APPENDIXES D AND E

Appendixes D and E as submitted by the research agency are not published herein. Loan copies are available from the TCRP.

Appendix D: Detailed LRT System Descriptions
Appendix E: Detailed Description of Traffic Control Systems

This appendix compares the TCRP Project A-5 research findings with those set forth in the reports prepared by the Institute of Transportation Engineers (ITE) Technical Committee 6Y-37 between 1986 and 1990.

Background

The objectives of ITE Technical Committee 6Y-37 were to review traffic engineering experiences and procedures for light rail systems throughout North America and to develop guidelines for the design of at-grade light rail crossings. The Committee compiled information from 15 light rail systems concerning their grade crossing design features and safety concerns. Systems evaluated were Boston, Buffalo, Calgary, Cleveland, Edmonton, New Orleans, Newark, Philadelphia, Pittsburgh, Portland, Sacramento, San Diego, San Francisco, San Jose, and Toronto. Seven of the 15 LRT systems identified by the ITE Technical Committee have also been interviewed and researched as a part of the TCRP Project A-5. They are: Boston, Buffalo, Portland, Sacramento, San Diego, San Francisco, and San Jose. The more recently opened LRT systems of Baltimore and Los Angeles were also analyzed as a part of the TCRP Project A-5.

The ITE Technical Committee 6Y-37 was convened in 1986, and a survey questionnaire was drafted and distributed to Committee members who were instructed to enlist the aid of traffic engineers, LRT operations specialists, and LRT planners. While route and LRT information were collected, a major portion of the ITE questionnaire concerned roadway geometry and related grade crossing design and policy issues. The questionnaire response forms were tabulated and summarized in 1988, and each agency was contacted and asked to review the initial findings and data and to provide additional relevant information. The report was finalized in 1989 and submitted in July of 1990. Since the report's completion (and during its preparation) several new LRT systems were built and various improvements and extensions were made to existing systems. Many of the systems reviewed had only been operating for a relatively short time so their experience and accident records were limited.

The Committee found a wide range of operational conflicts associated with the operation of an LRT system; the principal contributing factor to these problems appeared to be the result of giving inadequate attention to traffic control devices. The report noted that many areas lacked any controls, and where controls and devices were deployed, they were frequently unclear and confusing to motorists, or were passive warnings rather than direct controls.

Comparison of Findings

The TCRP Project A-5 found many of the same problems identified earlier by the ITE Technical Committee and introduced several other previously unidentified potential factors that may affect motorist and pedestrian behavior in the vicinity of LRVs.

- Table F-1 compares the problem types reported by ITE Technical Committee 6Y-37 with those observed in the TCRP Project A-5 case studies.

Table F-1 Problem Types Reported by ITE 6Y-37 and Observed in Case Studies

Problem Type	Observed in TCRP Project A-5	
Lack of priority leads to LRV delay	√*	1, 2, 3, 5, 9
Peds/motorist disobedience of traffic laws	√	ALL
Crossing gate breakage	N/A* (Above 35 mph)	---
Traffic queues block crossings	√	3, 4, 7, 8, 9, 10
Vehicles entering/exiting driveways stop on tracks	√	5, 6, 7, 10
Vehicles turning from minor street stop on tracks	√	7
Vehicles making U-turn on tracks	√	8, 9
Pedestrian interference	√	ALL
LRV blocks street at motorist/pedestrian crossing	√	7, 8
LRV-activated gates block crossing while at station	N/A* (Above 35 mph)	---
Vehicles turning left across path of LRV	√	1, 2, 5, 6, 8, 9, 10
Vehicle waiting to turn left blocks LRV	√	2, 5, 9
Through traffic in LRT lane delays LRV	√	2, 9
Unsafe loading/unloading in mixed traffic	√	2, 9
Crossing gates malfunction	N/A* (Above 35 mph)	---
Autos rolling stop across tracks	√	5, 7
Unusual crossing configuration	√	1, 2, 7
Diagonal crossings	NO	NONE

1	Baltimore
2	Boston
3	Buffalo
4	Calgary
5	Los Angeles
6	Portland
7	Sacramento
8	San Diego
9	San Francisco
10	San Jose

N/A*	Not Applicable
√	Observed in TCRP Case Study

- Table F-2 compares the contributing factors to crossing problems reported by the ITE Technical Committee 6Y-37 with those in the TCRP Project A-5 case studies.

