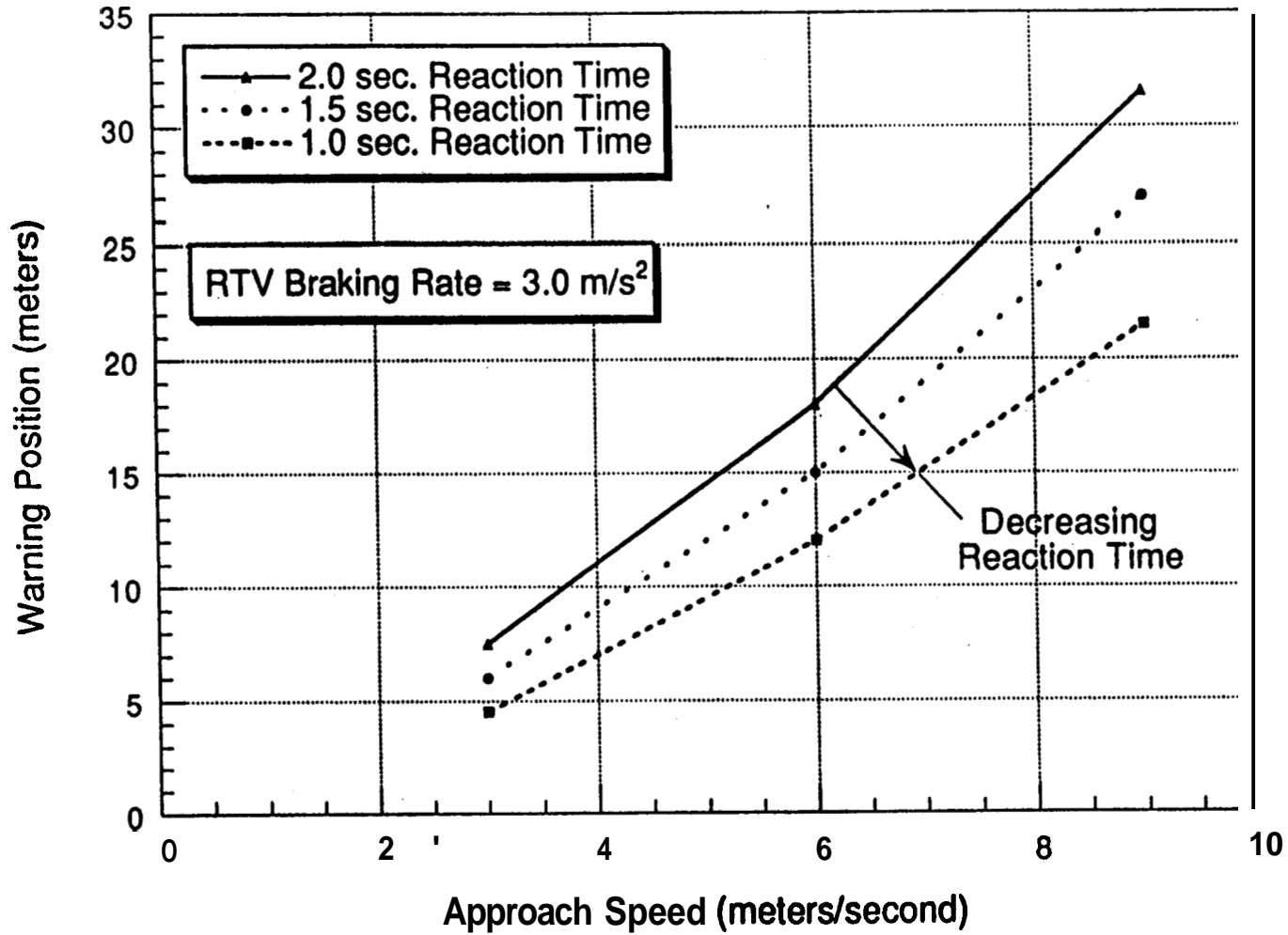


Figure 4.21 - Sensitivity of Warning Position to Reaction Time

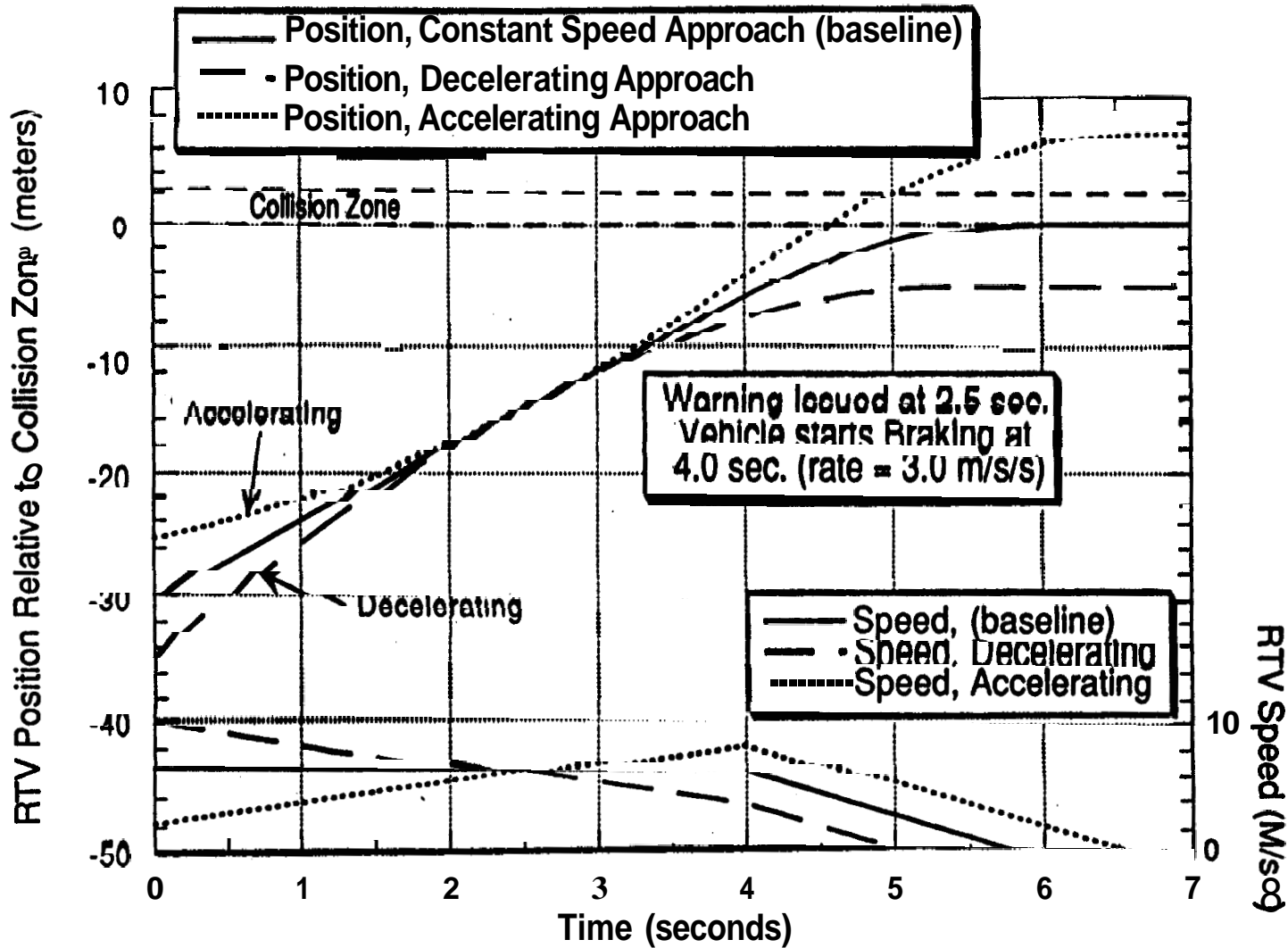


Figure 4.22a - Effects of Acceleration during Response Interval (Simultaneous Warning)

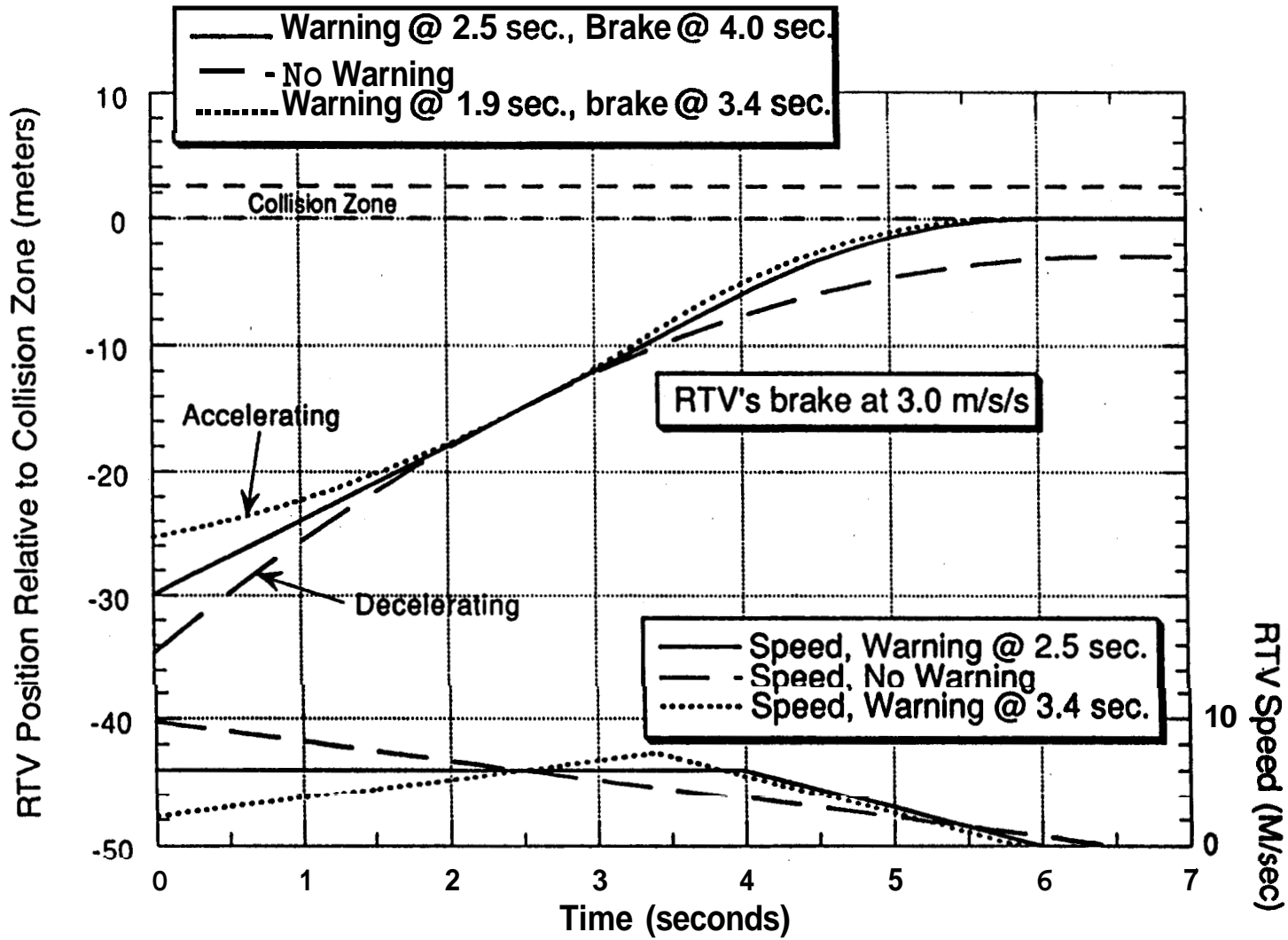


Figure 4.22b - Effects of Warning Time on Vehicle Trajectories

Table 4.1  
Parameter Values for Kinematics Analysis

Parameter	units	Nominal Value	Maximum Value	Minimum Value
RTV initial position	m	18 *	45 *	3
LRV initial position	m	97.5	150	10
RTV initial velocity	<del>cte</del>	0	9 **	0
LRV initial velocity	<del>cte</del>	15 **	-	-
RTV acceleration rate	m/sec/sec	1.5	-	-
RTV braking rate	m/sec/sec	1.5 ***	6	1.5
LRV braking rate	m/sec/sec	1.5	2.25	0.75
RTV driver reaction time	sec	1.5	1.0	2.0
RTV length	meters	4.7	-	-
LRV length	meters	30.5	-	-
Collision Zone length	meters	2.5	-	-

\* Only use higher values if RTV is moving rather than stationary at beginning of simulation run, in which case initial position is five times initial velocity.

\*\* 9 ~~cte~~ is approximately 20 mph, 15 ~~cte~~ is about 33.5 mph.

\*\*\* 1.5 m/sec/sec is about one sixth of a G; at this rate, in 3.0 seconds one's velocity changes by 4.5 m/sec or about 10 mph.

Table 4.2  
**Braking Rates Used in Kinematic Analysis**

Braking Rate m/sec/sec	Characterization	Comments
1.5	Gentle	Routine, commonplace
3	Moderate	Many drivers brake at this rate at least occasionally
4.5	<b>Severe</b>	Most people would consider this for emergencies only
6	<b>Extreme*</b>	Nearly all cars are capable of this rate, but is assumed that most drivers won't brake at nearly two thirds of a G

\* For new cars on dry pavement, the worst (lowest) average braking rates from 100 km/hr (about 60 mph) to a stop are on the order of 7.5 m/sec/sec. Most new vehicles' braking rates are closer to, or even over, 9 m/sec/sec. Obviously, factors such as bald tires, worn brakes, and wet pavement can decrease the braking performance significantly in any particular case.

The braking rate of 6 m/sec/sec is used primarily as a reference mark, providing an upper limit on braking performance for most drivers in the general public.



**Table 4.3**  
**Types of Collision Avoidance Actions for Automobile-Automobile Accidents\***

<b>Braking (no lockup)</b>	<b>Braking (lockup)</b>	<b>Steering</b>	<b>Brake &amp; Steer</b>	<b>Accelerate</b>	<b>Accelerate &amp; Steer</b>	<b>Other</b>
26%	21%	17%	28%	3%	2%	3%

\* as reported by Edwards and Malone (1982)

# 5. COUNTERMEASURES

## 5.1 INTRODUCTION

This chapter discusses the wide range of countermeasures that may be employed to reduce light **rail collisions**. Countermeasures **can** be classified in various ways. One dichotomy is between **hard and soft** countermeasures. Hard countermeasures involve physical devices -- ranging from conventional signs to advanced sensors. **Soft** countermeasures involve broader programs to **educate** drivers and more stringently enforce **traffic** laws.

Hard countermeasures can be further classified. Previously, grade crossing protection has been characterized **as** being passive or active. Here, we introduce a third category: reactive. These categories are defined as:

- Passive: static warning devices that warn the driver of a grade crossing or keep automobiles out of the trackway whether or not a train is present, e.g., signs **and** delineation.
- Active: warning devices that change states and restrict movement when a train approaches, e.g., crossing gates and traffic signals.
- Reactive: proposed warning devices that respond to illegal **or** unsafe automobile movements when a train approaches, e.g., automated encroachment alarms.

Typically, a grade crossing with active warning devices also has passive warning devices. Likewise, the proposed reactive countermeasures will typically have passive and active warning devices at the same grade crossing.

It is **also** useful **to** divide countermeasures--particularly hard technology countermeasures--into those that involve conventional and innovative technology. Conventional technologies are those that are widely deployed--signals, signs, knock-down delineators, and **so** forth--while innovative technologies are less widely used. Some **of** the latter, such as sensor-based reactive systems, are rather advanced, but there are other examples, such **as** audible alarms and strobe lights, that are quite commonplace in other contexts.

The focus of **this** chapter is on innovative, hard technology that could be **used** in advanced technology reactive system. Much of this technology could also be **used** in a less advanced, active, system, **and** these opportunities are **also** mentioned. For completeness, attention is also given **to** conventional, hard, technologies, and to **soft** countermeasures.

In the next section we discuss the nature **of** the accident problem these countermeasures are intended to address. Next we consider, in considerable detail, innovative countermeasures. Briefer discussions of conventional hard technologies, and of **soft** countermeasures, complete the chapter.

## 5.2 NATURE OF THE PROBLEM

### 5.2.1 Causes of Light Rail Crashes

More than **65** percent of all collisions on the San Jose Light Rail line have been left turn accidents. **An additional 10** percent were right turn accidents most of which are "left-turn-like" in the sense that a car turns in front of a train approaching from the rear. **Almost** all of these accidents occurred **when** a turning driver failed to notice or ignored the traffic control such as a red left turn arrow, and pulled in front of a train traveling the same direction. The LRV operators often lack **sufficient** warning to react in these circumstances, since the left-turn lane is usually close to the right-of-way for the median trackage.

The accident reports **revealed** several factors that lead drivers to violate the **left turn** arrows. The factors ranged **from** seeing the through traffic signal turn green and the adjacent through traffic move, to **anticipating** the leading left turn phase only to discover that it had been skipped for transit priority. In virtually all of the left turn accidents, the drivers erroneously assumed that they had **the** right of way, in spite of the red turn arrows or "No Left Turns" signs.

Almost all of the accidents we have studied, **occurred** when the automobile driver broke the law. In most cases, the driver did not realize a train was approaching and did not fully understand their duties **and** responsibilities at these special intersections.

### 5.2.2 Light Rail Crashes and the Nature of the Driving Task

The above facts are consistent with present-day understanding of how drivers and others engaged in **skill-based** activities make errors. Lourens (1990) summarizes recent developments in **this** area. Many tasks in driving can be viewed as highly trained, skill-based routines that do not require conscious control. While executing these tasks, the higher level decision phases **are** usually **bypassed** by stereotype rules and reflexive habits. The knowledge-based decision phases--~~those~~ involving conscious control--are only engaged when drivers are faced with a new situation or when the lower level processing is seen to fail. **James (1890)** observed that "habit **diminishes** the conscious attention with which our acts are performed."

Lourens asserts that errors **in** routine tasks are usually of a special nature. Cognition becomes "routinized", through **practice** and experience, to the point where it proceeds without the need for conscious **control**. **Once** a **skill** has been learned with the relevant sequence of steps to keep common hazards **under** control, the issue of safety rests on four factors:

1. unambiguous information to select and control the sequence;
2. absence of **overload** on monitoring of the sequence;
3. absence of **disruptive**, external changes during the sequence; and

4. **clear** signals of the need to switch out of "automatic pilot" and into a conscious level of functioning

**All** of these **factors** enter into the light rail crossing accident problem. Factor **1** contributes because of the superficial resemblance between light rail and conventional intersections. The resemblance **means** that individuals may continue a **skill-based** routine even when it is extremely **risky** and inappropriate, a problem related to Factor **4**. Factor **2** **is** relevant because **turning** maneuvers involve a substantial cognitive load, while the unexpected entry of light rail vehicle into **an** intersection during a turning maneuver is an obvious example of Factor **3**.

From the driver's perspective, the light rail crossing can easily appear to be **a** normal intersection. In fact, when no trains are present, they operate **as** such. With this in mind, we should examine the basic strategies that drivers **use** when making a left turn at a normal intersections, both with and without turn arrows. **As** soon **as** the through **traffic** receives the green, a **turning** driver will tend to complete as much of the left turn as possible without entering the oncoming flow of traffic, as shown in Figure **5.1**. If the driver thinks the intersection **has** a two-phase signal, he will do this to minimize the gap in oncoming traffic needed to complete the turn. If the driver believes the signal to be multi-phase, he may assume that he first green signal he sees is for left turns (since most multiphase signals follow this sequence), or that he can slip into the cross-traffic stream before it gets the green signal, or simply that he can save a few moments by moving beyond the left-turn stop line. Whatever the reason, once a driver initiates a left-turn manoeuvre he is unlikely pay more attention at the facing traffic signal. This disregard for traffic control devices reduces the effectiveness **of** existing countermeasures at light rail grade crossings.

For facing **traffic** and cross traffic, mistaking the light rail grade crossing for a conventional intersection **is** not critical. **An** approaching LRV will still be perceived by a driver who **is** using conventional driving strategies. The hazard arises for traffic traveling in the Same direction **of** the LRV. A driver in the **left** turn lane does not expect another flow of traffic on their left. Thus, they may fail to check their bliid spot. If the left turning driver fails to notice the left **turn arrows, or** chooses to ignore them, they run the risk of violating the right of way in front of an approaching train. At a normal intersection, this infringement is a minor traffic violation.

Minor **rule** violations such **as** this are common throughout society. In the industrial environment, there tends to be **a** reluctance or inability for the management to strictly enforce the rules (Edwards, **1981**). **As** a result, norms develop which are based on (slight) violations of the rules. The norms usually enable work to be completed quicker and easier. In the event of an accident, however, the violation of the rules is cited **as** a cause. Thus, error is considered avoidable by greater conscientiousness on the part of the human operator. Likewise, for **left** turns, it is the norm to allow movement on stale yellow signals or even fresh red signals. In terms of the left turn accidents, there is a greater need to draw drivers

attention to the control devices (red left turn arrows or "No Left Turn" signs) and improve compliance through increased enforcement and education.

The problem is exacerbated by the partial priority afforded to LRVs. Through familiarity with a given intersection, some drivers come to associate the onset of red for the cross traffic with the beginning of the leading left turn phase. The light rail system operates with 10 to 30 minute headways, and the LRV partial priority does not always skip the left turn phase. It is therefore a relatively rare event--even for regular users of these streets--to be in the turn lane when the left turn phase is skipped. Furthermore, it is only the first stopped driver that **has** to make the go/no-go decision based solely on the signals. It is thus very unusual for any given driver to experience the disassociation between other signals and the left turn arrow that **occurs when** the leading left turn phase is skipped.

A third facet of the problem derives from its occurrence during turning maneuvers. Hancock, et al (1990) examined the cognitive or mental workload during left turns, right turns and straight driving with specific application to hazard detection while making left turns. He makes a distinction between "sensory conspicuity": which depends on the physical qualities of an object that can be compared using external reference measures; and "cognitive conspicuity": which depends on the characteristics of the observer and the salience of the target, i.e., the target's meaning relative to the observer's present goals. Hancock asserts that the failure to detect a hazard is the result of a complex interplay between the observer and the object being observed. In particular, he examined the limitations of drivers' information processing and the competition for limited processing resources that **affect** the driver's ability to detect hazards during turning maneuvers. The results indicate a significant difference in cognitive processing time between turning maneuvers and straight driving, while there is only a slight difference in cognitive load during **left** and right turns. The error rate on a secondary task, detecting a light mounted on the dashboard, almost tripled during turning maneuvers and the response time increased by 33 percent. This higher error rate on the secondary task indicates a reduced level of residual attention when the primary driving task involves turning. Thus, during turning maneuvers, less residual attention is available to monitor the **surrounding** environment for potential hazards. Hancock's work reinforced earlier work by Miura (1986 & 1987), who found that **as** cognitive demands increase, for example, when driving in congested traffic, the reaction time on a secondary task increased. In this case the secondary task was responding to lights at various locations on the windshield. Furthermore, higher situational demands resulted in a narrower functional visual field. These findings are **confirmed** by the work of Williams (1982 & 1985). Williams found that **as** the cognitive load increased, the **correct** response rate to peripheral stimuli decreased.

In **sum**, the predominant form of light rail accident in San Jose--in which a motor vehicle turns into the path of a train approaching from the rear--is an understandable consequence of placing drivers in a situation that **is** actually unusual but superficially typical. Because of the

**latter**, drivers are likely to rely on skill-based routines which can lead to collisions with light **rail** vehicles. Moreover, the particular skill-based routine involved--making a left turn--**happend** to generate a high cognitive load, diminishing the capacity to process signs of **an** impending collision. In a legal sense, the collisions are almost always the fault of the driver, **just as** many industrial accidents **can** be attributed to workers' failure to strictly follow rules. **But in** both cases fault must also be attributed to the design of the system, for placing individuals in a situation in which a modest lapse in attention combined with a minor rule **violation** can lead to disastrous consequences.

## **5.3 INNOVATIVE COUNTERMEASURES**

### **5.3.1 System Goals and Requirements**

As a general proposition, a successful countermeasure device should accomplish at least one of **following** goals:

- Remind the driver that there are special risks in the given situation.
- Physically prevent the driver from taking these additional risks.

**Exam**ples of the former include a host of warning signs and signals. The most common **exam**ple of the latter **is** gates at railroad crossings. For a variety of reasons related to cost, **space** availability, and intersection capacity, crossing gates are considered infeasible for the San Jose system; nor can we conceive of any other promising physical preventive measures. We **th**erefore focus on the first of these design goals.

A **sec**ond countermeasure requirement is that it consider the needs of drivers who are already **aware** of the special risks at the intersection as well **as** those who are not. **An** alarm that **succes**sfully alerts unaware drivers could also delay the response or elicit an inappropriate **respon**se from aware ones. To illustrate, there have been cases in which drivers stopped in the left **turn** lane have misinterpreted the train horn **as** coming from a truck behind them and **turned** into the path of the train to get out of the way of the non-existent truck. Conversely, **since** the alarm **is** directed toward unaware drivers, it should address the expectations of such **driv**ers--i.e. those of drivers at conventional intersections. In particular, alarms should be **prom**inently located in the perceptual field of such drivers.

A **thi**rd design goal **is** that the countermeasure create a **signal** with a high clarity of **mean**ing. **This is** a challenging goal, with a number of different aspects. First, it should be verified that **wh**en drivers perceive the **signal** they interpret it correctly. This principal should govern both the content and placement of signals, whether visual or auditory, Second, the signal should be **clear**ly associated with the hazard. Thus, situations in which a train is actually approaching **shou**ld generate a different signal from situations in which there is no train. Finally, false

alarms should be minimized. In addition to differentiating situations when trains are and are not approaching, the alarm should differentiate according to whether a right-of-way incursion is about to occur. Otherwise, drivers may become habituated to the signal, associating it with non-hazardous situations.

A fourth goal — one that conflicts with the third -- is that the **system** provide consistent feedback. One **of** the best established rules of learning is that practice requires feedback for learning to occur. On the road, we do not always get feedback, **or** negative reinforcement, for our improper driving (e.g., when the police are not present). **This** goal conflicts with the third because it suggests that an alarm should be activated whenever a driver incurs a light rail intersection in violation of a traffic signal, whether or not a train is approaching. To resolve this conflict, one might **use** separate devices, one that is activated whenever there is an improper turn maneuver, and a second only when a collision is imminent.

### 5.3.2 Design

Horowitz and Dingus (1992) addressed the implications of the above requirements for the design of an alarm-based collision avoidance system for drivers. The authors advocate two alarm properties: graded sequence **of** warnings, and parallel change in modality. The alarm should have a graded response from mild to severe as a function of the time to collision. If the time to collision is too short, it is unlikely that any warning would aid the driver. Although a **mild** alarm would be effective in many cases, the greater benefit may be the contrast with **a** more severe warning. It should reduce the probability a driver will be startled by a more severe warning. If the mild alarm **succeeded** in attracting drivers' attention and preventing accidents, it would also decrease drivers' (and others') exposure to the more severe warnings, reducing habituation for drivers (and annoyance to others).

Horowitz and Dingus also suggest a modality shift **as** severity increases. In particular, they cite experience with visual and auditory displays in aircraft. When there **is** time to react, pilots prefer visual over auditory warnings. If immediate action is required, auditory signals are often superior. **Thus**, it may be beneficial to use visual warnings for the mild alarms and audible warnings for the severe alarms. Schoppert and Hoyt's (1967) findings concur with Horowitz and Dingus. In particular, they advocate the **use** of cross modality stimulation. Furthermore, **they** advocate the use of intermittent stimulation for **all** automatic signals.

The discussion below elaborate on this basic design concept, with special consideration to the modality and nature of the **alarms** to be included. Brief attention **is** also given **to** the targeting of the system **and** to the conditions under which it should be triggered.

### 5.3.2.1 Modality Issues

Visual, audible, and tactile stimuli are the only reasonable means of conveying warnings to drivers. Tactile stimuli are generally limited to passive systems (e.g., rumble strips). It would not be cost effective to incorporate tactile stimuli into **an** active or reactive countermeasure system. **As** such, we will limit the human interface to visual and audible **alarms**.

McCormick and Sanders (1982) address specific issues concerning the perception of visual and auditory stimuli. Current research suggests that when both visual and auditory inputs are **being** time shared, the auditory channel is more resistant to interference effects than the visual channel. Audible **alarms** also have a few undesirable properties, however. Drivers may have **difficulty** identifying the direction or meaning of an alarm, **as** when drivers mistook the train **horn** for a truck horn. Another problem with audible **alarms** is the susceptibility to masking from background noise and attenuation from the vehicle cab.

McCormick and Sanders (1982) advocate the use of audible alarms if the message calls for immediate action while visual **alarms** should be used when there is more time to react. Audible alarms are **also** preferred when the visual system of the receiver is overburdened, as it is during a left turn maneuver. McCormick and Sanders cite a study by Colquhoun (1975) where subjects conducted a vigilance task over several days. The subjects were presented with an audible signal, visual signal or both. The percent of signals detected increased from visual only to audible only to visual + audible. This study suggests that visual + audible stimuli are superior to single mode stimuli. **A** number of other researchers (Schoppert and Hoyt 1967; Horowitz and Dingus, 1992) specifically advocate a modality shift from visual to audible as the hazard severity increases.

#### 5.3.2.1.1 Visual Alarms

Visual fixations often indicate where cognitive attention is focused. Only the objects that are projected on to the fovea are in sharp focus. Visual perceptions are very selective and two mechanisms appear to control the process: one external and one internal. External control is evident whenever the blurred image on the periphery is highly conspicuous and is considered (by the brain) worthy of focused attention. The internal control is a function of our expectations concerning where in the visual field most of the information is located. Most **often**, the two mechanisms operate in harmony, e.g., when approaching a curve, a driver's visual fixations are governed by expectations on where the road should be **as** well **as** by the roadway edge markings, which constitute **high** contrast **targets** capable **of** attracting the driver's visual fixations (Shinar, 1978).

Delays or outright failures in detection are most likely to arise **from** poor target conspicuity (Olson, 1989). The strobe light appears to be the most effective device for commanding drivers' attention with visual stimuli. The strobe's high conspicuity has been attributed to the



fact that flashing lights rarely occur in nature and as such, they attract the attention of the human visual system.

In terms of the light rail **safety** proposals, the following sections will recommend a strobe system to attract drivers' attention to the left turn arrows and a wayside horn to elicit a reflex head **turn** reaction and thus, bring an approaching train into the visual field. These devices will capitalize on conspicuity in peripheral vision, drivers' perceptions of importance, and ability to provide a graduated response.

Ruden, et al(1977) conducted an extensive research project to improve the effectiveness of conventional railroad grade crossing protection. The primary focus of their work was flashing lights, as the noise level inside moving automobiles can obscure **horns**, signs and other audible **alarms** (specifically train based alarms). Flashing lights are more conspicuous because they occur rarely in nature, and the visual system is not well prepared for the flash stimulation.

Ruden, et al, examined both incandescent and strobe light arrays at various flash rates and duty cycles. Among their findings, the following are relevant to the current study:

- Red and blue are good daytime and nighttime colors, respectively.
- Warning devices should be placed **so** as to fall within a visual angle of 10 degrees as measured **from** the driver's line of sight, in order to attain a high detection probability.
- For incandescent lights, flash rates in the range of **1-1.5 Hz** were most conspicuous. Flash rates exceeding **1.5 Hz** resulted in reduced "attention-getting" properties. This finding is attributed to filament heating and cooling characteristics of the light source.
- Xenon flash tubes (in one, two and three tube combinations) without colored filters dominate the attention-getting property of a standard pair of **20.3 cm (8 inch)** railroad flashing lights. Red filters reduce the effectiveness of the strobe lights to less than that of the standard railroad flashers.
- There is a definite increase in the attention-getting property of strobe lights as the flash rate is increases and in particular, when three strobe lights are used to simulate motion (**phi** phenomenon).
- The multiple white strobes were most conspicuous at irregular flash patterns and at flash rates totaling **6-8 Hz**.
- Doubling strobe intensity improves conspicuity in daylight and at night with competitive backgrounds.
- Red filters reduce strobe intensity by an order of magnitude while blue filters reduce strobe intensity by a factor of **3-4**.

- The researchers strongly advocate three strobes over two and two strobes over a single strobe.
- The strobes should be bright enough to be noticed, but, they should not be blinding.

After laboratory testing, field tests were conducted at a railroad grade crossing in Richmond, CA. The crossing was characterized by heavy automobile and train movements. Three horizontally mounted strobe lights were installed **76 cm (30 inches)** above the standard railroad flashers and served **as** a supplemental warning device. The strobes were **set** to flash: left, center, right, center, left, etc. The outer heads were each set to flash at **2 Hz** and the center light trailed the flash of each outside light by 50 ms. Different output intensities were selected for daytime and nighttime operations. A photo cell was **used** to establish the appropriate output level. The strobes were operated from April **1, 1977** through July **19, 1977** without incident. During observation periods, the strobes did not appear to disrupt drivers.

Another auxiliary grade crossing strobe system is mentioned in Progressive Railroading (Anonymous, **1980**). The supplementary device is similar to that tested in Richmond three years earlier. The main difference is the use of three blue strobes instead of white strobes. The researchers tested red, blue, yellow, and clear strobes and blue was found to be superior in all instances. This decision was partially based on the fact that the human peripheral vision is more susceptible to blue-green light than to red, particularly at night. The author also notes that, due to the use of blue lights on emergency vehicles, the color has taken on the connotation **of** an emergency situation.