Table F-2 Contributing Factors to Crossing Problems

Contributing Factors[1]	Possible Solutions	Observed in TCRP Project A-5 Case Studies
Track Station Location	Changes in Track/Station Location/Station Access	
Traffic Control Devices a) Malfunction b) Lack of Clarity c) Lack of Driver Knowledge d) Intentional Disregard e) Insufficient Devices for Traffic Volume, Speed, Climate	Improvements a) Adjust/Maintain Devices b) Standardize Devices/Relocate Devices c) Educate Motorists d) Greater Enforcement e) Add Needed Devices (e.g. Signal Priority, RR Gates)	√ √ √ √
Frequent Crossings & Possible Conflicts	Reduce Number of Crossings and Complexity a) Close Crossings b) Restrict Turns c) Install Grade Separation d) Install Physical Barriers (Ped. Gates) e) Increase Horizontal Separation between LRV and Parallel Traffic	√ √
High Traffic Volumes	Separate LRT and Motor Vehicles a) Install Grade Separation b) Restrict Turns c) Install Physical Barriers (Ped. Gates) d) Increase Physical Separation	√ √
Jurisdictional Resistance to Change and Redesign for the LRT Environment	Change in Policy	√

[1] (Source: ITE LRT Committee 6Y-37, *Final Report*, July 1990)

Summary of ITE Technical Committee 6Y-37 Conclusions

A summary of the Technical Committee ITE 6Y-37 conclusions are listed below with comments reflecting the initial findings from TCRP Project A-5.

1) *Direct control of motor vehicle traffic is more effective than the use of warning or advisory signs. An exception may be where low-volume, private roadways interfere with low-speed LRV operations. Here inert, wayside devices together with audible warning devices may be sufficient.*

   There were several instances recorded where private low-volume driveways had a noticeable effect on LRV operations, such as San Jose, Sacramento and Los Angeles. In San Jose, low-speed LRV operations seemed to encourage motorists' disregard for the existing, active devices. It appeared that many motorists were not intimidated or compelled to wait for slow moving LRVs. Field observations of a broad number of non-standard passive and active warning and advisory signs indicated that these devices and advisory signs may be less effective than incorporating <u>standard</u> direct control aspects and schemes.

2) *Signal priority or preemption can facilitate and enhance safety of LRT operations. Priority and preemption systems are further enhanced when integrated with traffic signal coordination and other measures defined below.*

   The research supports this conclusion. An important factor not addressed in the original ITE report is the relevance of motorist expectations. Based on conversations with LRV operators, it was discovered that if a motorist expected a particular phase that had been preempted, they would be more likely to ignore the signal (perhaps assuming that a failure in the detection system has occurred) and drive in front of the LRV's path. This problem was identified in Los Angeles, Portland, San Diego, and San Jose. Preemption should <u>follow</u>, not precede protected left-turn phases. LRVs should not preempt the same phase in successive traffic signal cycles.

3) *Side-of-street alignments create excessive operating conflicts where there are frequent crossings.*

The problems with side-street running and the numerous conflicts that result from this alignment have been well-documented. Whereas the initial ITE report indicated that these problems were especially acute at intersections and crossings with limited sight distances, the research found that many conflicts arise out of driver and pedestrian confusion about the <u>direction</u> of LRV operations and the effects of complex roadway geometries on driver decision making. These conflicts are compounded when there are multiple LRVs operating in opposite directions.