In addition to the grade crossing installations mentioned above, strobe lights have been installed at a number of intersections throughout the country. Often the installations were demonstration projects and only a few published articles have been located. The earliest published report (Wilburn, **1975**) describes the installation of a Halo strobe light at an intersection in Eugene, Oregon. The Halo Traffic Light consists of a red incandescent light surrounded by a white strobe light. The high-intensity strobe was set to flash at **1 Hz** while the normal red indication is on. The light was placed between two existing traffic signal head and was used for eight months during **1974** to reduce the number of "Running the Red" accidents. The test was scheduled to last for one year, but **was** terminated prematurely when vandals shot out the traffic signal. The author notes that the signal effectively attracted drivers attention and appeared to be effective at reducing the number of "Running the Red" (no such accidents were recorded during the test period, however, four such accidents occurred during the same period one year earlier). The **two** drawbacks of the device were the susceptibility to vandalism and the confusion with a flashing red light. The preliminary conclusions were that the Halo strobe was an effective device for attracting drivers attention, but, that it would lose effectiveness if it were **used** at numerous locations. Implications to the

current study suggest that any strobe light device should be distinct from conventional traffic signals and their **use** should be limited to the light rail grade crossings.

The Maryland State Highway Administration also initiated a strobe study in **1979** (Styles, **1982**). Two intersections were equipped with Halo strobes and another was equipped with a Barlo strobe. The Barlo Lights consist of a horizontal white strobe light mounted in the center of the normal red indication and is typically **set** to flash at rates over **1.5 Hz**. **All** of the intersections had high speed approaches and visibility constraints. Accident rates were examined for the two years before/after strobe installation and yielded mixed results. The author concludes that the red strobe signal "appears to be effective at only certain intersections." It is important to note that: "[n]o red violations were observed on any **of** the strobe [quipped] approaches which suggests that the strobes control this movement. Through on yellow movements occurred on the strobe approaches, but generally these movements were considerably less than expected ...." Styles concludes that the red strobe signal appears to be effective in reducing right angle, rear end and total accidents at certain locations; but, no overwhelmingly conclusive evidence appears to exist to support either the effectiveness or ineffectiveness of the signal. He recommends further study of the device and that those intersections equipped with strobes should continue as such while additional strobes should be placed sparingly. In **an** appendix, the author notes **36** other strobe installations at intersections in **13** states.

The primary goal of the three published strobe studies was a reduction of right angle accidents at high speed rural intersections. No effort was made to reduce left turn accidents (e.g., equipping a **left** turn arrow with a strobe light) and as such, there was little impact on accidents resulting **from** turning maneuvers. The last report by Styles suggests that the strobe signal can improve signal compliance. The **left** and right turn accident reports suggest that many of the offending drivers were unaware of an LRV overtaking from behind. Thus, improved signal compliance should reduce the number of automobile-LRV collisions.

In addition to the three site specific reports, three other reports were identified on the use of strobe lights at intersections. Eck and Sabra (**1984**) summarized the findings **of** Swenson (**1981**) and Styles (**1982**) and provided follow up information to Styles report. In particular, of the states contacted, three were moving away from strobes due to concerns about the device, e.g., neighborhood opposition and an incident where a strobe "blew up". If the strobes are activated sparingly, neighborhood opposition should be **minimized**. The nature of the explosion should be investigated before any strobe devices are deployed, it underscores the need for care and proper handling, but, a single event should not preclude **future use** of strobe lights.

Ryan (**1984**) surveyed nationwide use **of** strobe supplemented red signal indications. He identified and contacted **10** jurisdictions using the devices. Of the jurisdictions identified, the State of North Carolina had more than **40** locations where strobes were in **use**, the State of

Maryland had **six** locations and all other jurisdictions had three or fewer. The strobes were installed for two principal reasons: in an attempt to reduce excessive accident rates, and in an attempt to draw driver attention to an unexpected signal. In most installations, the "number of accidents" and "accident rates" decreased **after** strobe installation. Due to the small sample size, little statistical significance can be attached to these improvements. Some jurisdictions felt the strobes were effective while others did not, there was no clear consensus. One jurisdiction felt that the strobes effectiveness was reduced **as** local drivers became accustomed to the device.

**Eck** and Sabra (1985) provides a follow up to their earlier work and to Ryan's paper. They sent **211** surveys about traffic control devices to various agencies and received **65** responses. Out of these responses, they identified four state agencies with a total of **10** strobe installations at high speed intersections and one local agency with two installations. The reasons given for strobe installation were: number of accidents, speed problems and red violations. The cost of strobe installation per intersection approach (in pre **1985** dollars) ranged from **\$400** to **\$1000** with an annual maintenance cost between **\$50** and **\$200**.

A number of studies have found that increasing flash frequency, decreasing flash duration, irregular flash patterns and simulated motion improve conspicuity. **An** early paper by Gerthewohl (1954) found that at low contrasts, short and fast flashing signals are more conspicuous than long and slow flashing ones. The results at higher contrasts were confounded by the fact that the total luminous flux emitted per second was normalized over the range of flash frequencies. Laxar and Benoit (1993) found that the highest frequency tested, **4 Hz**, with the smallest duty cycle (i.e., the on-time/off-time ratio), 0.3, was most effective. They suggest that higher frequencies and lower duty cycles may be more effective and refer to a paper by Katchmar and Azrin (1956) that found stroboscopic flashes of **10 Hz** were judged better warning signals than those of lower frequencies. Hopkins and Holmstrom (1975) (as quoted in Ruden, et al, 1977), found that "the alerting effectiveness (and distinctiveness) of flashing lights increases as flash duration decreases (for constant radiated energy), down to durations of approximately **0.1** second." They further state that a duration of **0.1** second or less is a basic objective of any improved crossing warning. On the other hand, McCormick and Sanders (1982) stress that the flash rate should be well below that at which a **flashing** light appears **as** a steady light (the flicker-fusion frequency), which is approximately **30 Hz**. They suggest that frequencies in the range **of 3** to **10 Hz** are effective for attracting attention.

Ruden, et al (1977) note that progressively increasing flash frequency can be **used** to project the feeling of increasing urgency. Results of the "Cyberlite" experiments conducted in the early **1970's** support this point. The Cyberlite **is** an supplemental brake light installed above the rear bumper. The light is activated by the brake pedal and is pulsed in a controlled fashion at a rate, duty cycle, and intensity that varies exponentially with deceleration. The flash

frequency ranged over **1 Hz** to **7.6 Hz**. On March 1, **1972**, field operations were begun using **343** taxis of the **San Francisco Yellow Cab Company** fitted with Cyberlites. Operations were continued through February 1, **1973**. **No** public education program was associated with the project and only limited news coverage **occurred** at the start of the test. Over the five years prior to testing, the Yellow Cab Company experienced **7.9** rear end collisions per million miles. **During** the study, the Cyberlite equipped **cabs** averaged **3.51** rear end collisions per million miles while a control group averaged **8.91** rear end collisions per million miles, **see** Table **5.1**. The taxi drivers did not appear to become more cautious **because** of the Cyberlites, there was no change in the number of collisions in which the **taxi** drivers rear-ended another vehicle (Voevodsky, **1974**). Initially, the Cyberlites were **set** for a maximum brightness of **1700** candlepower. The high intensity generated some complaints and the intensity was reduced to **600** candlepower. The accident rate immediately increased from one collision per two weeks to six. A compromise was finally reached at **1200** candlepower and the rear end collision rate leveled off at one collision a **week** from the Cyberlite equipped taxis (Goldrath, **1972**).

**As** with many traffic safety devices (e.g., concrete barriers along the highway), strobe lights have a potential downside: the risk of inducing seizures. Popkin and Waller (**1988**) note that most states permit epileptic drivers to drive after their seizures **appear** to be under control for a period of one year. In **California**, according to The Epilepsy Foundation of America (EFA), California Department of Motor Vehicles (CADMV) considers seizure **free** periods of **3, 6,** and **12** months when reviewing each individual driver's case. Moreover, the authors found that, out of a sample of **112** people treated for epilepsy, only **26** percent were on record as being epileptics with the Department of Motor Vehicles (DMV).

Some epileptics are vulnerable to seizures induced by **flashing** lights, including strobes. According to the EFA, "A small number (less than **5%**) of persons with epilepsy have their seizures triggered by a sensory stimulus. The most common seizure triggers **for** patients with this type of epilepsy are flashing lights, which trigger absence (petit **mal**) attacks (a few seconds of a blank, absent stare with loss of contact with the environment). In rare cases, the petit **mal** seizures can trigger more severe seizures.

The EFA further reports that:

**In light-sensitive (photosensitive) patients, seizures are most commonly triggered by flash rates of 10 to 20 flashes per second. The flashes must** . . . . Neon signs and movies, for instance, are usually harmless. Watching television is also usually safe.... Strobe lights—as at rock concerts, for instance—can definitely trigger attacks, as can flickering sunlight. This **most often occurs** when riding on a bicycle or in a car through alternating shadows and sunlight. Some persons are also sensitive to light passing through venetian blinds. Headlights of oncoming cars in heavy traffic can occasionally trigger attacks. In very rare cases, the degree of photosensitivity may be so great that even light reflected off rippling water might precipitate a seizure.

Wilkins and Lindsay (1985) note that about three percent of all patients with epilepsy are susceptible to visually-induced seizures. The seizures are often the result of flicker from sunlight interrupted by road-side trees or reflected from the surface of a lake. The television is another common source of flickering light. It is well known that certain patterns of stripes, such as the metal tread on escalators, can also be highly epileptogenic. Some patients are so sensitive that they can not read books without risking a seizure from the successive lines of print. Approximately 30 percent of those individuals sensitive to flashing lights will also be sensitive to stationary patterns of striped lines.

The flash frequency at which epileptiform EEG abnormalities are likely to be induced lies between 15 and 20 Hz in most cases, however, some individuals may be maximally sensitive to other frequencies. Wilkins and Lindsay cite one study of photosensitive patients where 19 percent of the subjects exhibited a photoconvulsive response to flashes at 5 Hz, 81 percent at 30 Hz and 21 percent at 60 Hz. It is important to note that the refresh rate, or flicker, of a television set is 30 Hz viewed at close distance and 60 Hz viewed from further distances (half of each scan line is refreshed every 1/60th of a second, thus, the picture appears to oscillate at 30 Hz when viewed close up and flicker at 60 Hz when viewed from a distance). These findings suggest that an array of strobe lights flashing at 5 Hz would be about as hazardous as a television set.

Increasing the intensity of a flashing source increases the likelihood of a photoconvulsive response and increasing the level of ambient illumination can reduce the likelihood. Thus, a strobe installation having two intensities, one for daytime conditions and one for nighttime conditions, would be less likely to induce seizures.

Wilkins and Lindsay note that blue light may be less epileptogenic than other colors at the same intensity and red more so. The benefits of blue filters are reaffirmed by Takahashi and Tsukahara (1992). The authors found that blue sunglasses can be beneficial in preventing photosensitive seizures. The benefits are attributed to attenuating shorter wavelength light and possibly to a luminance diminution. These findings suggest that blue filters on any strobe devices should reduce the chance of inducing seizures in photosensitive epileptics.

Finally, legal precedence exists for flashing devices in the range of 5 Hz on the roadway. Berkeley Police cars are equipped with a pair of yellow strobe lights that have a combined frequency of 4 Hz. And the Motor Vehicle Code reads: "Any motorcycle may be equipped with a means of modulating the upper beam of the headlamp between a high and a lower brightness at a rates of 200 to 280 flashes per minute..." (CADMV, 1991) This translates to a flash rate of 4.7 Hz. There is no reason to believe that a strobe device would be any more conducive to inducing seizures than a modulating headlight. Further research may be required to establish an acceptable level of risk.

### 5.3.2.1.2 Audible Alarms

There is evidence to show that audible alarms are effective for reducing accidents at grade crossings. In particular, the Federal Railroad Administration (FRA) examined a train whistle ban in **1990**. A nighttime whistle ban ordinance was imposed on the Florida East Coast Railway in **1984**. The ban only applied to gated crossings and required a special advance warning sign for motorists that read, "**No Train Horn, 10 PM - 6 AM**". The nighttime accident rate at the **511** impacted crossings tripled during the first five years of the ban. At **89** similar crossings where the **ban** had not been imposed, the nighttime accident rate only increased by **23** percent. **CSX** Transportation, which operates in the same counties and was **not** impacted by the ban, saw a net decrease in accidents over the same five year period at **similar** crossings. The FRA concluded that **train** whistles (i.e., train based audible **alarms**) are effective in reducing grade crossing accidents (**FRA, 1990**).

**An** audible alarm is expected to be particularly effective at a light rail intersection, since RTV speeds are lower and warning distances consequently less. Indeed, such an alarm has already been tried at San Jose, but the practice **was** ended because of complaints from neighbors. The use **of** such an alarm **in** a manner that reduces neighbor annoyance will be considered below.

The most promising audible alarm appears to be a wayside horn, either as a stand alone warning device or a component of a multimodal alarm system. A directional horn, placed close to the automobile driver will allow for alarm levels loud enough to penetrate the acoustically insulated cabs of modern RTVs while being quiet enough **so** that it **will** have minimal impacts on the surrounding neighborhood. Sound reduces in intensity in accordance with the inverse square law. Thus, if the distance from the horn to the driver is halved, the sound pressure level can be reduced fourfold, or **6 dB**, while maintaining the same loudness to the driver (**Cox, 1972; McCormick and Sanders, 1982**). Furthermore, **if** the alarm is only activated in the event of emergency, and not with the passing of every train, local residents **will** be more likely to tolerate the occasional disturbances.

The idea of using wayside horns to protect grade crossings is not a new one. Longrigg (**1975**) proposed a reactive warning system that utilizes directional, audible alarms to protect a grade crossing. **At** conventional grade crossings, such a device may not be effective **because** of high automobile approach **speeds**. At an intersection with a light **rail** grade crossing, however, such a device could be very effective. Turning automobiles tend to travel at low **speeds** and the alarms **can** be placed close to the vehicles. The Los Angeles Metropolitan Transportation Authority is currently experimenting with wayside horns that **can** be activated **from** an approaching LRV. **They** are **also** considering the possibility of automatically activating the horns **as** the train approaches (Meadow, **1994a & b**).

The literature review suggests that the wayside alarm should be in the range of **90 dB** (e.g., subway train at **6 m (20 feet)**) and **140 dB** (e.g., **37 kW (50 hp)** siren at **33 m (100 feet)**). The

potential for injury rules out an **alarm as loud as 140 dB**, and some lower limit will have to be determined. It should be loud enough to penetrate the passenger compartment of most vehicles but quiet enough **so that** a driver with an open window **will not** be injured or startled. In particular, the intensity should depend on background noise. The alarm should be activated very infrequently, both to **minimize** neighborhood disturbance and to decrease the probability of driver habituation. Alternately, two distinct activation levels **can be used**, a relatively quiet level sounded for most trains and a high intensity level for the relatively rare emergency situations. McCormick and Sanders (1982) advocate:

- Avoiding extremely intense signals that **can** cause a startle response and actually disrupt performance.
- Establishing intensity relative to ambient noise level in order to avoid both masking and excessive loudness.
- Using signals with frequencies different from those that dominate any background noise, to minimize masking.
- Using interrupted or variable signals rather than steady-state ones.
- This will tend to minimize perceptual adaptation by drivers.
- Testing the signals to be **used** on a representative sample of the potential driver population to verify both the detectability and the effectiveness of the alarm.
- Avoiding conflict with previously **used** signals. If a new signal is somewhat similar to signals already in use, it should also have a similar meaning.
- Facilitating changeover from previous signal. For example, if an auditory signal replaces a visual one, it is preferable to continue both modes for a while, **so** people become accustomed to new auditory **signals**.
- Using frequencies between 200 and 3000 Hz, because the ear is most sensitive to this range.

**To** overcome the difficulties in identifying the direction and meaning of an audible signal, a wayside alarm should be distinct **from** other sounds in the road environment. The primary goal is to find a sound that conveys the urgency of the situation, that is associated with a single event and that always requires the same specific response. A klaxon or buzzer alarm may satisfy these requirements. In addition, the **alarm** should be placed such that the source is not easily confused with following vehicles. Placing the horn next to the first position in the turn lane, just to the rear of the driver compartment, should reduce confusion over the source. Such placement should elicit a head turn reflex reaction in the direction of the sound. For the first driver in the turn lane, the **head** turn reaction should bring an approaching **LRV** into the



field of view. Driver **response** to any wayside horn should be measured in a safe environment before deploying such a device in the field.

The masking problem **must also** be dealt with. According to McCormick and Sanders (1982), the effects of masking **vary** with the masking sound and the sound being masked. In general, the higher intensity **of the masking** sound, the greater the masking effect. For pure tones and narrow band noise, the greatest masking effect occurs near the frequency of the masking tone and its harmonic overtones. For low intensity masking tones, the masking effect is somewhat confined to the frequencies around the that of the masking tone, but, at higher-intensities, the masking effect spreads **to** higher frequencies. Active noise cancellation or filtering may reduce the effects of **masking**. **By** incorporating a microphone and microprocessor based filter, it should be possible **to** reduce the background noise through destructive interference.

### 5.3.2.2 Targeting

The kinematic analysis in Chapter 4 compares alarms targeted at the LRV and RTV operators, concluding that the RTV alarm is more promising because of the RTV's superior braking ability and lower speed **in the** situation being considered. While that analysis clearly shows that a collision avoidance system should target the RTV, the issue of whether or not to also target the LRV should **also** be considered.

Alarms targeting the **LRV** are comparatively simple to design. Communication could be via wayside signals or cab **signals**. Because the light rail operators are a highly trained by the transit agency, the specific signal properties are rather flexible.

**An** LRV traveling at **55 km/h (35 mph)** can take ten seconds and **78 m (255 feet)** to come to a complete stop under **normal** braking conditions. Although the light rail operators **look** for motion cues in the **turn lane** (e.g., brake lights, position of the front wheels and driver's head movements), it can be **difficult** to detect forward motion from **78 m** behind an automobile. **As** such, an active warning system can be used to provide as much as an additional two seconds warning for light rail operators. Under normal braking conditions, this could provide more than **a 20 percent** speed reduction, which, according to Chapter 2, will tend to reduce the probability that the **collision will** result in injuries.

The **main** disadvantage **of** targeting the LRV is that, in some cases, this could lead to collisions that would **have** otherwise been avoided through the LRV clearing the intersection ahead of the incurring RTV. **If** only the LRV were targeted, this outcome might be avoided with some fairly simple **logic** governing when the signal should be activated. If both the LRV and RTV are targeted, **the** logic becomes more complex, since the response of the RTV to the signal must be considered. **If** the RTV slows **in** response to the signal, the probability of the train clearing the intersection before the incursion in the absence of a warning signal increases.

If the LRV is targeted, the **system** should have have a positive response, indicating when no vehicle movement are detected **as well as** when one is. Furthermore, it should have a fail-safe state that indicates the device is malfunctioning. It must be reliable, or operators **will** start to disregard it. Finally, if a wayside system is used, it should be placed out of view from the roadway and it should not use colored signals, **as** drivers may assume the signals control automobile movement.

### 5.3.2.3 Triggering

The final issue to be considered in **this** section **is** when to trigger the alarm. The **rules** for this **will** depend on three conditions: (1) the presence of an RTV in the left-turn lane when the left-turn signal is red; (2) an RTV making **an** illegal **left** turn; and (3) an LRV approaching an intersection. It is clear that **at least** one of these conditions must exist for any special signal to be activated. It is also obvious that conditions (2) and (3) together should always trigger the alarm. It remains to consider whether anything short **of** this should also do **so**.

The least stringent, and in **that** Sense most conservative, approach is to require only condition (1). The problem is that the **alarms** would be very common and that in most cases there would be no train approaching. **This would** greatly reduce the association between the alarm and the hazardous situation it is designed to indicate.

Conditions (1) and (3) together might also be a trigger. This would increase the association between the signal and the hazard. Furthermore, since drivers would be targeted before they begin turning, they **would** have greater mental capacity to detect and interpret the signal. On the other hand, the alarm would again be quite common. This would lead to habituation on the part of drivers, and annoyance to neighbors in the signal were too intense (loud or bright).

Another alternative would **be to** require only condition (2). The advantage of this approach is that it results in consistent feedback: whenever an improper turn **is** made, the system response **is** the same. **This** disadvantage **is** that the association between the signal and the hazard is again diluted.

One **can** try to capture the **advantages** of **all** these various alternatives with a graduated and differentiated response. **The response can** be graduated, **as** Horowitz and Dingel (1992) recommend, **so** that some **level** of warning is given when conditions (1) and (3) hold but that the nature and intensity of the **signal** change if condition (2) is detected. The response can also be differentiated by giving **all** drivers who make illegal left **turns** a signal admonishing them for their hazardous behavior.

### 5.3.3 Recommendations for a Prototype System

Innovative **safety** technologies should be subject to extensive testing and refinement prior to full deployment. **Based** on **analyses** and literature of this and the previous chapters, however,

it is possible to recommend a prototype for such a system. The key features of the recommended system are (1) that it primarily target the RTV; (2) *mix* active and reactive elements; and (3) offer a graduated, multimodal response beginning with a strobe light whenever and LRV is approaching an intersection, transitioning to a wayside horn when an RTV incursion into the LRV right-of-way **is** imminent. It may also be desirable to include a consistent “negative feedback” **response**. whenever and illegal left turn through an LRV intersection **is** made, even if **no** train **is** approaching. Such a signal, if included, should be clearly differentiated from the others, **so** that their association with an impending train arrival **is** not lost.

More detailed recommendations for the prototype system and variants thereof appear below.

### 5.3.3.1 Strobe System

- Place an array of three strobe lights near the primary turn arrows. Both should be as close as possible to the visual fixation point for turning drivers at intersections that do **not** have a LRV crossing or left **turn arrows**. When establishing this location, the analysis should account for the wide median required for light rail operations.
- Restrict strobe use to light rail grade crossings. If the devices are used for other intersections, the clarity **and** specificity of their **meaning** will be compromised.
- Keep the warning specific to the unperceived hazard. The strobe lights should therefore only be activated when a train is traveling in the same direction as the adjacent traffic. The effectiveness of the countermeasure will be reduced if it is activated for trains traveling in both directions. From the driver’s perspective, a train approaching from the opposite direction is a different phenomena than one traveling in the same direction. In the former case, the train will usually be perceived while in the latter, the train will frequently go undetected until it enters the crossing, **as** confirmed by the accident history. Activating the signal for both situations **will** increase drivers’ learning time and decrease the number of drivers who associate the strobe lights with an unperceived hazard. Bowman (1993) notes that motorists expect that **similar** traffic control devices **will** always have the same **meaning** and will require the same motorist action regardless of where they are encountered.
- **Set** the average flash frequency at about **5 Hz**, a frequency that approaches the maximal conspicuity. It should be **low** enough that the risk of inducing seizures is comparable to or less than that of other **sources** in the roadway environment. (Note that a number **of** the intersection and grade crossing installations mentioned above **used** frequencies in excess of **5 Hz**.)
- Examine the **use** of duty cycles (on-time/off-time ratio) below 1.
- The strobes should not be blinding, just bright enough to attract attention. Two brightness levels should be **used**, one for daytime conditions and one for nighttime conditions. The

selection should be made using a photo cell or some other sensor, and should **not** be based on time of day. The **two** intensity levels will allow for maximal conspicuity without blinding drivers **at** night and will further reduce the chance of inducing seizures in photosensitive individuals.

- Use three strobe lights, approximately **50** cm (**20** inches) apart to simulate motion. In particular, use **a flash** sequence **of** left, center, right, center; repeat. **Again**, the net flash frequency should be on the order of **5 Hz**.
- Use blue filters **over** the strobes. Research has shown that blue objects appear closer than any other color, peripheral detectability is highest for blue light, response time is lowest for blue light and blue filters appear to reduce the chance **of** inducing seizures in photosensitive individuals. Furthermore, the use of blue filters on emergency vehicles has created an association between blue lights and emergencies. If legislation precludes the use of blue filters, then white light should be used.
- Examine the possibility that the strobe lights distract drivers attention away from the relevant control device. If **so**, intermittent strobe activation should be considered. For example, the strobes could be activated for half a second and then turned off to allow the driver to fixate **on** the control device. If the hazardous turn continues, reactivate the strobes for a slightly longer duration.
- Consult with the National Epilepsy Foundation to ensure that seizure risk from strobes is minimized.

### 5.3.3.2 Audible Alarm

- Place a directional, audible alarm just to rear of the driver of the first vehicle in the **turn** lane. Use an **alarm** that is distinct from vehicle horns or emergency sirens, possibly a buzzer or **klaxon**. **By** placing the horn next to the driver's compartment, a lower volume can be used to achieve the same response.
- If the audible alarm is one facet **of** a multimodal warning system, it should be reserved for the most urgent levels **of** alarm, when the driver has to react quickly to avoid an accident. The alarm should **be** sounded infrequently, both to prevent driver habituation and neighborhood **annoyance**.
- If the audible **alarm** is used **as** a stand alone system, at least two levels of warning should be provided. **A** relatively quiet alarm that is sounded whenever a train enters the crossing and a higher level **alarm** that is only sounded in emergencies.
- If sufficient warning **exists**, use a graded response; however, the limited reaction time may make such a **feature** ineffective. When time permits, a graded response will reduce the chance of startling drivers.

- Examine the **use of** active noise cancellation to filter out background noise and increase the effectiveness**of the** warning alarm.

### 5333 Operation

- Use a graduated response. For example, there might be three response levels, **as** follows:
  1. Flash **the** center strobe once, every time a train approaches the intersection in the same direction **as** the traffic. **This** will provide a gentle reminder to drivers that they are at **a** special intersection and that a potentially unperceived hazard is present. **Furthermore**, it **will** attract drivers attention to the relevant control device. **If a** constant warning time **can** be provided, the strobe should be activated a second **time as** the through traffic signal turns green to reinforce turning drivers' compliance**to** the turn arrow.
  2. If a **driver** passes a predetermined threshold, trigger all three strobes to simulate motion. Such an activation should be a rare event and should **only** occur when a **hazard** is present. The first level of activation, a single flash, reduces the chance **of surprising** a driver with the second level of activation, multiple flashes, and creates**a** clear relationship between stimulus and severity.
  3. If a **driver** fails to comply to the second level response and continues the turn, two responses should occur: a modality shift to **an** audible alarm and an increase in the warning level on the strobe lights. Visual alarms are preferred when there is time to **respond**, but, audible alarms elicit quicker responses. The strobe lights should **alternate** flash patterns or increase the conspicuity factor in some manner.
- Present drivers with the same stimulus or series of stimuli for **all** trains. **Also attempt to** provide **a** constant warning time--interval between warning onset and when a train enters the crossing.
- If a reactive countermeasure, responsive to drivers' actions, is not implemented then the first level response **of a** single strobe flash or short series of flashes should be considered **as an** active counter**measure**.
- At intersections **where** left turns are prohibited, there are no left turn arrows, just static signs to prevent **turns** across the tracks. The same methodology should apply at these intersections. **Instead** of turn arrows, however, the relevant control device is the "**No**Left Turn" sign. **Three** holes should be cut in a static sign and the strobe lights placed behind the holes to attract drivers' attention.
- Consider adding an **additional** visual **signal** that reprimands **all** drivers who make illegal left turns and LRV intersections, whether or not a train was approaching. The signal should call the drivers *attention* to the special hazards of making an illegal turn through this type of intersection.

## 5.4 CONVENTIONAL HARD TECHNOLOGY COUNTERMEASURES

### 5.4.1 Signal Modifications

From the drivers' perspective, the light rail grade crossing can easily appear to be a conventional intersection. Signal modifications can take two approaches. The first attempts to reduce the probability of signal misinterpretation by physically changing the signals. Second, signal operation in LRV intersections can be standardized and made as similar as possible to signal operation in non-LRV intersections. The former strategy, since it requires no changes to current signal timing and pre-emption procedures, is more straightforward. A typical intersection along the light rail line may have four sets of through traffic signals and two sets of left turn arrow signals. Furthermore, at most intersections, left turn movements are controlled by the through traffic signal and gaps in the oncoming traffic. Thus, a driver who fails to notice the turn mows will cue off of the through signals and pull out on to the trackway (since it is short of the oncoming traffic). The problem is compounded by three factors: there are more through signals than arrows, the surface area of the green ball is much greater than that of an arrow, and the transmittance of a green filter is much greater than a red filter. Thus, the through traffic signals have a greater probability of being perceived by a driver. To counter the perception problem and clarify the meaning of the through traffic signals, we propose a change from the green balls to green arrows.

Efforts should be made to reduce the chance that a turning driver will mistake the through traffic signals for controlling turning movements. Judicious use of programmable visibility heads, louvers and arrow filters on through traffic and cross traffic signals can improve left turn arrow compliance. If a turning driver cannot see the cross traffic signals, they can not cue off of them. If a vertical arrow is used for the through traffic signal, instead of a green ball, the signal clearly indicates the permitted movement. Furthermore, the illuminated surface area is comparable to the left turn arrow. Thus, reducing the chance that a turning driver will mistake the through traffic signals for the turning movement.

Operational modifications should revolve around minimizing the variation in signal operation. Examples include:

- Standardizing light rail grade crossings throughout the system, and if possible, between systems. Thus, drivers will only face a couple of unusual intersection configurations.
- Making light rail grade crossings function the same from the driver's perspective, whether or not an LRV is present. Transit priority that skips a normal signal phase can catch drivers by surprise. If possible, the normal sequence of signal phases should not be disrupted. Priority should be achieved by shortening phases and providing a "green wave" to the transit vehicles.

- Making the **light** rail grade crossings accommodate (undesirable) driving habits common at conventional intersections. E.g., the norm for left turns at conventional intersections is to allow movement on a stale yellow or even a fresh red signal.

While these changes are likely to yield a safety benefit, this must be balanced against increases in delay--whether to LRVs or RTVs--that they may cause. Assessing these impacts requires complex analysis ~~that is~~ beyond the scope of this report. Suffice it to say that signal timing and pre-emption strategies for street railways should include *safety* considerations as well as level-of-service ones.

## 5.4.2 Passive Devices

### 5.4.2.1 Signage

Advance warning signs have been used to at conventional grade crossings and to inform drivers of unusual road geometry from the early days of automobile travel. Over years, additional advance warning signs have come into use for unexpected features or situations that require particular care on the part of the driver, e.g., W3-3 Signal Ahead Sign or W10-2, 3, and 4 (parallel) Railroad Advance Warning Signs, see Figure 5.2.

Section 8B-3 of the Manual on Uniform Traffic Control Devices (FHWA, 1988) reads: "The W10-2, 3, and 4 may be installed on highways that are parallel to railroads. The purpose of these signs is to **warn** a motorist making a turn that a railroad crossing is ahead."

A number of studies have found that cognitive load is higher for turning maneuvers (e.g., Hancock, et al, 1990). Driver attention is divided at the intersection and cognitive processing power is limited. The additional demands of turning reduce driver vigilance for detecting warnings and hazards (Lourens, 1990; McCormick and Sanders, 1982). Furthermore, the work of Heckhausen and Gollwitzer (1987) suggest that people are more receptive to new information before they make a decision rather than after making a decision. Thus, it is desirable to present information to turning drivers as soon as possible. An advance warning sign would bring the safety information out of the busy intersection environment. It would provide a reminder while the driver is not burdened by the additional task of turning and before they reach the point of making the go/no-go decision.

The Manual on Uniform Traffic Control Devices (MUTCD) parallel advance warning signs may not be the best sign for the median light rail grade crossing. It is difficult to show that the tracks are in the **median**, as shown in Figure 5.2. Specifically, W10-2 (Figure 5.2A) suggests that the track is along the shoulder, not the median, while the variation depicted in Figure 5.2B could be mistaken for showing **two** roadways instead of median trackage.

Another problem with the MUTCD parallel advance warning signs was found by Womak, et al (1993). The researchers surveyed **1,745** Texas drivers with **46** multiple choice questions.

Each question presented a traffic control device in the context of normal applications. When asked the meaning of **W10-3** Parallel Advance Warning Sign: **69.3** percent of the drivers correctly chose, "If you turn onto the side road, you ~~will~~ cross a railroad track." However, **21.7** percent of respondents were confused about orientation and chose, "**You** will cross a railroad track, then **come** to an intersection ahead."

Schoppert and **Hoyt (1967)** advise that traffic engineers should **use** uniformity **as** a basic principle **of** signing. However, they should develop unique warning systems for unique situations. The principle of uniformity is upheld if these unique systems are reserved for unique situations. Furthermore, a grade crossing protection system should provide adequate advance warning for **every** crossing. To avoid the confusion about the median trackage and orientation, it **is** recommended that San **Jose** investigate an advance warning sign based on the passive warning sign currently in place at the arterial median intersections, **as** shown in Figure 5.3. **An** additional arrow could be added to clarify that through movements are allowed at the intersection, **as** shown Figure 5.3B.

It may be possible **to** improve the effectiveness of the advance warning sign by adding control instructions. Staplin and Fisk (**1991**) investigated the effects of providing advance information about left turn rule (e.g., left turn on green arrow, etc.) to drivers as they approached an intersection. The researchers used a driving simulator to investigate the response to different left turn controls with and without advance signs. In particular, subjects were to determine, as quickly as possible, if they could safely proceed into the intersection and make a left turn. Staplin and Fisk measured reaction time and whether or not the response was correct. The subjects responded to the signal about **0.2** seconds sooner when provided with an advance **sign** than without the advance sign. Furthermore, accuracy was substantially greater for the go than for the no-go decisions. This is in line with Sell's (**1977**) finding that instructions should be phrased in terms of the positive, or desired course of action, and McCormick and Sanders (**1982**), who find that most linguistic research indicates that active, affirmative statements generally **are** easier to understand than passive or negative statements. Finally, Whitaker and **Stacey (1981)** found that permissive stimuli ("DO") produced faster responses than did prohibitive ("DONOT").