4) *Direct traffic control and/or improved geometric design of minor crossings and driveways, particularly for side-of-street running, is highly beneficial. Elimination or minimization of "on-line" mid-block alleys, driveways, and minor street access, is an effective means of reducing conflicts.*

The TCRP Project A-5 research identified several instances where standardized direct traffic control signal devices replaced passive turn prohibitions. The field research indicated that alleys and driveways generally have been kept to a minimum. Exceptions were found in Sacramento (12th Street), San Jose (First and Second Streets), Los Angeles (Flower Street), Boston (Linden/Commonwealth), and San Diego ("C" Street).

5) *"Mixed-flow" operation, (LRV and autos sharing the street) reduces the efficiency of both modes.*

Although the focus of TCRP Project A-5 research does not address efficiency and travel time to the same degree as safety and conflict minimization, there are several improvement measures that would serve to increase the efficiency of LRT in mixed-flow operations. Mixed-flow operations generally have been limited to a few locations by the most recent, post 1970 LRT systems. At those locations where mixed-flow is employed, however, the delineation of the LRV's dynamic envelope appeared to minimize operations delays due to illegally parked autos and trucks. On the other hand, some systems, such as Boston, have closed inefficient mixed-flow segments (Arbor Way) and substituted LRT operations with buses.

6) *Where employed, gates or traffic signals should be installed following such design guidelines as the American Railway Engineering Association (AREA)*

Manual of Railway Engineering and relevant local guidelines (e.g., California Public Utilities Commission General Order 143).

Because of the scope of the TCRP Project A-5 focused on sections of systems where operating speeds are under 35 mph, the research did not examine gated grade crossings, which are typically found where LRVs operate at speeds exceeding 35 mph. Several of the ten LRT systems surveyed incorporate gates to protect LRT grade crossings. Because of the unique characteristics of LRT rights-of-way (e.g., median alignments and contra-flow operations), many grade crossings and device installations require special modifications not covered under the standard existing specifications.

The ITE Report also contained the following additional conclusions regarding traffic control devices:

1) *Signs designed with clear, easily understood symbols and words providing a clear distinction between LRT and motor vehicles are more effective. Devices governing motor vehicles should be consistent with the Manual of Uniform Traffic Control Devices (MUTCD) wherever possible.*

The field data survey revealed a wide variety of alignments and conflict mitigation measures, as well as a wide variety of symbols, nomenclatures, and sign conventions. Some LRVs are referred to as TROLLEYS (San Jose, Boston, and San Diego), others as TRAINS (Portland) and some are referred to as

STREETCARS (San Francisco). While symbols are often a better means of communication, there was also a wide variety of symbols used to depict an LRV. Furthermore, some of the symbols currently used depict the front view of an LRV while others present a side view.

2) *The most effective motor vehicle controls use signals, arrow indications and regulatory signs. Generally, warning or advisory signs are used only to supplement the principal controls.*

The TCRP Project A-5 research team found that the primary type of traffic control is the most important factor to consider when evaluating the worthiness of a supplemental sign or advisory warning. While warning signs may provide a worthwhile supplement to a principal control, a non-standard warning or advisory sign may be counterproductive. In addition, the TCRP research found that warning signs should only be used to inform the motorist and/or pedestrian of the increase in risk level due to the presence of an LRV.

3) *If LRV signals are simple and distinctly different from auto signals, they can be instantly comprehended by the trained LRV operator. (Examples include the "bar," position dot "cat eye," the "positioned bar" signal aspect recently adopted in Baltimore, Maryland, or the "T" used in California). Several Committee members objected to the California "T," believing it is not distinct enough from auto signals.*

The videotaped field inventory of the LRT properties allowed the research team to observe and learn about LRT operations from actual LRT operators. LRT operator input was extremely limited during the ITE research. Because of their physical position above most automobiles and limited control tasks, LRV operators are able to rely on a greater number of overt and covert signals and clues to determine the status of the signal ahead and make educated guesses about the often erratic behavior of nearby motorists and pedestrians.

4) Furthermore, the Committee concluded that segregated LRV signals, those located and angled to be visually separate from the motorist's signals, are less confusing. Signals need not be unnecessarily distracting to those auto drivers whose paths are unlikely to interfere with LRT operations (e.g., flashing warning signs should not distract motorists in lanes on the opposite side of the street from a side-running track).

Like the ITE Technical Committee, the TCRP Project A-5 research team found several locations where LRV related signals were unnecessarily distracting and confusing to the motorist (e.g., Boston, Los Angeles, and San Jose). The TCRP Project A-5 research refers to this condition as "signal clutter." Research to date has indicated that several LRT agencies have taken steps to reduce this clutter and to minimize the number of visible signals and aspects. For example, San Jose has removed some far side LRV signals, reduced the number of heads, and added louvers to focus the signal towards the appropriate vehicle. Los Angeles is planning to do the same.

5) Consistency in the application of traffic control devices works to reduce confusion.

While the ITE report discussed the implications of the wide variety of traffic control devices, the TCRP Project A-5 research team has inventoried and documented this wide array of devices. Both efforts have reached the same conclusion; greater consistency should be the goal as new systems are being planned and/or existing systems are being retrofitted. Research efforts have also recognized the limiting economic and political implications of a complete "re-signalization" of those systems with less than ideal signalization schemes.

1. Evaluation of a Traffic Engineering Treatment Implemented at One LRT System

1.1 Case Study A: Effect of Changing Leading to Lagging Left Turns (Los Angeles LRT System)

The leading left-turn phasing, when used in combination with median-running light rail traffic control, has been a safety concern for the Los Angeles LRT system. With a leading left-turn phase, left-turning motorists receive the green left-turn signal before the through traffic receives a green. When an LRV approaches the intersection, the natural signal phasing sequence is sometimes disrupted, cancelling the left turn phase, to give priority to the LRV. That is, the motorists waiting to make left turns exclusive in the left-turn lane is pre-empted and would not receive the leading left-turn signal during that cycle. Evidence from accident reports indicates that some left-turning motorists anticipated the leading left-turn signal by observing the instant when the traffic signal on the cross street turned red. As a result, motorists started to make left turns without checking for a green left-turn arrow indication, which places motorists on a collision course with an overtaking LRV.

In other instances the LRV will not alter the normal signal phasing sequence, but will proceed through immediately after the end of the left-turn phase. If a left-turning motorist violates the red left-turn signal at the end of the left-turn phase (runs the red) it would then collide with an overtaking LRV. With a lagging left-turn phase, left-turning motorists receive a green left-turn signal after the LRV and the through traffic has received their green.

As a result, seven intersections along the median-running section of the Los Angeles Metro Blue Line in the City of Long Beach were changed from a leading left to a lagging left in August 1991, in an attempt to reduce the number of left-turn accidents. The numbers of left-turn accidents from the seven treated intersections were obtained for both the before and after periods. The numbers of left-turn accidents from other twelve similar intersections receiving no change were also obtained for both periods and represent the comparison condition. The before period is from July 1990 to August 1991. The after period is from September 1991 to June 1994.

The accident data in the before and after period for the treatment and comparison groups to evaluate the effectiveness of this signal change (as described in Chapter 4 of the main report) are presented in Table G-1.

Table G-1 Los Angeles LRT System Case Study

PERIOD	NUMBER OF LEFT-TURN ACCIDENTS	
	7 TREATED SITES	12 COMPARISON SITES
Before (7/90-8/91)	14	9
After (9/91-6/94)	17	13

Source: Los Angeles County Metropolitan Transportation Authority.

In this evaluation, left-turn accidents at the seven intersections form the treatment group, while left-turn accidents at the twelve nearby intersections not receiving the change represent the comparison condition.