It is recommended **that** the signal control strategy be presented with the parallel advance warning sign and phrased in active, positive terms--"left turn on green arrow only" rather than "do not turn on **red** arrow". In this manner, drivers can be warned **of** special conditions and instructed about the **correct** course of action. Forbes (**1972**) noted that, when multiple signs are on the same pole, subjects tended to detect the top signs first. Likewise, **Luoma (1986)** found that there was **a** greater probability of perceiving the top signs than the bottom signs. Since compliance with the left turn arrows will ensure safe operation, regardless if a driver is aware of the grade crossing, the control strategy should be placed above the grade crossing warning, see Figure 5.3C.



Many traffic engineers believe that drivers do not look at signs. 'One engineer suggested asking any driver "what's the last sign you saw?" Typically, the driver won't remember. But this is like asking a driver, "what's the color of the last traffic signal you saw?" Again, many drivers would not remember, but, the low frequency of accidents suggests that drivers do notice signals. The failure to recall such facts is because they are stored in short term memory and are quickly forgotten when they are no longer useful.

More formally, many studies have established that drivers, after being pulled over, can not recall the traffic signs they have just passed. But these studies merely measure conscious recollection, not sign perception.

One of the best examples of this kind of study is the work done by Johansson, et al on highways in Sweden, results from which appear in Table 5.2. Johansson and Backland (1970) concluded from these results that (as reported in McCormick and Sanders, 1982), "the road sign system to a high degree does not achieve its purpose." Except for the speed limit sign, all of the signs have the same triangular shape. The range of recall rates suggests that drivers must notice the signs and then dismiss any signs perceived as insignificant. The pattern of results is very interesting since it suggests that the percent of correct answers may be related to what can be labeled as the subjective importance of the sign or the risk involved in violating its message (as reported by Shinar, 1978).

Although there is evidence that drivers detect the signs, there is still the problem of perceived significance. A driver who has passed several hundred animal crossing signs (MUTCD W 11-3) on the highway without seeing wildlife on the road will have a lower probability of perceiving an animal crossing sign as important, while another driver who has recently struck a deer will place a higher level of importance to an animal crossing sign. Fisher (1992) notes three important issues in Johansson's work. First, the effects of forgetting during the delay between passing the sign and being asked to recall it. Second, the "emotional disturbance" (as noted by Johansson and Backland, 1970) caused by the sudden stopping of drivers at roadblocks. Third, Johansson's work measures recall, not perception or effectiveness.

Henderson (1987) clearly shows the rapid degradation of short term memory. One study cited by Henderson shows the probability of recall dropping off approximately exponentially as a function of time, from 90 percent with no delay to 5 percent with an 18 second delay. Luoma (1986) found a decreasing probability of sign recall over time. Subjects viewed a series of slides taken from a driver's perspective, each slide was displayed for one second with approximately five seconds between slides. One slide in each sequence contained a sign and two to four slides were shown after the slide with the sign. The subjects were then asked a number of questions about the sequence of slides, most of which dealt with other stimuli than the sign. After a 10 second delay, subjects had a 60 percent probability of recalling a sign and after a 30 second delay had a 17 percent probability of recalling a sign. It is important to note that the subjects were not in a driving environment and did not have to react to the information conveyed in the sign.

The "emotional disturbance" caused by being pulled over may be reflected as a bias in Johansson's results. A driver does not expect to be pulled over unless they have violated a law. Empirically, it is reasonable that drivers would place highest priority on a speed limit sign. Furthermore, the Police Control sign is reinforced by the presence of police. **So**, the survey method may have induced a bias into the measurements. Fisher (1992) avoided these biases by posing **as** a hitch-hiker on a rural highway in South Africa. Approximately 100m pasted a preselected sign, Fisher asked the driver, "**Do** you remember what was shown on the last road signs we passed?" **His** results are shown in Table 5.3. For both signs tested, **56** percent of the drivers could recall the sign.

Fisher's results suggest that recollection and action are not strongly correlated. In particular, **39** percent of Condition 1 and **43** percent of Condition 2 subjects who could not recall the target signs **did** make the appropriate control adjustments before **passing** the target sign. This finding is similar to that of Sell (1977), who found some subjects could remember seeing safety posters, but very few could describe them. At the same time, the behaviors proscribed in the posters increased by as much as **12** percent. Lourens notes, "there can be a surprising degree of dissociation between verbally expressed knowledge and the tacit knowledge which guides skilled behavior." Like the act **of** walking, or a professional musician in concert, many **of** the driving **tasks** are carried out subconsciously and **may** be difficult or impossible to explain verbally.

No sign will **be** noticed (or understood) by all drivers. Therefore, as much redundant information **as** possible should be provided, without overloading cognitive capacities. It might not be **advisable** to add signing to the grade crossing environment because of all of the existing distractions; however, an advance warning would provide information to the driver in a new environment. Furthermore, repeated exposure to advance warning signs that proscribe the correct course of action would function as a propaganda campaign to regular drivers in the area.

#### 5.4.2.2 Knock Down Delineator

Informal interviews with LRV operators in San Jose and field observations have shown that left **turning** drivers frequently begin their **turning** maneuvers before traversing the crosswalk--moving diagonally across the left-hand lane **or** even remaining in that lane in the case of U-turn--**as shown in** Figure 5.4. **As** a result, it can be **as little as** one second from the time a driver takes **their** foot **off** of the brake and when they enter the LRV dynamic envelope, well less than the five seconds required for a LRV traveling at **56 km/hr (35 mph)** to stop using the emergency brakes.

If drivers were physically prevented from initiating a **left** turning maneuver before traversing the crosswalk, **it** would provide **an** additional two to three seconds of warning before they entered the LRV dynamic envelope (**assuming** an acceleration between half and one m/s/s (2 to 3 mph/s). **If the** additional warning time were used for **LRV** braking, it could allow the

operator to reduce the LRV speed by as much as **9.4 m/s (21 mph)**, see Table **5.4**. Because drivers will have to proceed further into the intersection before beginning a turning maneuver, the delineators will effectively reduce the length of the hazard zone for potential LRV-automobile collisions.

The Los Angeles Metropolitan Transportation Authority advocates that, "The crosswalk edge that separates the vehicle lanes from the crosswalks should have **curbing** installed, between track areas, along the entire length of the track crossings where vehicles are not allowed." (Meadow, 1994a & b). Space constraints along the San **Jose** light rail line preclude the installation of curbing.

Knock down delineators, on the other hand, can provide a safe and effective means of restricting automobile movements in the crosswalk. A typical delineator consists of a replaceable, **8 cm (3 in)** wide, **1.3 meter (4 ft)** tall plastic post and a permanent base. The base can either be epoxied to the surface of the pavement or embedded in the pavement. Reflective tape or reflective decals are usually applied to the top of the post. Caltrans, among other state DOT's, have come to use the knock down delineator as a standard tool for highway traffic control.

A Caltrans traffic engineer reported that, as long as the installation is done properly, delineators can achieve near perfect compliance. He also estimated the **total** installation costs to be between **\$35** and **\$45** per device, depending on the quantity. The delineators are available from several manufacturers. One distributor claimed that their pavement anchored delineators could sustain **20** to **30** hits at **high** speeds before failure. Swanson and Woodham (1988) evaluated the cost and performance of **six** different flexible delineators. They found a wide range performance and cost. Their results are summarized in Table **5.5**. Although Swanson and Woodham focused on **soil** anchored delineators, it is projected that the performance and costs ranges are similar for pavement anchored delineators.

The primary delineator placement is on the far side of the crosswalk, in line with the curbing between the left turn lane and the trackway, as shown in Figure **5.5**. This creates a visual barrier to encourage turning drivers to **start** their **turns** after traversing the crosswalk. To reinforce desired behavior, it is recommended that a decal displaying arrows or reading "**KEEP RIGHT**" be used. Using a Type **3** Object Marker (**OM-3L**) (MUTCD designation for a sign with diagonal black and yellow stripes) may be undesirable, as many drivers are unfamiliar with the meaning of this sign. In a multiple choice survey, Womak, et al (1993) found that **only** **61.9%** of the drivers chose the "correct" response for **OM-3R**: "There is something at the **edge** of the roadway you should avoid hitting." The study did not address the directional nature of the sign.

The dynamic envelope of the LRVs extends **97 cm (38 inches)** beyond the rail head. So there should be sufficient room for the delineator posts between the trackway and the **turn** lane. It

is unlikely that a driver would be able to make a left **turn** before the delineator without hitting the **curb** or the delineator. Assuming a 2.4 meter (8 ft) wide vehicle, it would have to be at an angle greater than 42 degrees to fit between the delineator and the curb.

The primary delineator placement can be supplemented with striping extending the visual line of the **curb** to the delineator post. It is recommended that a secondary delineator be placed on the near side of the crosswalk, at the end of the **curb** to visually reinforce the limited clearance in the crosswalk.

The knock down delineators **can** serve **as** passive control devices, providing an additional two to three seconds warning to LRV operators. Or, they can be an integrated component of a reactive countermeasure by increasing the time-to-collision for **turning** drivers and creating a warning zone that drivers have to traverse before fouling the LRT right **of** way.

## **5.5 SOFT COUNTERMEASURES**

There is a need to educate the driving public about their duties and responsibilities at light rail grade crossings. **An** education program is critical for startup systems where drivers are unfamiliar with street railways. Because a **small** error can result in a catastrophic accident, there is a need to reinforce compliance. This can take the form of positive reinforcement, e.g., a busboard reading, "The light rail agency would like to thank you for helping us make this our safest year"; or, punishment, e.g., police enforcement. Because enforcement can be easily directed at the actors involved, it is much more feasible to implement, however, the transit agency should not overlook inexpensive means of education and positive reinforcement.

### **5.5.1 Enforcement**

Mer a year of revenue operations, the Los Angeles Metropolitan Transportation Authority (**LAMTA**) initiated a 90 day demonstration project with 10 sheriffs deputies assigned to enforce grade crossing safety along the Metro Blue Line (Meadow, 1994a & b). During the demonstration period, the sheriff's department issued an average of 260 citations per deputy per month. The deputies surveyed the first 1500 violators and established that 45 percent **of** the violators along the arterial median section frequently **used** the intersections with light rail grade crossings. Of greater interest were the reasons given for the violations:

"Thought it was safe"--40 percent

"In a hurry"--25 percent

"Didn't **see** signal"--28 percent

Because of the initial success of the program, additional funding was allocated to keep six deputies on the light rail-traffic detail. During the following nine months, the sheriffs department issued an average of **60** citations per deputy per month. The decreased citation

rate suggests that a strong initial campaign with continued enforcement at lower levels can be effective for reducing light rail grade crossing violations.

In addition to the conventional police enforcement, LAMTA **has** conducted an ongoing demonstration project to **evaluate** photo enforcement. **High** resolution cameras, housed in bullet proof boxes, capture still photos of grade crossing violators in the act. A citation is mailed to the vehicle owner within **72** hours of the offense. Through the photo enforcement program, LAMTA claims to have achieved **as much as** an **84** percent reduction in grade **crossing** violations.

Photo enforcement **has** a number of drawbacks, including the large time lag between offense and punishment, thus, **making** it difficult for the driver to recognize **cause** and **effect** relationships. Second, non-offenders cannot **learn** from others' mistakes, **as** they do not witness violator apprehension. To counter these deficiencies, **LAMTA** uses advance warning signs to inform drivers of the surveillance. At a gated grade crossing, the warning signs, in conjunction with the issuance of a warning, reduced the number of grade crossing violations from 0.5 per hour to **0.28** per hour over a six month period. After the devices were operating for **six** months, the **sheriff's** department started issuing citations. The violation rate declined to **0.16** violations per hour at the end **of** three months. The signs have also proven to be effective in reducing the number **of** illegal left turns at an arterial median grade crossing, protected by conventional traffic signals and left turn arrows. After the installation of warning signs and issuance of warnings, the red left turn arrow violation rate has dropped twenty five percent in **two** months (from **2.0** violations per hour to **1.5** violations per hour) (Meadow, **1994a & b**). Extended performance at the signalized intersections is unavailable at the time of writing.

Long Island Railroad (LIRR) **has also** achieved positive results with police enforcement. The number of crossing gates run-through by drivers has declined from **361** in **1990** to **217** in **1994**, a reduction of **40** percent (Vantuono, **1995**). LIRR's strategy includes stationing marked patrol cars at three or four crossings each day during the peak hours. The high visibility enforcement is supplemented with unmarked police cars. Pedestrians and motorists alike can be fined **\$150-\$250** for a first time offense.

Enforcement should be consistent, whether or not a **train** is present. Drivers will usually encounter the light rail grade crossings when no LRVs are around. Compliance to **turn** arrows must be maintained at these intersections under all situations, **as** drivers are often unaware of a train overtaking them from behind. In other words, poor driving habits learned when no **LRVs** are present are likely **to** persist in front of **an** approaching LRV.

The education benefits can be **as simple as** witnessing another driver pulled over by the side of the road. The perceived financial risk of a fine becomes a proxy for the inappropriately low perception of a safety risk. Sanders (**1975**) found that at conventional grade crossings, driver

awareness of law enforcement appeared to yield more careful behavior overall and tended to increase awareness in general.

## 5.5.2 Prevention and Education

Unlike punishment, which is primarily directed at the offender, prevention and education is directed towards all possible offenders or some subset thereof. Some drivers and pedestrians have learned illegal practices that are safe under many conditions, but, may be very risky at a light rail grade crossing. There is a need to educate those individuals who do not know their actions are illegal. It is also important to address those motorists and pedestrians who knowingly violate the law. Their experiences at conventional intersections or when LRVs are not present at light rail grade crossings may foster an inappropriately low perception of risk, i.e., a false sense of security.

As already suggested, the enforcement strategies described above also have a preventive function. The education benefits of police enforcement can be increased with posted signs warning of the fines or enforcement. Violation warnings have been used to enforce speed limits, HOV restrictions, conventional grade crossings and light rail grade crossings. Although little has been published on the effectiveness of these signs, informal talks with Caltrans traffic engineers suggest that these devices can be effective. Preliminary results of their study indicate that the "Minimum Fine for HOV Violation \$271" signs have had a positive impact on compliance. Based on the preliminary results of the Caltrans study, it is recommended that San Jose consider installing left turn violation warning signs at one or two demonstration intersections.

On the other hand, Shinar (1978) asserts that, "Less threatening interventions such as notification of violations and mild warnings are more effective in improving driver record than more threatening approaches. This differential effect is also commonly obtained in attitude change in other areas of behavior." This suggests that a stern warning for first time offenders may be more beneficial than a harsh penalty. The driver may simply fail to realize the severity of their actions. Shinar continues, "The effects of the program are more likely to be reflected in a reduction in the violation rate than the accident rate." Finally, he notes that short behavior modification campaigns tend to have little or no effect in the long run, as they attempt to modify well-established habits. Thus, a continued, but possibly reduced, effort is necessary to maintain short term gains.

With respect to grade crossing protection, Knoblauch, et al (1982) asserted that education and engineering should come before enforcement. Educating the target audiences can yield greater benefits; furthermore, effective grade crossing enforcement may not be feasible with police priorities. Shinar (1978) notes that it is difficult to modify established behaviors, everybody thinks they are an expert driver. As a result, he suggests the greatest long term effects can be gained from driver education, before unsafe practices are internalized. LAMTA

has acknowledged the benefits of driver education and **has** lobbied California legislators and the Department of Motor Vehicles (DMV) to emphasize grade crossing safety in DMV Driver Handbooks (Meadow, 1994a & b). Further benefits can be gained by producing educational material for driving schools and promoting light rail issues in their curriculums.

Koenig **and Wu** (1994) discuss the long term effects of a multimedia campaign to reduce left **turn/pedestrian** accidents. It included radio, television newspaper and magazine ads, busboards, pamphlets, press releases and other promotions targeted both at pedestrians and drivers. **The** initial campaign ran for a month and a **half** during 1990 and **a** second, month long, **campaign** limited to television **was** repeated three months later.

To estimate the market penetration, Koenig and Wu **used** random number dialing *after* both campaigns. To establish a base line measurement, the researchers also conducted a penetration survey before the first campaign. Prior to the initial **campaign**, a base line of 10 percent **said** they had recently noticed a traffic safety campaign. The **affirmative** responses rose to **24** percent after the first campaign and 18 percent after the second campaign. The lower number **of** affirmative responses after the second campaign is attributed to the fact that the campaign was limited to television. Affirmative responses to a non-existent safety campaign **did** not change significantly between the three surveys.