A statistical test is required to determine whether the implemented signal change has resulted in reductions in left-turn accidents involving LRVs at the treated intersections, relative to the untreated intersections. This is equivalent to performing the following hypothesis-testing problem:

- H_0: R = 1 (Signal change from leading to lagging left-turn phasing has no impact.)
- H_1: R < 1 (Signal change from leading to lagging left-turn phasing is beneficial.)
- Reject H_0 if the test statistic, $Z_{obs} < Z_{critical}$.

First calculate the odds ratio using Equation (4.2),

$$R = \frac{(17 \times 9)}{(14 \times 13)} = 0.84$$

This odds ratio reflects an observed 16 percent decrease in left-turn accidents at the treated intersections, relative to the trend at the untreated intersections. Next, it is necessary to test whether this calculated odds ratio is less than 1.0.

One then calculates the test statistics using Equation (4.3),

$$Z_{obs} = \frac{\ln(R)}{\sqrt{\left(\frac{1}{B}\right)+\left(\frac{1}{A}\right)+\left(\frac{1}{a}\right)+\left(\frac{1}{b}\right)}} = \frac{-0.174}{\sqrt{\left(\frac{1}{14}\right)+\left(\frac{1}{17}\right)+\left(\frac{1}{9}\right)+\left(\frac{1}{13}\right)}} = -0.309$$

From a table of the standard normal variable, for Probability of a Type I error (α) of 0.05:

$$Z_{critical} = -1.645.$$

Because $Z_{obs} > Z_{critical}$, H_0 is accepted. Therefore, one concludes that the calculated odds ratio is not significantly different from 1.0 at the 0.05 level. This implies that the signal change implemented at seven intersections on the Metro Blue Line has not statistically reduced left-turn accidents more than the margin expected from random variation. The observed 16 percent fewer left-turn accidents at the seven intersections was probably a result of random variation.

1.2 Case Study B: Effect of Installation of Active TROLLEY COMING Signs (San Jose LRT system)

Active TROLLEY COMING signs were installed at the far side of intersections in San Jose to warn left-turning motorists traveling in the same direction and to the right of the LRT tracks that an LRV was approaching the intersection. The sign is activated (i.e., lit in yellow) 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. The motorists may have been unaware of LRVs approaching from behind. It was believed that these active signs could provide timely warnings of LRVs approaching the intersection 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.

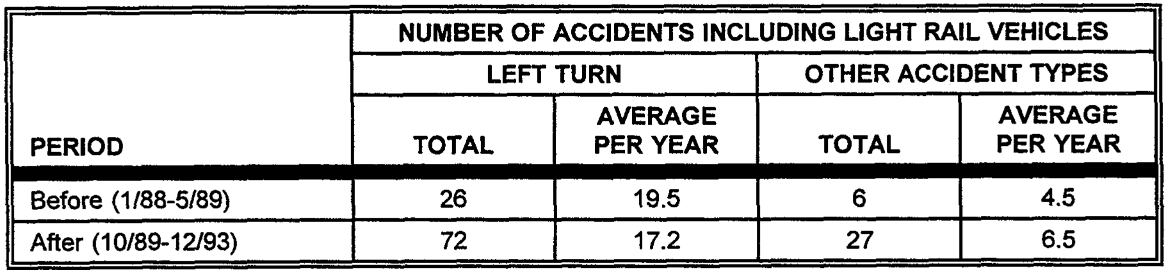
The comparison condition consists of other types of collisions between LRVs and motor vehicles not affected by the active TROLLEY COMING signs. These include: right-angle accidents (in which the motorists traveling on cross streets which received no active signs) and right-turn accidents (along right 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.

The accident data in the before and after periods for the treatment and comparison groups to evaluate the effectiveness of the active TROLLEY COMING signs (as described in Chapter 4 of the main report) are shown in Table G-2.

In this evaluation, the numbers of left-turn accidents form the treatment group, and the numbers of other accident types form the comparison group.

Table G-2 San Jose LRT System Case Study



	NUMBER OF ACCIDENTS INCLUDING LIGHT RAIL VEHICLES			
	LEFT TURN		OTHER ACCIDENT TYPES	
PERIOD	TOTAL	AVERAGE PER YEAR	TOTAL	AVERAGE PER YEAR
Before (1/88-5/89)	26	19.5	6	4.5
After (10/89-12/93)	72	17.2	27	6.5

Source: Santa Clara County Transportation Authority.

A statistical test is required to determine whether the active TROLLEY COMING signs have resulted in reductions in left-turn LRT accidents, relative to the trends in other LRT accident types. This is equivalent to performing following hypothesis-testing problem.

- H_0: R = 1 (Active TROLLEY COMING sign has no impact.)
- H_1: R < 1 (Active TROLLEY COMING sign is beneficial.)
- Reject H_0 if the test statistic, $Z_{obs} < Z_{critical}$.

First the odds ratio is calculated using Equation (4.2),

$$R = \frac{(72 \; x \; 6)}{(26 \; x \; 27)} = 0.62$$

This calculated odds ratio reflects an observed 38 percent decrease in left-turn accidents after the implementation of the active TROLLEY COMING signs, relative to the trend in the comparison condition.

Next, one tests whether this odds ratio is statistically less than 1.0 by calculating the test statistic using Equation (4.3),

$$Z_{obs} = \frac{\ln(R)}{\sqrt{\left(\frac{1}{B}\right) + \left(\frac{1}{A}\right) + \left(\frac{1}{a}\right) + \left(\frac{1}{b}\right)}} = \frac{-0.478}{\sqrt{\left(\frac{1}{26}\right) + \left(\frac{1}{72}\right) + \left(\frac{1}{6}\right) + \left(\frac{1}{27}\right)}} = -0.945$$

From a table of the standard normal variable, for Probability of Type I error (α) of 0.05:

$$Z_{critical} = -1.645.$$

Because $Z_{obs} > Z_{critical}$, H_0 is accepted. Therefore, we conclude that the calculated odds ratio is not significantly different from 1.0 at the 0.05 level. This implies that active TROLLEY COMING signs have not statistically reduced left-turn accidents more than the margin expected from random variation.

2. Evaluation of the Same Traffic Engineering Treatment Implemented at Several LRT Systems

This section describes the statistical procedures for conducting before and after analyses for sites in several systems. It assumes that traffic engineering treatments corrective actions, such as installing TROLLEY COMING signs, are implemented at locations within several LRT systems. Therefore, within each LRT system, the accidents form the treatment group, and other accident types (which are not affected by the active TROLLEY COMING signs) form the comparison group. The average overall effectiveness across all LRT systems is evaluated using a method developed by Griffin.[1]

2.1 Statistical Analysis

1) For each *i*-th LRT system, calculate an odds ratio (R_i) using Equation (4.2). Then, let:

$$L_i = \ln(R_i) \qquad \text{(Eq. G.1)}$$

Repeat these calculations for all LRT systems.

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[1] Griffin, L.I., III (1990) "Using before-and after design with yoked comparisons to estimate the effectiveness of accident countermeasures implemented at multiple treatment locations." Texas A & M University, Texas Transportation Institute.

2) Next, calculate the weighted average log odds ratio for all LRT systems. In this regard, first define the weight for each *i*-th system as:

$$w_i = \frac{1}{\left(\frac{1}{A} + \frac{1}{B} + \frac{1}{a} + \frac{1}{b}\right)} \qquad \text{(Eq. G.2)}$$

The weighted average log odds ratio for all LRT systems is:

$$L = \frac{\sum w_i L_i}{\sum w_i} \qquad \text{(Eq. G.3)}$$

And the average R for all systems can be expressed as:

$$R_{avg} = \exp(L) \qquad \text{(Eq. G.4)}$$

- $R_{avg} < 1$ implies that the treatment is effective in reducing the number of accidents overall.
- $R_{avg} > 1$ implies that the treatment is harmful overall.
- $R_{avg} = 1$ implies that the treatment has no overall impact.