The researchers conducted a conflict analysis at five intersections during five time periods: prior to **the** first campaign, immediately after the first campaign, immediately before the second campaign, immediately after the second campaign, and one year after the first **measurements** were taken. After controlling for external factors, the researchers found that the two media campaigns did not have a significant immediate impact; however, the long term impact was determined to be significant. After 12 months, the probability **of** a turning driver yielding to pedestrians increased by **36** percent, when controlling for other variables. Because the campaign specifically addressed left turn movements, the researchers compared yielding behavior **between** left and right turning drivers. They found that drivers were **23** percent more likely than average to yield to pedestrians than right turning drivers.

Sell (1977) **is** a thorough overview of **safety** propaganda and provides several examples **from** traffic, **industrial** and residential settings. The **aim of safety** propaganda is to:

- **give** more knowledge **of** safety factors
- change peoples' attitudes **so** that they are more inclined to act safely
- **most** importantly, to ensure that safe behavior takes place

To be effective, **safety** propaganda must be **seen**, understood, and acted upon. To this end, it should be targeted at specific behaviors. General **safety** campaigns which have a message like, "safety matters" or "drive safely" if the drivers hold the common opinion that they are already safe drivers. The propaganda must show that something can be done, not that accidents are

inevitable. Similarly, driver information systems should tell drivers the safe course of action, not just tell them that a train is approaching.

Sell points out that **all** too often, safety campaigns are evaluated on attitude surveys or tests of knowledge. These measures may or may not be related to behavior, much in the same manner that stated preference differs from observed preference.

In one study, Sell examined the response to *safety* posters in an industrial setting. Specifically, the posters urged workers to hook slings back on gantry cranes instead of letting them dangle loose. The percentage of "hooked" slings were observed during the **13** weeks following the installation of the posters. The greatest increase was **13** percent, from **42** percent before the campaign to **55** percent after. Interviews with the slingers revealed that although some could remember that the posters had been displayed, very few **could** accurately describe them, even though they were still up. Conscious recollection is not required for a behavioral change.

Sell cites a number of studies where noticeable behavior changes occurred some time after exposure to the safety campaign. In particular, one fire safety campaign that involved a massive leaflet mailing had its greatest effect **18** months later. This supports the long term findings by Koenig and **Wu**.

Sell concludes that safety posters and other propaganda can be made to produce the desired behavior modification. To be effective, they should:

1. Be specific to a particular task and situation.
2. Give positive instruction ("**Do...**").
3. Be placed close to where the desired action is to take place.
4. Build on existing attitudes and knowledge.
5. Emphasize non-safety aspects.

They should **not**:

1. Involve horror, **as** horror appears to bring out defense mechanisms in the target audience.
2. Be negative ("Do not..."), **because** this *can* show the wrong way of acting when what is required is the **correct** way.
3. Be general, because almost all people think they act safely. **This** type of propaganda **is** thus seen **as** only relevant to other people.

These guidelines are in accordance with McCormick and Sanders (1982), who note that most linguistic research indicates that active, affirmative statements generally are easier to understand than passive or negative statements.



One example where propaganda **can** be used at the intersection is in signing. The accident reports suggest that some **left turning** drivers cue off of the cross traffic signals (i.e., the signals for **traffic** perpendicular to the light rail line), anticipating a leading left turn phase. It is impossible to completely mask the cross traffic signals **from** the **turning** drivers. Programmed visibility heads may be able to achieve some **success** in **this** area, but, the **high** cost **of** installation and reduced visibility on the cross street does not warrant **this** investment. On the other hand, using the principles described by Sell (1977), a simple sign reading "watch for trains" underneath the cross traffic signals should yield some improvement. The sign proscribes the **correct** action to take. Further, it serves to remind the drivers that the light rail grade crossing is a special intersection, and they should snap out of automatic pilot and into a **conscious** level of processing.

The two transit agencies cited for their enforcement programs **also** maintain educational programs. **LIRR** offers **free** educational programs for schools and community groups, distributes grade crossing **safety** literature at stations, sponsors public service announcements on radio and television, and participates in Operation Lifesaver (Vantuono, 1995). **LAMTA** has an impressive education program that includes participation in Operation Lifesaver and Trooper on the Train safety programs, school and community outreach presentations, a rail safety place mat game at local fast food restaurants, enlisting scout troops to distribute safety literature at grade crossings, **safety** posters in local businesses, **safety** reminders in local church bulletins, and regular meetings with local businesses (Meadow, 1994a & b).

Startup street railways can face a large safety learning curve with the local community. Education campaigns are particularly important for such operators. Even if **full** blown media campaign does not **prove** to be cost effective for an established transit agency, **LAMTA** has demonstrated that there are a number of **low** cost avenues for **safety** education that should not be overlooked. The transit agency can single out specific audiences in need of special attention, such **as** visitors to the city. Literature and posters at rental agencies and billboards along major entrances to the metropolitan area could be beneficial in reducing the number **of** out **of** town drivers involved in light rail accidents.

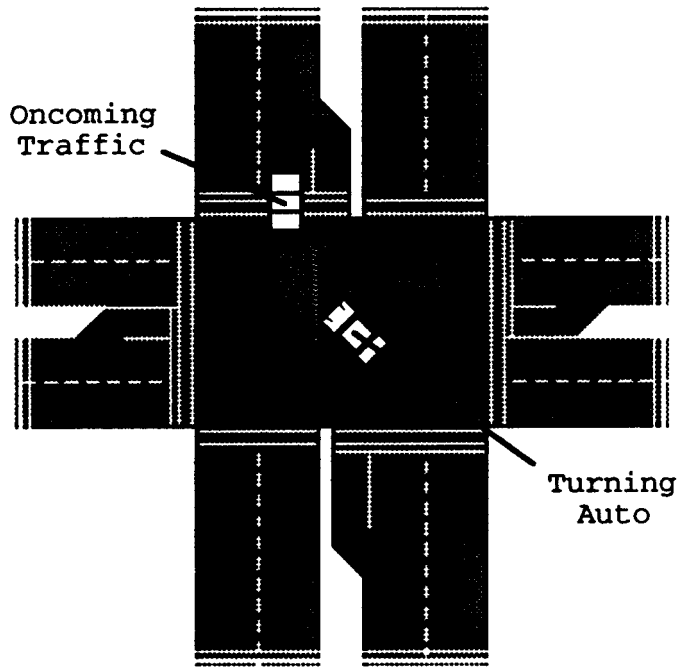
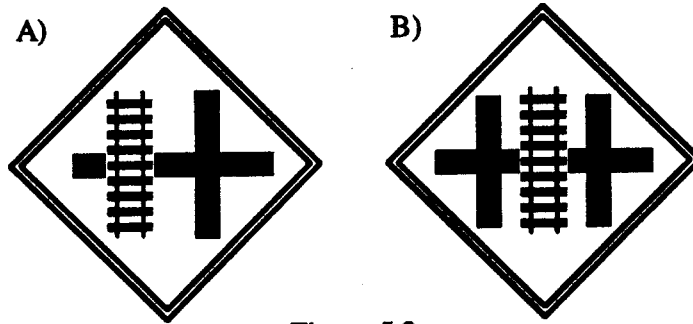
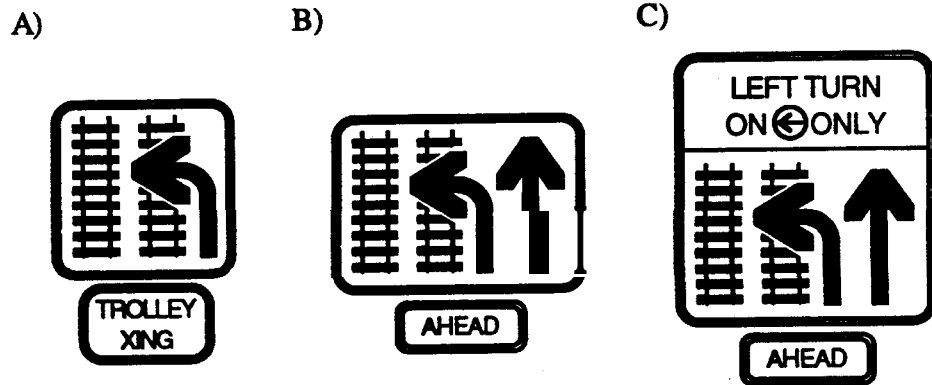


Figure 5.1  
Left Turn Movement at Conventional Intersection



**Figure 5.2**  
**Advance Warning Signs (A) W10-2 Parallel Railroad Advance Warning Sign (B) Modified W10-2 Suggesting Median Trackage. Note ambiguity suggesting two distinct roadways.**



**Figure 5.3**  
**Recommended Warning Sign Modifications (A) Existing Static Crossing Warning Sign. (B) Proposed Parallel Advance Warning Sign. (C) Proposed Parallel Advance Warning Sign Proscribing Signal Control at Grade Crossing.**

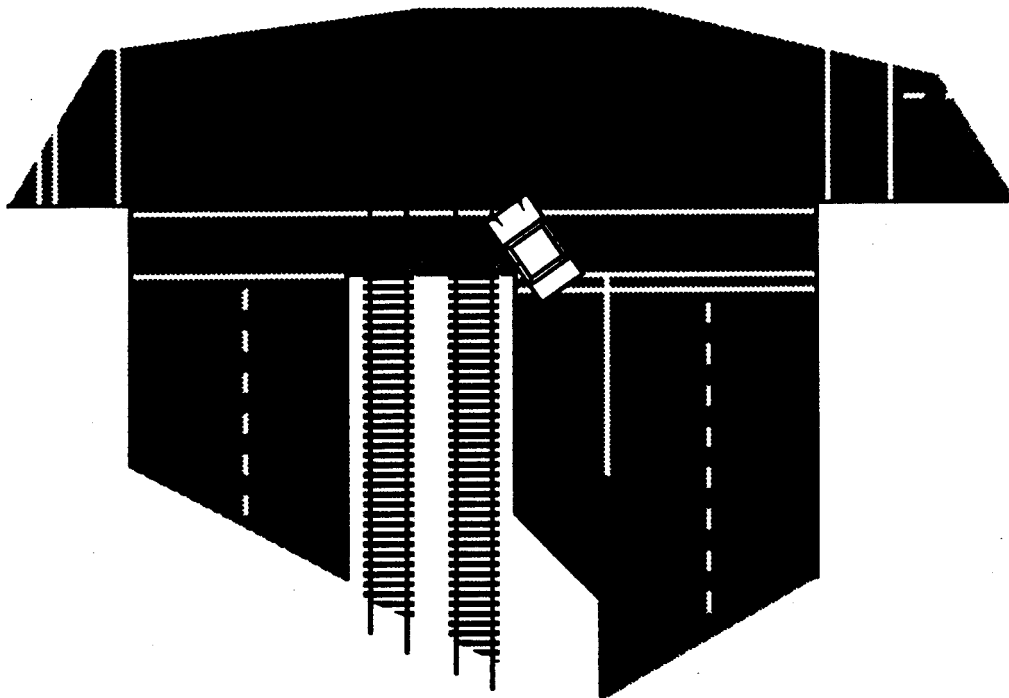
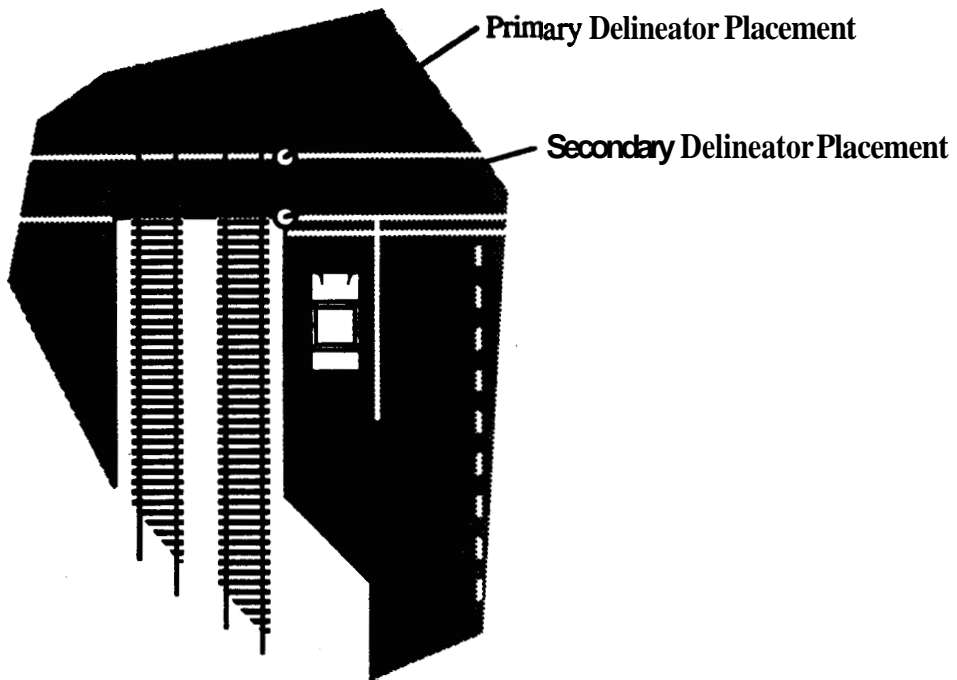


Figure 5.4  
Diagonal Turning Movement



**Figure 5.5**  
**Delineator Placement**

**Table 5.1**  
**Rear End Collision Statistics During the Cyberlite Demonstration Project \***

	Rear End Collisions		Drivers Injured		Cab Damage (1972 \$)	
	Cyberlite	Control	Cyberlite	Control	Cyberlite	Control
Average per million km	2.18	5.54	0.40	1.04	247	647
Average per million miles	3.51	8.91	0.65	1.67	398	1041

\* as reported in Voevodsky, 1974

**Table 5.2**  
**Percent of Drivers Correctly Recalling the Last Sign They Passed When Pulled Over**  
**Approximately 1km Past the Given Sign.**

	50 km/h Speed Limit	Police Control	Break in Road	Other Danger	Pedestrian x-ing	Wild Animals
1966 data *	78	63	55	18	17	n/a
1970 data †	76	66	29	26	62	55

\* From Johansson & Rumar, as reported in Shinar (1978), Lourens (1990) and Henderson (1987)

† From Johansson & Backlund, as reported in McCormick and Sanders (1982) and Henderson (1987)



**Table 5.4**  
**LRV Speed Reductions for Given Braking Times**  
**Using Normal and Emergency Brakes.**

	braking time	
	2 s	3 s
<b>Normal Braking</b> (3.5 mph/s)	7 mph	10.5 mph
<b>Emergency Braking</b> (7 mph/s)	14 mph	21 mph

**Table 5.3**  
**Condition 1: Driver Control and Recall for Pedestrian**  
**and 80 km/h Signs**

Recall	Speed		Total
	Maintained	Reduced	
Correct	20	16	36
Incorrect	17	11	28
Total	37	27	64

**Condition 2: Driver Control and Recall for Minor**  
**Right-Hand Junction Sign**

Recall	Speed		Total
	Maintained	Reduced	
Correct	13	5	18
Incorrect	8	6	14
Total	21	11	32

**Table 5.5**  
**Lifecycle Costs and Performance for Six Delineators as Reported by**  
**Swanson and Woodham**

<b>Product</b>	<b>Manufacturer</b>	<b># hits to failure</b>	<b>cost/ hit **</b>
<b>Flexopost</b>	<b>Proven Products, Portland OR</b>	<b>10</b>	<b>\$0.93</b>
<b>CRM-375</b>	<b>Carsonite, Carson City, NV</b>	<b>15</b>	<b>\$1.00</b>
<b>Curve Flex</b>	<b>Carsonite, Carson City, NV</b>	<b>15</b>	<b>\$1.00</b>
<b>Safe-Hit</b>	<b>Unistrut Western, Denver, CO</b>	<b>10</b>	<b>\$1.63</b>
<b>J.B. Flexible</b>	<b>BCA Equipment Co., Bronx, NY</b>	<b>40</b>	<b>\$0.42</b>
<b>Flex Hinge</b>	<b>Amerace Corp., Niles, IL</b>	<b>10</b>	<b>\$2.24</b>

\*\* includes post, labor and mobilization costs in 1988 dollars.

## 6. ECONOMIC ASSESSMENT

### 6.1 INTRODUCTION

This chapter brings together the results of the previous ones to estimate the economic value of alternative strategies for reducing the costs of light rail collision accidents on the San Jose light rail system. This economic assessment is subject to a range of uncertainties including:

- The **cost** of collision accidents (and hence the benefit of reducing them);
- The **effectiveness** of the strategies;
- The **cost** of the strategies;
- Values of relevant investment parameters such as interest rate and project lifetime.

In light of these uncertainties, it makes little sense to attach a single economic value to any given alternative. Rather, we adopt a probabilistic approach in which the above uncertainties are explicitly accounted for, yielding a range of economic values.

We employ net present value and benefit-cost ratio as the primary economic valuation measures. The net present value is defined as the present value of all benefits minus the present value of all costs associated with a given project, while the benefit-cost ratio is the ratio of these quantities. In either case, discount rates are used to convert costs and benefits that occur in the future to their equivalents in present time. There are other valuation measures, such as internal rate of return and payback period. The interested reader will be clearly see how the methods presented in this chapter can be employed to evaluate these measures.

We assess these valuation measures from the standpoint of both the transit agency and society at large. In the first case, we are concerned with whether the Santa Clara County Transit Agency, acting in its own narrow self-interest and employing its own funds, is likely to earn a sufficient return on an investment in improved safety at light rail intersections. In the second case, we are determining whether there is adequate societal benefit to justify a specific public appropriation for such an investment. That these are very different questions was shown in Chapter 2, where it was pointed out that since TA is very rarely at fault in a legal sense for crashes involving its light rail vehicles, it pays only a small fraction of the crash costs.

The remainder of this chapter is organized as follows. In Section 6.2 we specify the project to be assessed. In section 6.3 we develop equations for the present value of the benefits and costs from this project. These equations involve a set of variables whose values are uncertain. In section 6.4 we capture this uncertainty by defining triangular probability density functions (PDFs) for each uncertain variable. These PDFs are then used to perform a Monte Carlo simulation of net present values of the benefits, costs, and resulting economic valuation

measures, the procedures and results of which are considered in section 6.5. Finally Section 6.6 offers conclusions of this chapter.

## 6.2 PROJECT TO BE ASSESSED

As noted in Chapter 5, there are a large range of promising countermeasures that may reduce light rail collisions. A full economic analysis would consider a large number of countermeasure strategies, ranging from the least to the most capital intensive. As we move across the continuum, we expect that we increasing expenditures will yield higher levels of effectiveness. Theoretically, the “optimal” alternative will be the one offering the greatest difference between the benefits of reduced accidents and the costs of implementation. If safety investments are subject to decreasing returns, the optimal will also be highest investment such that the additional benefit of that investment is higher than the additional cost, when compared to the next lowest investment level.

We do not attempt such a full-blown analysis here, for the simple reason that it would require us to assume a relationship between cost and effectiveness for which we have essentially no information. Rather, we assess a single alternative, the main features of which are:

- Sensors at each at-grade intersection that measure position, velocity, and acceleration according to the specifications described in Chapter 4;
- A graded response as suggested in Chapter 5. The alarms would include strobe lights when the possibility of an incursion into the light rail right-of-way is first detected, and a wayside horn that is triggered when the probability of such an incursion becomes sufficiently high.

This is a “high end” alternative with respect to the level of technical sophistication and cost. We choose it for two main reasons. First, advanced technology countermeasures are the primary (though not the exclusive) focus of this study. Second, it is possible to extract “ball park” estimates of all necessary variables from published literature and industry sources.

Third, analysis of this alternative helps us to bracket the range of alternatives that should be subjected to further study in a second phase of this research. If it were determined here that an advanced technology countermeasure is not promising, then subsequent work should de-emphasize it in favor of more conventional countermeasures described in the Chapter 5. Conversely, if the outcome of this analysis is more favorable, then such a countermeasure would be included as part of the spectrum of options that would be subject to more rigorous analysis in future research.

An essential feature of this alternative is that it include installations at all 51 at-grade intersections, regardless of accident incidence or whether left turns are permitted. Since accident incidence by intersection varies widely, one might consider focusing countermeasures

on a smaller number of high accident countermeasures, such as the 12 which have had 5 or more accidents over the 1988-1993 period (see Figure 2.6). However, there are both legal and human factors reasons for maintaining a high level of uniformity in the treatment of the at-grade intersections. While the details of the installation may vary according to whether left turns are permitted, or whether the intersection is in the arterial median or transit mall portions of the system, it seems appropriate—at least in this “first” cut analysis—to have the same levels of investment and technology in all cases.

### 6.3 COST AND BENEFIT FORMULAS

To assess the above alternative, we employ simple models of its benefits and costs. The models involve variables whose values are uncertain. For purposes of this section, however, overlook this problem by presenting equations that could be evaluated if the relevant values were known.

#### 6.3.1 Costs

We assume a certain initial cost of installation at each intersection, composed of two elements: the cost of the sensor and controller system, and the cost of the alarms that this system would activate. Thus the initial cost will be:

$$IC = NI \cdot (C_{SC} + C_{AL})$$

where:

$IC$  is the initial cost;

$NI$  is the number of intersections;

$C_{SC}$  is the sensor/controller cost;

$C_{AL}$  is the alarm cost.

The other cost of the system is an annual maintenance and upkeep cost, which is also assumed to be the same for each intersection. Thus the annual cost is:

$$AC = NI \cdot C_{MU}$$

where:

$AC$  is the annual cost;

$C_{MU}$  is the annual cost of maintenance and upkeep per installation.

To determine the present value of these costs, we must discount future maintenance and upkeep costs to their present-day equivalents. For simplicity, we employ continuous

discounting so that the present ( $t=0$ ) value,  $PV$ , of a cost (or benefit),  $X$ , realized at time  $t$  (measured in years) is:

$$PV(X, t) = e^{-It} \cdot X$$

where:

$I$  is the annual discount rate, expressed as a fraction.

Thus the present value of the total cost of the alternative is:

$$PVC = IC + AC \cdot \int_0^L e^{-It} dt = IC + AC \cdot (1 - e^{-IL})/I$$

where:  $0$

$L$  is the project lifetime.

### 6.3.2 Benefits

The benefits of the project derive from the reduced incidence and/or severity of collisions between LRVs and RTVs. Given the uncertainty about project impacts on both incidence and severity, there is little to be gained from distinguishing these impacts explicitly. Rather, we assume that the project will reduce the total cost of the collisions by some fraction. Thus, the annual benefits of the project are calculated as:

$$AB = CRI \cdot ACR \cdot CPC$$

where

$AB$  is the annual benefit;

$CRI$  is the fraction of total crash costs eliminated as a result of the project;

$ACR$  is the annual number of crashes;

$CPC$  is the average cost per crash.

Note that references to "crashes" in the above definitions mean those crashes that the project is intended to address. In the present context, this means crashes involving left and right turns.

Again, we must convert this annual figure to its equivalent present value. This we the present value of benefits from the project,  $PVB$ , is given by:

$$PVB = AB \cdot (1 - e^{-IL})/I$$

### 6.3.3 Economic Assessment Measures

Given the present values for project benefits and costs, the net present value and benefit-cost ratio are calculated as the difference and ratio of the quantities, respectively:

$$NPV = PVB - PVC$$

$$BCR = PVB / PVC$$

The threshold for project acceptability is when  $PVB=PVC$ , of equivalently when  $NPV=0$  and  $BCR=1$ . For projects that meet this requirement,  $NPV$  and  $BCR$  capture somewhat different things. The former measures the magnitude of a projects net benefits, while the latter captures the intensity of such benefits. Absent budget constraints, the  $NPV$  is the more relevant measures. When such constraints are binding, so that decision makers are concerned with getting “the most bang for the buck”, the  $BCR$  is more salient.

## 6.4 VARIABLE VALUES

With one exception ( $NI$ , the number of at-grade intersections), values for the variables that determine  $PVB$  and  $PVC$  are uncertain. In the case of some variables, for example the costs of installing the system, the uncertainty is of purely a technical nature, while for others, such as the interest rate or the accident cost, the uncertainty also has moral, ethical, and public policy dimensions. Whatever the source, the uncertainty over the value of any given variable can be captured by defining a probability distribution for that variable. For purposes of this analysis, we assume that these distributions are all triangular, as illustrated in Figure 6.1. As Figure 6.1 illustrates, a triangular distribution is fully defined by three parameters--a maximum value, a minimum value, and a most likely value, or mode. As the difference between the maximum and minimum values increased, so does the uncertainty.

Table 6.1 provides the maximum, minimum, and most likely values for each of the variables required to calculate  $PVB$  and  $PVC$ . A discussion of the values follows:

### 6.4.1 Discount Rate

The discount rate should reflect the opportunity cost of investing funds in a given project and in addition capture the level of risk associated with the project. At the present time, rates of return for the safest investments--U.S. Treasury securities--are around 5 percent, and we therefore use this value as the minimum. The most likely value of 10 percent roughly coincides with the rate of return on mid-grade corporate bonds, while the maximum of 15 percent reflects the long term performance of investments in the stock market.



#### **6.4.2 Installation Cost—Sensor and Control System**

Phone conversations with industry sources (identified and contracted using new product announcements in *ITS World*) suggest that a video-based sensor system and controller could be installed at a cost of about **\$10,000** per intersection. We set the minimum and maximum at half and twice this figure, respectively.

#### **6.4.3 Installation Cost—Alarm System**

The alarm system will consist of a strobe light system and audible alarm. **As** noted in Section **5.3.2.1.1**, previous experience with strobe lights at roadway intersections suggests an installation cost, in early **1980** dollars, of **\$400** to **\$1000** per intersection approach accounting for inflation and assuming two approaches per intersection, the strobe system cost per intersection would be in the **\$1000-\$2500** range. The cost for the audible alarm is more speculative. Assuming that it **is** of the same magnitude as the strobe lights, the total alarm installation cost per intersection will range from **\$2000-\$5000**. We use the midpoint of this range--**\$3500**--as the most likely value.

#### **6.4.4 Annual Cost**

Industry sources suggest that the annual maintenance and upkeep cost for the sensor-control system will be about **\$200** per intersection. Again referring to Section **5.3.2.1.1**, the annual maintenance cost for the strobe system is reported to be between **\$50** and **\$200** per intersection approach in early **1980** dollars. At **two** approaches per intersection, and again assuming that the audible alarm would generate annual costs of a comparable magnitude, we estimate an total annual alarm cost of **\$250** to **\$500** in current dollars. Adding the sensor-controller system costs, we assume of total annual cost of between \$400 and \$800, with a most likely value of \$600.

#### **6.4.5 Crash Cost Impact**

The estimates for this variable are based on previous studies of the effects of a change in a warning system **used** in a roadway environment. It **must** be noted, however, that the system being assessed here **differs** in important ways from those that were considered in these studies. We incorporate the uncertainty arising **from** these differences by giving the impact variable a wide range and, to be conservative, assuming that the impact will be probably be less than that of the previous systems.

The most carefully studied pulsed-light warning system, discussed in Section **5.3.2.1.1** was the Cyberlite, a supplemental brake light that pulsed at a rate, duty cycle, and intensity that varied exponentially with deceleration. When Cyberlites were installed on **343** San Francisco

taxis in 1973, it was found that the number rear end collisions, as well as the number of drivers injured and cab damage resulting from them, decreased by about 60 percent.

A clue about the effectiveness of an audible alarm can be found from the impact of banning nighttime train whistles on the Florida East Coast Railway in 1984, reported in Section 5.3.2.1.2 The nighttime accident rate at gated crossings affected by the ban was found to triple over the first five years after it was imposed. Put another way, the whistles seem to have reduced accident rates by about 67 percent.

On the basis of these findings, we can calculate a naive upper bound estimate of the impact by assuming the strobe would be as effective as the cyberlites, the audible alarm as effective as the train whistle, and that the effects of these alarms are independent. In that case, the fractional accident reduction from a system combining both alarms would be  $(1 - (1 - 0.67) * (1 - 0.60)) = 0.87$  -- in other words the system would prevent nearly 9 out of every 10 crashes. There are many reasons to believe that this is an optimistic figure, however. These include:

- The short time drivers have to respond in order to avoid a crash;
- The fact that the driver population being targeted has already failed to detect or respond to conventional signs, signals, and alarms.

Based on these considerations, we estimate the maximum impact of the system at 0.75. On the other hand, we expect that the will have an impact of at least a third of this upper limit, or 0.25. We set the most likely value of the impact at the midpoint of this range: 0.50.

#### 6.4.6 Crashes per Year

The system is designed to reduce crashes involving RTVs making left (or occasionally right) turns into the path of LRVs traveling in the same direction. Table 2.1 shows the incidence of such accidents in the San Jose system over the first six years of operation. If we assume the accident history represents random fluctuations about an unchanging average annual rate, the estimate for that average is 19 and the 95 percent confidence interval is approximately 15-23. There is also some evidence, by no means conclusive, that the accident rate is trending downward. We therefore reduce the minimum value for crashes per year by two, obtaining minimum, most likely, and maximum values for turning crashes per year of 13, 19, and 23 respectively.

#### 6.4.7 Cost per Crash

Table 3.5 summarizes cost per crash for left-turn accidents. The average total societal cost per crash is \$21.6 thousand, while the transit agency cost is \$4.6 thousand. The societal cost estimate includes assumptions about such imponderables as the cost of pain and suffering. In addition, there is statistical uncertainty about the proportion of left-turn accidents that result in

injuries or fatalities, the average social cost of which is about **20** times greater than those resulting in property damage only. We thus use a wide range for the social cost per crash: with a minimum of \$10 thousand, a maximum of **\$30** thousand, and a most likely value of **\$20** thousand.

Agency **costs** per crash are also reported in Table 3.5. The average for left-turn accidents is **\$4.6** thousand. Reflecting greater confidence in our ability to **assess** these **costs**, we **use** **\$3** thousand, **\$4.5** thousand, and **\$6** thousand **as** the **minimum**, most likely, and maximum values.

#### **6.4.8 Project Lifetime**

Industry sources reveal that, with suitable upkeep and maintenance, the system should last at **least** 10 years. We use 10, **15**, and 20 years as the **minimum**, most likely, and maximum lifetimes respectively.

### **6.5 SIMULATION**

We **used** the estimates from the previous section to simulate distributions for the economic valuation measures developed in Section 6.3. In each simulation, we generated 1000 values for *PVC*, *PVB*, *NPV*, and *BCR*. To generate one set of such values we followed three basic steps:

1. We generated eight random values from a uniform [0,1] distribution.
2. We converted these values to values for the eight random variables defined in the last section. To do this we used the cumulative distribution function, **P(x)**, which gives the probability that a random variable with a given distribution is less than **x**. To convert a random variable, **p**, from step 1 to random variable with a given distribution, we solve the equation **P(x)=p** for **x**, using the **P(x)** that corresponds to that distribution. For example, if we use **p** to generate a random value for the discount rate, and **p=0.5**, the resulting discount rate would be 0.10.
3. Use the results from step 2 and the formulas in Section 6.3 to calculate the economic valuation variables.

Repeating the above steps 1000 times gives us 1000 **sets** of economic valuation results. These are then used to calculate a number of **summary** statistics, such **as** the average **NPV**, or the probability that the **NPV** is positive.

The procedure was **carried** out **twice**, once based on the social cost per crash, and once based on the agency cost per crash.

## 6.6 RESULTS

Simulation results are summarized in Table 6.2 and Figures 6.2-6.5. Table 6.2 presents parameters for simulated distributions of the economic valuation measures, as calculated from the standpoint of both the agency and society at large. Figures 6.2-6.5 are cumulative distribution functions for these measures.

The project is probably justified from when the total societal cost of crashes is considered. The mean *NPV* is about \$400 thousand, and the probability that the *NPV* is positive is around 0.8. The mean *BCR* is 1.44, implying that we expect about \$1.40 in benefits per dollar expended on the project. An optimistic appraisal—one with a 0.8 probability of being too positive—would set the *NPV* at about \$800 thousand and the *BCR* at around 1.9. Under a pessimistic scenario—one with a 0.8 probability of being too negative—the project would just miss “penciling out.”

The project is certainly not justified from the standpoint of the agency. It would be expected to lose about \$700 thousand on its investment, realizing about \$0.33 in benefit per dollar expended. Even under an optimistic scenario it is unlikely to recover half of its investment, and in a pessimistic scenario it could lose close to \$1 million.

Since the project is probably in the interest of society, but not worthwhile from the standpoint of the agency, it would be an appropriate candidate for federal or state funding. A grant of \$700 thousand would compensate the agency for its expected losses. Coincidentally, this would just about pay for the expense of installing the system at the most likely cost levels (from Table 6.1,  $(\$10000 + \$350) \times 51 = \$688,500$ ). Thus, the economic characteristics of the project fit neatly into current transit funding arrangements whereby capital costs are funded largely from federal sources while operating costs are mainly covered from local sources.

## 6.7 CONCLUDING REMARKS

This analysis is admittedly preliminary. Further work is required to specify the collision avoidance system being assessed, and then to more accurately predict its cost and effectiveness. The analysis is also incomplete since it considers only a single alternative. It is one thing to conclude that an advanced technology countermeasure is better than nothing, and quite another that it is better than more conventional and less expensive alternatives. Such comparisons should also be the subject of further research.

Nonetheless, our results support some useful conclusions. The first is that further study is justified, in the sense that it is likely to lead to a system that yields positive social benefits. In this regard, it should be emphasized that although the analysis is confined to the San Jose light rail system, the system developed in subsequent work could be deployed in many other systems, yielding a total benefit far in excess of that calculated here. Second, it seems clear

that this system cannot pay for itself from the standpoint **of** the transit agency. This suggests that additional research on funding issues should accompany the technical activities. Questions to be addressed should include how to allocate limited capital dollars between safety enhancements and other types of investments, and how to recover costs **of** such projects from the agencies and individuals that benefit from them.

**This d y s i s** has been carried out at a time when **costs** of information and communications technologies are declining continually. It **is** therefore likely the **costs of** the system considered here will **follow this** trend, resulting in higher **net social** benefits and perhaps even a net benefit to the agency itself eventually. This is a further justification for proceeding with system development.

Figure 6.1--Triangular Probability Density Function

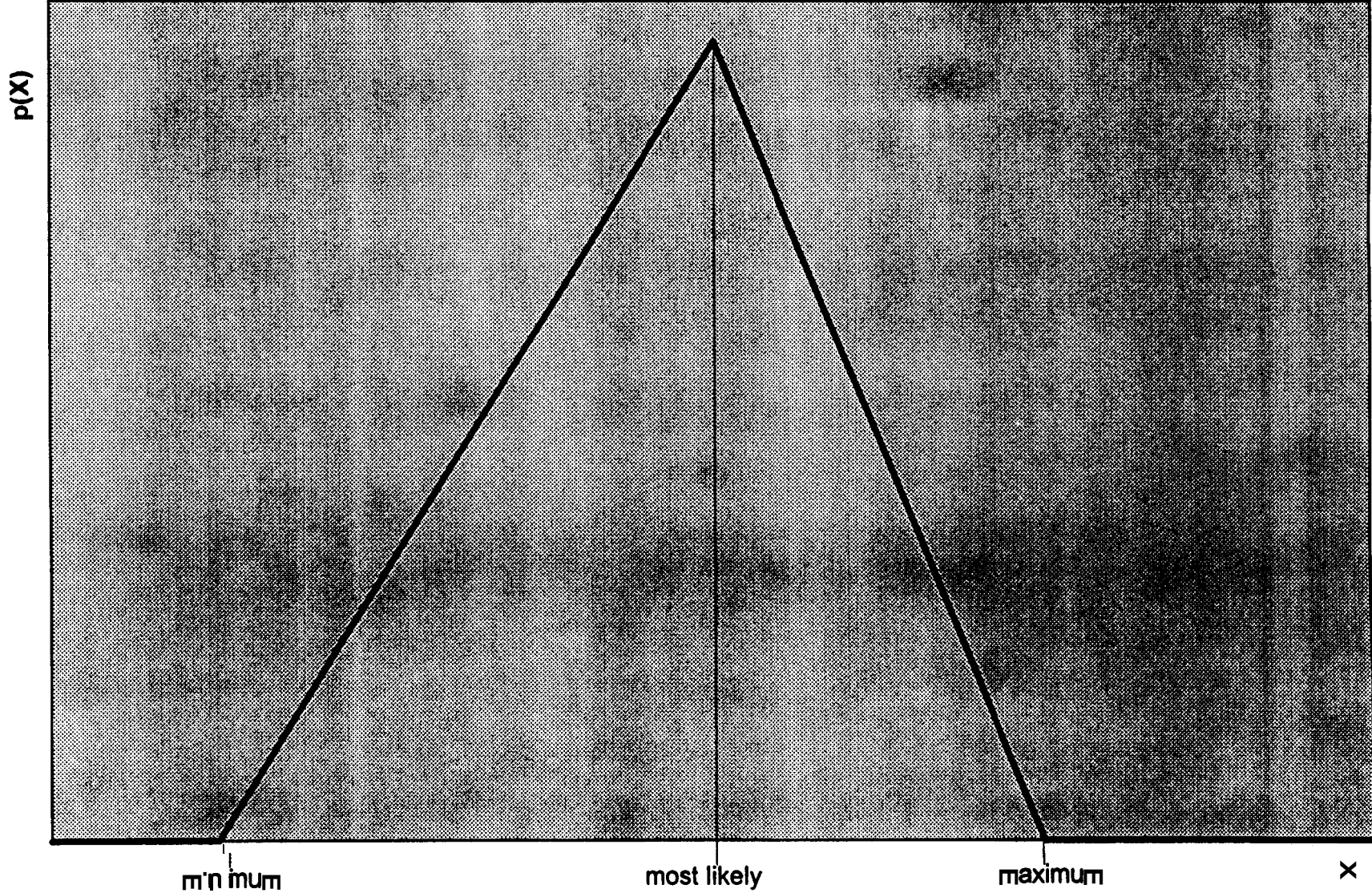


Figure 6.2--Cumulative Distribution Function for Social Net Present Value (NPV)

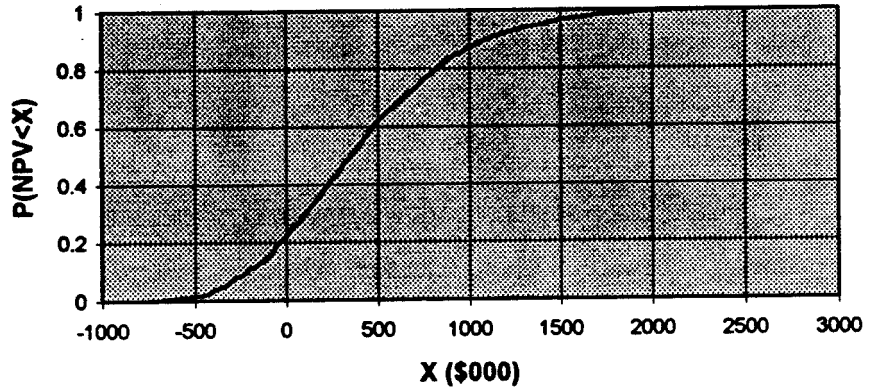


Figure 6.3--Cumulative Distribution Function for Social Benefit-Cost Ratio (BCR)

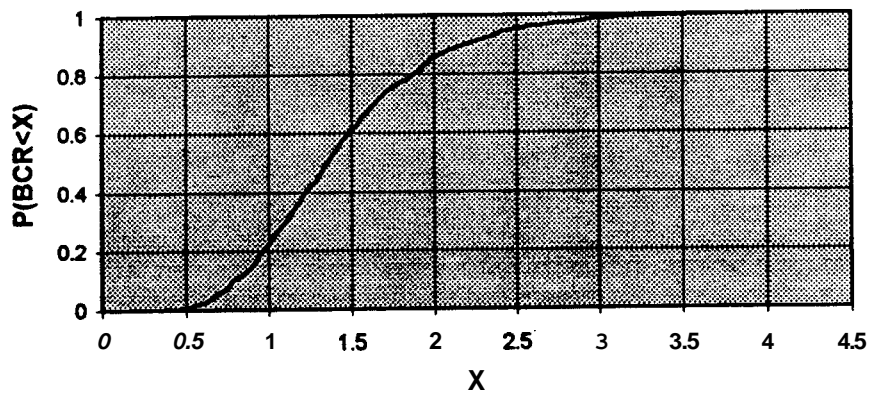


Figure 6.4--Cumulative Distribution Function for Agency Net Present Value (NPV)

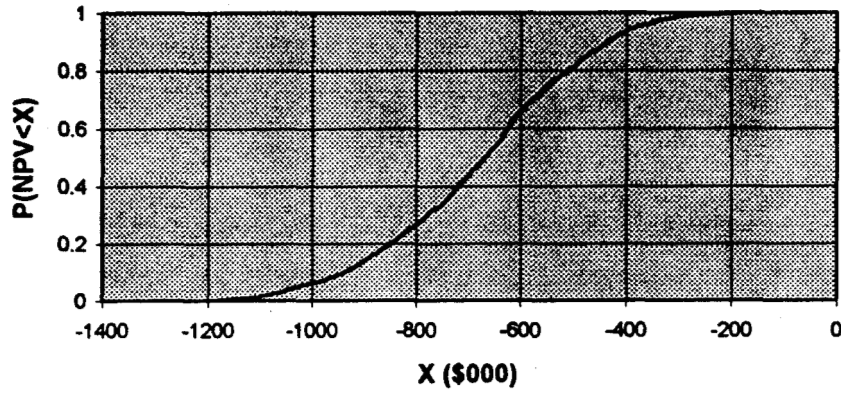


Figure 6.5--Cumulative Distribution Function for Agency Benefit-Cost Ratio (BCR)

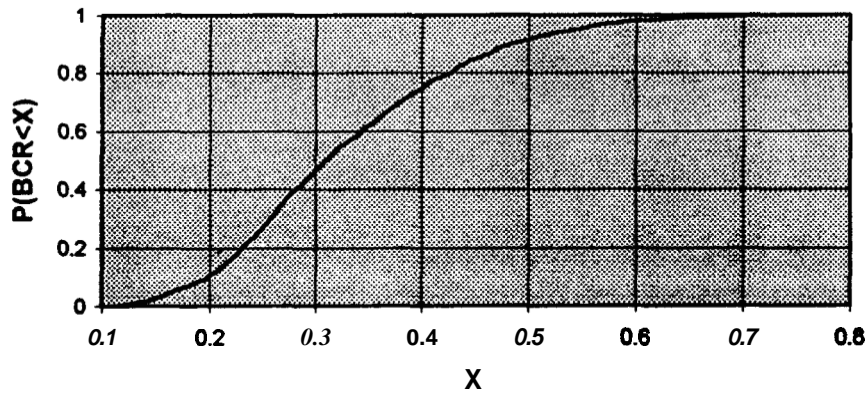




Table 6.1--Distribution Parameters for Assessment Model Variables

PARAMETER	DISCOUNT RATE	SENSOR/ CONTROLLER COST	ALARM COST	ANNUAL COST	CRASH COST IMPACT	CRASHES PER YEAR	SOCIAL COST PER CRASH	AGENCY COST PER CRASH
minimum	0.05	\$5000	\$2000	\$400	0.25	13	\$10000	\$3000
most likely	0.1	10000	3500	600	0.5	19	20000	4500
maximum	0.15	20000	5000	800	0.75	23	30000	6000

Table 6.2--Summary of Simulation Results

STATISTICAL PARAMETER	SOCIAL		AGENCY	
	NET PRESENT VALUE(\$000)	BENEFIT-COST RATIO	NET PRESENT VALUE(\$000)	BENEFIT-COST RATIO
Mean	414	1.44	-680	0.33
Std. Dev.	525	0.56	193	0.12
Median	355	1.36	-669	0.31
First Quintile	-35	0.97	-850	0.23
Fifth Quintile	824	1.88	-509	0.43

## 7. CONCLUSIONS AND RECOMMENDATIONS

Light rail systems that operate on roadway media present a unique challenge to the traffic engineer. If motor vehicle drivers conscientiously followed the rules of the road, and were attentive to signs and signals, there would be no problem. Real-world drivers, unfortunately, are not always conscientious or attentive. These shortcomings, for the most part, stem not from indifference to safety but from habits and expectancies that have formed over their years of driving. From that experience drivers know--or think they know--the boundary between mere rule violations and truly risky behavior. *Also* on the basis of that experience, drivers learn to predict and anticipate signals without the need to carefully observe them. These are the realities that must be anticipated when changes to a road system, such as those associated with a light rail installation, invalidate prior experience.

In the case of the San Jose light rail system, and other similar ones, the specific experiences in question pertain to roadway intersections along the shared right-of-way. The light rail system creates an additional stream of traffic to the left of the left-most roadway lane. The presence of this traffic stream makes very risky a number of previously low-risk, if illegal, turning maneuvers. Signal timing modifications designed to facilitate the flow of the light rail vehicles adds to the problem by confounding driver expectations of signal order. A final complicating factor is the intermittence of the light rail vehicle traffic stream, which reduces the exposure of drivers to events from which the hazards on the new environment can be learned.

Special passive and active signage was installed to mitigate the dangers from the above set of circumstances. For the vast majority of drivers, these countermeasures have been adequate. The San Jose light rail system is therefore very safe. Nonetheless, the existing countermeasures have proved to be insufficient for some drivers. The consequences are documented in Chapters 2 and 3 of this report. Light rail vehicles in the San Jose system have been involved in between 20 and 30 collisions per year, about 80 percent of them with motor vehicles in intersections. Collisions in the latter category are estimated to cost the transit operator about \$100,000 per year, and society as a whole about \$400,000 per year. Beyond these economic impacts, each collision represents a conspicuous disruption to the community that, regardless of legal liability, is associated in the public's mind with the light rail system. Such a perception is especially unwanted in a system so heavily dependent on public subsidy.

This research has considered the technical and economic feasibility of enhancing the existing countermeasures in order to reach the small but significant set of drivers who persist in making unsafe maneuvers in light rail intersections. Both conventional and advanced technology countermeasures have been considered. There are a broad range of conventional countermeasures that might usefully be tried. These are enumerated in Chapter 5. However, if we consider only conventional technologies, we encounter a potentially insurmountable dilemma. These countermeasures are directed at a segment of the driving population whose behavior has proven difficult to modify. There is serious question whether any but the most

intrusive--loud audible signals--or expensive--conventional railroad crossing gates--countermeasures would reach these people. By the same token, conventional countermeasures that are effective for this group are likely to prove excessively annoying or costly to the population at large. For example, it proved necessary to remove warning bells from the San Jose system when they proved bothered people in the neighborhood.

The application of advanced technology may solve **this** dilemma. By using such technologies to design *reactive* countermeasures with a response of graded severity and intrusiveness, it may be possible to generate warnings that are intrusive **as** they need to be, but only *when* they **need** to be. In addition to sparing the general population of unnecessary annoyance, such systems will prevent habituation to the more severe signals. With such systems in place, even **the** most insensate drivers are likely to notice the warning signal **as** they proceed with a hazardous maneuver.

The technology for such systems clearly exists. **All** that is required is a sensor capable of detecting potentially hazardous movement of the vehicle and an actuator that responds to this signal with visual and auditory signals of progressively greater intensity. The more difficult question is whether such a system would actually prevent collisions. To be effective in this regard, the system must not only alarm the driver, but also elicit a desirable and timely response. Much of the research reported here is concerned with projecting the effectiveness of an advanced technology system in these terms.

A large part of the answer comes the kinematic analysis presented in chapter 4. The first conclusion from that analysis is that it is the motor vehicle rather than the light rail vehicle that should be the primary target of the warning system, since it can stop much more quickly. A second conclusion is that, under a variety of plausible acceleration rates, braking rates, and reaction times, it would be possible for the system to issue a warning in sufficient time for the intruding vehicle to avoid a collision by stopping short of the collision zone. Even when such a stop cannot be made, the driver could often take evasive action to forestall a collision. Finally, even when a collision occurs, any braking that occurs prior to it reduces the expected severity of the crash, based on the accident severity analysis in Chapter 2.

The most important unanswered questions are how the population of drivers targeted by this system--that is, drivers who have already failed to notice existing warning systems--would respond to the signals it actuates, and what types of signals would elicit the most desirable response. It is one **thing** to notice a warning, and another to correctly interpret and react to it. **This** distinction is particularly important when the warning **pertains** to an unexpected event, and when misinterpretation of the warning could result in an outcome worse than having no warning at all. In the present context, **expectancy** could cause the driver to interpret the warning to mean an impending collision with a road vehicle, and take evasive action that increases the risk of collision with the light rail vehicle. The fact that some drivers have mistaken the train horn for a truck horn points to the plausibility of this scenario.

A carefully designed program of laboratory and field research **is** required to address these issues. In generic terms, the **aim** of the research would be to design and assess the performance **of** actuated warning systems for unexpected hazardous conditions in a roadway environment. The laboratory program would involve simulated driving experiments in which subjects attempt to evade unexpected hazards. The impact of a variety of systems warning of these hazards could be tested. Results would be applicable not only to the light rail intersections, but also to other *safety* problems **of** a similar character. Such problems may become more commonplace **as** advanced technology alters the driving environment to which generations of drivers have become habituated.

**Work** on the sensor system should **be** carried out in parallel. Here the **focus** would be on the design of algorithms from which **sensor** data can be **used** to quickly and reliably detect hazardous maneuvers. This work *can* be largely accomplished in the laboratory using video tapes from the field.

The outcome of the sensor and warning system research should then be synthesized to assess the feasibility and expected effectiveness of the system, and, if warranted, develop a prototype design. The design would take into account tradeoffs between the numbers of false alarms, avoided (and perhaps induced) collisions, and system cost. Cost factors developed in this research could help to inform these trade-offs. The prototype system would then be field tested, refined, demonstrated, and **finally** deployed of a widespread basis.

Given the continuing interest in *shared* right-of-way light rail throughout the United States, and the incidence and cost of collisions between light rail and road vehicles, the above program is expected to be cost-effective. Most of the benefits **will** accrue to society at large rather than to light rail operators, who are rarely found liable for these collisions. The expenditure for the proposed collision avoidance system should be viewed as an investment in roadway safety rather than one in light rail transit. Moreover, it is an investment that is likely to contribute to the mitigation **of** a broad range of new road safety problems that may emerge **as** modernization of the system proceeds.

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