3) Next, perform hypothesis testing to determine whether the calculated value of R_{avg} from Equation (G.4) is significantly different from 1.0. The following test statistics are calculated.

Table G-3 Test Statistics for Treatment and Homogeneity

SOURCE	TEST STATISTIC	DEGREES OF FREEDOM
Treatment (G.5)	$L^2(\Sigma w_i)$	1
Homogeneity (G.6)	$\Sigma w_i L_i^2 - L^2(\Sigma w_i)$	*n*-1
Total	$\Sigma w_i L_i^2$	*n*

In Table G-3, *n* is the number of LRT systems being evaluated.

To test whether on the average the treatment is effective for all LRT systems, set up the following null and alternative hypotheses:

- H_0: $R_{avg} = 1$ (the treatment has no overall impact)
- H_1: $R_{avg} < 1$ (the treatment is beneficial overall), or
  $R_{avg} > 1$ (the treatment is harmful overall).

The test statistic (X^2_{obs}) is $L^2(\text{é}w_i)$ as shown above in Equation (G.5). When H_0 is true, X^2_{obs} is distributed as a chi-squared random variable with one degree of freedom.

4) Next, compare the value of the calculated test statistic (X^2_{obs}) with the value of a chi-squared of one degree of freedom (from a chi-squared table in any mathematics or statistics textbook). The latter is called $X^2_{critical}$.

For Observed R_{avg} Less Than 1.0

If $X^2_{obs} > X^{2(1)}_{critical}$, reject H_0. This indicates that the observed R(average) is significantly less than 1.0. It implies that the treatment, on the average across all LRT systems, is effective in reducing the number of accidents.

For Observed R_{avg} Greater Than 1.0

If $X^2_{obs} > X^{2(1)}_{critical}$, reject H_0. This indicates that the observed R_{avg} is significantly greater than 1.0. It implies that the treatment (on the average) across all LRT systems, results in an increased number of accidents.

5) Finally, because the hypothesis testing in Steps 3 to 4 involves testing of the average effectiveness of the treatment across all LRT systems, a question arises concerning whether individual LRT systems show homogeneous effects of the treatment. This question can be answered by further hypothesis testing:

- H_0: Effect of the treatment is homogeneous among all LRT systems.
- H_1: Effects of the treatments are not homogeneous among all systems.

The test statistic is calculated using Equation (G.6). If H_0 is true, this test statistic is distributed as a chi-squared random variable with (*n*-1) degrees of freedom, where *n* is the number of LRT systems being evaluated. One rejects H_0 if this test statistic is greater than $X^{2(n-1)}_{critical}$, where the latter is obtained from a chisquared table. If one accepts H_0, it follows that all LRT systems exhibit homogeneous effects of the treatment.

A hypothetical example showing an application of this evaluation method is presented in the next section.

2.2 Example Application

This example illustrates how the evaluation method described in the previous section can be used to evaluate the effectiveness of an LRT treatment deployed at more than one system. The accident data shown in this example are hypothetical and are not based on real-world observations.

Suppose three LRT systems implemented signal phasing changes two years ago, in which the "leading" left-turn phasing was changed to the "lagging" left-turn phasing at 50 percent of the signalized intersections within each system in an attempt to address left-turn collisions between LRVs and motor vehicles at signalized intersections. The remaining 50 percent of the signalized intersections within each system did not receive any signal change and will be used as the comparison condition. This is similar to Case Study A (Section 1.1), except that now the goal is to evaluate the overall average effectiveness of this signal change among all three LRT systems. Within each LRT system, the treated intersections form the treatment group, and the untreated intersections form the comparison group.

Accident data from each of the three LRT systems in the before and after periods are as shown in Table G-4. For the effectiveness evaluation, the data for each system are tabulated separately.

Table G-4 Hypothetical LRT Systems Analysis

LRT SYSTEM	PERIOD	NUMBER OF LEFT-TURN ACCIDENTS	
		TREATED SITES	COMPARISON SITES
1	Before After	15 10	25 20
2	Before After	25 20	15 15
3	Before After	30 32	25 30

It is desired to determine whether the signal change implemented at intersections of three different LRT systems, on the average, is effective in addressing the left-turn accident problem. The steps are as follows:

1) Perform a hypothesis testing of the average impact of the signal change across the three LRT systems. In this regard, we define:

- H_0: $R_{avg} = 1$ (Change has no impact.)
- H_1: $R_{avg} < 1$ (Change is beneficial.)

2) Next, calculate the odds ratio (R) for each LRT system using Equation (4.2):

For System 1:

$$R_1 = \frac{(10 \ x \ 25)}{(15 \ x \ 20)} = \mathbf{0.833}, \ and$$

$$L_1 = \ln(R_1) = -0.183$$

Similarly, we calculate:

For System 2:

$$R_2 = 0.800, \textit{ and}$$

$$L_2 = -0.223$$

For System 3:

$$R_3 = 0.889, \textit{ and}$$

$$L_3 = -0.118$$

3) Next, calculate the weight for each odds ratio (Equation G.2), for use in calculating the weighted average odds ratio for all three systems.

For System 1:

$$w_1 = \frac{1}{\left(\frac{1}{15} + \frac{1}{10} + \frac{1}{25} + \frac{1}{20}\right)} = 3.89$$

Similarly,

For System 2:

$$w_2 = 4.46$$

For System 3:

$$w_3 = 7.30$$

From Equation (G.3), calculate the average log odds ratio:

Taking the antilogarithm, this yields $R_{avg} = \exp(L) = 0.848$.

$$L = \frac{\sum w_i L_i}{\sum w_i} = \frac{3.89(-0.183) + 4.46(-0.223) + 7.30(-0.118)}{3.89 + 4.46 + 7.30}$$

$$L = -0.165$$

4) Using all quantities calculated in Step 3, derive the test statistics using Equations (G.5) and (G.6), as shown in Table G-5.

Table G-5 Test Statistics for Treatment and Homogeneity

SOURCE	TEST STATISTIC	DEGREES OF FREEDOM
Treatment	0.424	1
Homogeneity	0.030	2
Total	0.454	3

5) In testing whether the calculated R_{avg} is indeed significantly less than 1.0, compare the test statistic (for treatment) with a standard chi-squared value with one degree of freedom (or $X^2_{critical}$, from a mathematics table). Reject H_0 if the test statistic > $X^2_{critical}$.

$X^2_{critical}$ is found to be 3.84 (for $\alpha = 0.05$). Because the calculated test statistic of 0.424 is less than $X^2_{critical}$, H_0 is accepted. Thus, one concludes that the average odds ratio is not significantly different from 1.0. This implies that the implemented signal change at the three LRT systems has no significant impact on left-turn accidents.

6) Finally, test whether the signal change has a homogeneous safety impact at the individual LRT systems. This is equivalent to testing the following hypothesis:

- H_0: Treatment's effect is homogeneous for all systems.
- H_1: Treatment's effect is not homogeneous for all systems.

This requires comparing the test statistic (for homogeneity), which is calculated above to be 0.030, with a standard chi-square value for two degrees of freedom (or $X^2_{critical}$). Reject H_0 if the test statistic is greater than $X^2_{critical}$.

$X^2_{critical}$ is found to be 5.99 (for $\alpha = 0.05$). Because $0.030 < 5.99$, H_0 is accepted. This leads to the conclusion that the impact (or lack thereof) of the implemented signal change is homogeneous for all three LRT systems.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate the information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 400 committees, task forces, and panels composed of more than 4,000 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is interim president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and interim vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transit Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation