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16. Abstract

Many local and regional transportation authorities in Texas are proposing retrofitted bicycle facilities—those added to existing roadways without changing the curb-to-curb width—under the Congestion Mitigation and Air Quality (CMAQ) Program and the Selective Traffic Enforcement Program (STEP). As custodian of the federal money for these programs, the Texas Department of Transportation (TxDOT) must approve or reject these proposals according TxDOT design standards, which are based on the American Association of State Highway and Transportation Officials (1999) *Guide to the Development of Bicycle Facilities*. This research was undertaken to provide additional tools to evaluate the suitability of an on-street bicycle facility for both motorists and cyclists, especially as the tools apply to the approval or rejection of bicycle facility retrofits. The additional tools for evaluation of this study developed primarily from approximately 3,500 observations of motorists passing cyclists and over 4,000 observations of motorists unaffected by cyclists at 24 sites across Texas. These observations led to multivariate regression models of the lateral position of motorists and cyclists based on geometric and traffic characteristics such as motor vehicle lane width, percentage of truck traffic, presence and width of bicycle lane, and presence of a center turn lane. The research also included a review of roadway design literature relevant to bicycle facility retrofits and an analysis of bicycle-car crash data from the Houston-Galveston Area Council for the years 1999-2001. The results of this research and that of another bicycle facility evaluation tool, the Bicycle Compatibility Index developed by the Highway Safety Research Center at University of North Carolina at Chapel Hill, were used to create the *Written Guide to Selecting Among Limited Right-of-Way Streets and Designing Geometric Solutions for the Provision of Bicycle Lanes*, later renamed the *Texas Guide for Retrofit and Planned Bicycle Facilities*.

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Evaluation of On-Street Bicycle Facilities Added to Existing Roadways

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1. Introduction

1.1 Purpose of this Study

The Texas Department of Transportation (TxDOT) sought additional guidance and information to evaluate and design on-street bicycle facilities with emphasis given to retrofit bikeways. TxDOT's role as the administrator of several federally funded programs, including the Statewide Transportation Enhancement Program, the Congestion Mitigation for Air Quality, the Safe Routes to School Program, etc., have placed the agency in the role of evaluating on-street bicycle facility designs for local transportation authorities in the state of Texas. Many local entities are trying to provide an increasing number of facilities for cyclists primarily to convert car trips to bike trips in an attempt to mitigate air quality and congestion problems. The dual problem of poor air quality and high amounts of congestion are endemic to highly developed urban areas where the possibility of expanding the curb-to-curb width of a roadway is often impossible or prohibitively expensive. In this all too common scenario, local transportation authorities have attempted to provide bicycle facilities by reducing space for motor vehicles and allocating it to cyclists without changing the overall width of the roadway. This process will hereafter be referred to as *retrofitting* and the resulting facility as a *retrofit.*

As for many transportation agencies, the American Association of State Highway and Transportation Officials' (AASHTO) *Guide for the Development of Bicycle Facilities* (1999) serves as TxDOT's official guide on this topic. The guide provides minimum and recommended design recommendations for bikeways. Some factors warranting consideration are not well defined by AASHTO. AASHTO's guide is unclear about what adjustments should be made to mitigate any negative impacts of a particular facility design and does not give any indication of what the consequences of these impacts are for either the cyclist or the motorist. AASHTO's guide also does not provide evidence of the consequences for cyclists or motorists of choosing one design option over another. These consequences are extremely important when the roadway environment presents a marginal situation for adding a bicycle facility. This confusion is further exacerbated by conflicting demands from different segments of the cycling community, each with its own concept of an acceptable facility. Further, the AASHTO guide does not provide criteria for selecting an alternate route for an on-street facility in the event that a specific bikeway design appears unlikely to provide adequate safety and operational options for both motorists and cyclists.

For these reasons, TxDOT desired empirical evidence of the actual behavior of cyclists and motorists traveling on roadways with retrofit bike routes when confronted with various roadway and traffic characteristics. A particular emphasis was to be placed on roadway designs based on minimum widths and standards as these were most likely to be encountered in bicycle facility retrofits. With this approach, TxDOT hoped to avoid the provision of bicycle facilities that served only one segment of the population or compromised the services of the roadway for motorists.

1.2 Research Approach

To provide the guidance TxDOT sought, our initial step was a literature review of relevant roadway characteristics, focusing on the effects associated with roadway width, median treatment, and the existing on-street bicycle facility type. Next, we reviewed a national bicycle crash data study in conjunction with the crash data generated by the Houston-Galveston Area Council (H-GAC). However, the thrust of the research was to gather observations of cyclist-motorist interactions at a wide variety of sites with differing geometric and traffic characteristics. Because retrofit bikeways generally result from 'squeezing' a bicycle facility onto an existing roadway, the field observations focused on the lateral positions of both cyclists and motorists traveling on roadways with retrofit bikeways. The field observations also included a separate before-and-after test in which 8-inch stripes were used to demarcate the bicycle lane instead of the more common 4-inch stripes. The observations from the field were quantified and then analyzed using multivariate regression analysis. The results of this analysis, in combination with other published research, generated predictive tools for assessing the effects on motorists and cyclists using various roadways with retrofit bicycle facilities on differing roadway configurations. These tools were published as a part of the *Written Guide to Selecting Among Limited Right-of-Way Streets and Designing Geometric Solutions for the Provision of Bicycle Lanes* (hereafter referred to as *The Texas Guide for Retrofit and Planned Bicycle Facility Design*), which can be found in the last chapter of this report.

2. Roadway Design Elements

2.1 Introduction

When a bicycle facility is added to an existing roadway, the two elements of the road design likely to change are the width of the motor vehicle lanes and the width of the median. These changes will have operational and safety effects that need to be considered when evaluating on-street bicycle facility retrofits from the perspective of both cyclists and motorists. The type of bicycle facility—in this case, a bike lane or a wide outside lane—will be key factors in the analysis. The following material presents a summary of pertinent literature available on the topics of median treatments, motor vehicle lanes, and on-street bicycle accommodations.

2.2 Medians

There is a wealth of literature regarding the topic of median treatments on urban and suburban roads. The most discussed median treatments were no median, flush medians (one-way and two-way continuous left-turn lanes), and raised medians (alternating left-turn bays). Most of the literature available addresses either design standards or threshold values for traffic characteristics that generate a need for some type of median treatment. This project, however, needed to document the effects of incremental changes to median treatments on motorists. Only two studies from the literature search attempt to provide operational and safety impacts of medians in this manner.

2.2.1 Multilane Design Alternatives for Improving Suburban Highways (Harwood 1986)

Harwood established delay (operational) measures and accident rate (safety) changes based on the comparison of a two-lane, undivided cross section to a variety of other cross-sectional designs: 1) two-lane streets with raised or flush medians, 2) undivided four-lane streets, and 3) five-lane streets with raised or flush medians. To develop the estimates of operational and safety impacts, the researchers conducted an exhaustive literature review (at that time) on the topic of medians, analysis of crash data from state highway systems in California and Michigan, and computer simulations.

Like other median studies, the final product of the report was a series of guidelines for instituting various cross-sectional designs. However, the author also appended much of the incremental data analysis and associated tables, which are of particular interest to this study. The safety analysis considered the effects of cross-section design (four-lane undivided road, three-lane road with two-way left-turn lanes (TWLTLs), etc.), type of development (commercial/residential), average daily traffic (ADT), driveways per mile, unsignalized intersections per mile, and truck percentages. The operational analysis generated from computer simulations considered number of through lanes, presence or absence of a TWLTL, length of simulated section, location of individual access points, traffic volume and arrival distribution, travel speed, and left- and right-turn volume at individual access points.

The strength of the research, in regard to this study, is the range of cross-section designs analyzed in the study; nearly every possible configuration observable in the field was considered by the researchers. The weakness of the research is the confidence level associated with the estimates and the variation from these estimates that could be encountered in the field. The author noted that the computer simulation results were "validated for a limited set of field data collected in Omaha and Lincoln, Nebraska…[but were] more highly variable than was desired, and inconsistencies in the model predictions were found in a few cases" (Harwood 1986). Similarly, the accident rates for various roadway configurations were highly variable. The study also states that factors like distribution of traffic in a 24-hour period, peak-hour volumes, and directional split of the traffic could affect the values generated in this study. These effects are better controlled using the method of analysis in the following study.

2.2.2 Capacity and Operational Effects of Mid-Block Left-Turn Lane (Bonneson and McCoy 1997)

This study quantified safety and operational impacts of roads with no median (undivided roads), two-way left-turn lanes, and alternating left-turn and raised medians. Data was collected from 32 field studies in 8 states and 4 cities as well as from 3-year accident histories for 189 street segments in 2 states. In addition to calculating direct values, the data was also used to calibrate a computer simulation model where 117 simulation runs expanded the range of the field data. The variables in the evaluation of operational effects included median treatment, number of through traffic lanes, flow rate, access point density, and left turn percentages. The analysis also generated delay values for turning vehicles. The variables included in the evaluation of safety effects were median treatment, adjacent land use, ADT, access point density, presence or absence of on-street parking, and property-damage-only accident percentage.

The incorporation of field data to calibrate the computer simulations was a significant improvement over Harwood's 1986 study. Moreover, Bonneson and McCoy (1997) extended the estimates of delay based only on hourly traffic volumes to calculate delay incurred over the course of a year by developing an average 24-hour distribution of hourly traffic volumes for streets of given ADT from the general distribution of ADTs from the field. In this way, a more complete picture of operational effects was presented.

A significant weakness of this study is that it considers only streets with four or six lanes of through traffic. The absence of data for two through lanes is a significant impediment to the goals of this study. This leaves the possibility of using the data for four- and six-lane cross sections from Bonneson and McCoy (1997) and two-lane data from Harwood (1986). Bonneson and McCoy (1997) addressed this idea in their analysis because Harwood's study is the only other study to undertake a similar research question: "[The] comparison indicated that the (values) found in this research are about one-half to one-third of those reported by Harwood for similar volumes and driveway densities" (Bonneson and McCoy 1997). They gave three factors that likely accounted for the differences. One of these was the use of staggered (symmetric about the length of the road) versus unstaggered access points along the analyzed segment in the computer simulations. These differences in estimated operational delays cannot be reconciled without repeating the data analysis or computer simulations. This observation highlights how natural variation in the field can limit the ability of a model to reliably or universally predict operational impacts.

2.3 Motor Vehicle Lanes

Reductions in lane width are generally associated with reductions in speed and, hence, capacity. The Highway Capacity Manual for 1994 gives a reduction in free flow speed for motor vehicles of 1.9 mph when moving from a 12-foot lane to an 11-foot lane and a 6.6 mph reduction in free flow speed when moving from a 12-foot lane to a 10-foot lane (the values are not given in the 2000 manual because of a change in analytical methodology). However, there is not a complete consensus on this subject. The process of relating safety and operational effects to lane widths is always confounded by related factors such as ADT, access point density, and cross-section geometries. For example, wider lanes decrease the amount of same direction sideswipe accidents and increase the amount of room for avoidance measures, but these increases in safety can be partially or entirely offset by the negative safety effects of increased speed associated with wider lanes. This causes problems in posing confident values for the effects of lane width. A sample of studies on the topic and their observations related to the issue of uncertainty follows.

2.3.1 Design Factors That Affect Driver Speed on Suburban Arterials (Fitzpatrick et al. 2000)

This study predicted a change in 2.9 mph per foot of lane width with a high level of variance, and this relationship was found to be affected by the presence or absence of a median treatment. These factors were also secondary to posted speed limits: "When all variables are considered (including lane width), the only significant variable for straight sections was posted speed limit." Decreases in speed were also associated with increases in access point density.

2.3.2 Some Partial Consequences of Reduced Traffic Widths on Urban Arterials (Heimbach, Cribbins, and Chang 1983)

The results of this study were based only on four-lane, undivided roads. Narrowing lanes from 12 feet in width by 1 or 2 feet tended to decrease speeds by 0.6 mph and 1.0 mph per foot of reduction for off-peak and peak hours, respectively. Collision rates did not respond to reductions in widths linearly, but could be estimated to increase between 3 and 5 percent per foot reduction in lane width.

2.3.3 The Effects of Road Design on Speed Behavior: A Literature Review (Martens, Comte, and Kaptein 1997)

From Europe, this review documented one study that had figures similar to Heimbach, with a 1.1 mph reduction for every 1-foot reduction below 13 feet of width. Notably, the review presented the following observation: "It is very difficult to measure the effect of pavement width itself, independently of other road design factors. This can probably explain the fact that the relationship between width of pavement and driving speed was established in some studies…whereas in other cases no effects could be found" (Martens, Comte, and Kaptein 1997).

2.3.4 Effective Utilization of Street Width on Urban Arterials (Harwood 1990)

This study gives effects of lane width in terms of capacity reductions. Compared to a 12-foot lane, these reductions amount to 3 percent less capacity on an 11-foot lane, 7 percent on a 10-foot lane, and 10 percent on a 9-foot lane. Most interestingly, a survey of highway agencies in the study reports that 88 percent of respondents have used lanes of 10 feet or narrower in urban designs, although there was no indication as to which classes of streets received these reduced widths.

2.3.5 Review of Accidents and Urban Arterial Cross-Section Treatments (McClean 1997)

The study formulated a comprehensive accident model influenced by side street intersection density, commercial activity, horizontal and vertical alignments, and lane width. The results showed a 2.4 percent to 3.0 percent increase in accidents per foot of reduced lane width from 12 feet to 10 or 11 feet, although side street density had the greatest affect on accident rates.

2.4 Bicycle Facilities

A preliminary investigation of safety and operational impacts of bicycle facilities has revealed a preference in the field for designated bicycle lanes over wide outside lanes for on-street bicycle routing. Hunter et al. (1999) revealed better traffic law adherence by cyclists and less adjacent lane encroachment of motor vehicles with bicycle lanes when compared to wide curb lanes (bicycle routes). Harkey et al. (1997) showed that bicycle lanes reduced motor vehicle encroachments on adjacent motor vehicle lanes and increased the distance a cyclist rode from the curb when compared to wide outside curb lanes. The observed distance between cyclist and motorist was less with bicycle lanes compared to wide outside lanes on signed bike routes; motorists and the cyclists did not take measures to move farther from the other. This served as significant evidence of an increased comfort level associated with designated bicycle lanes for both groups. The study found that bike lane widths between 4 and 5 feet had almost no effect of bike lane width on the lateral position of cyclists, i.e., the amount of separation between cyclists and motorists, and the change in the lateral position of the motorist during a passing event. Harkey et al. (1998) also developed a bicycle compatibility index in 1998 for the Federal Highway Administration using cyclists' perceptions of 80 unique roadway segments. The study generated a rating system of cyclist comfort from 1 to 6 for road segments, and multivariate analysis allowed the researchers to establish the contribution of individual roadway design elements and traffic characteristics to the ratings. The presence of a bicycle lane raised the rating level one full point when holding constant all other factors. The contribution of a bicycle lane to the compatibility of a road segment for cyclists was greater than any other factor studied.

2.5 Discussion

The multitude of variables addressed in available research on motor vehicle lanes and median treatments presents problems for developing a guide to locating space on an existing roadway for bicycle facilities. The number of factors that influence a particular variable can easily confound the results and fail to provide any generality. For example, whether or not access points are staggered produced differing results in the two studies on medians discussed earlier, and actual roadways would surely be a mix of these conditions. There also appears to be a lack of consensus on the magnitudes of effects in the studies. The effect of lane width on observed speed and capacity of a roadway varied among all of the studies cited earlier. In summary, the number of variables influencing the operational and safety performance of a roadway for motorists and the uncertainty of their effects make impractical the goal of precisely identifying the impacts of a bicycle facility retrofit on motor vehicles.

From the literature review emerge some broad trends useful to retrofit bicycle facility design and evaluation. The elimination of turning lanes introduces a significantly higher delay in traffic movement and an increase in accident rates than is observed when narrowing motor vehicle lanes. Designated bike lanes appear to have operational advantages over wide outside lanes for both motorists and cyclists. These observations will help to interpret results from the field research and develop a general guide for adding bicycle facilities to existing roads even if the precise impacts on one or both of the actors cannot be wholly predicted.

3. Bicycle Crash Data Analysis

3.1 Introduction

There are a number of pitfalls associated with drawing conclusions from bicycle accident data. The most commonly mentioned problem with bicycle accident analysis is underreporting, which is also encountered in motor vehicle accident analysis. Although there is no perfect solution, often estimates can be developed or, in some cases, assumptions can be made about the number of unreported accidents or their relationship to reported accidents. However, a far more serious problem encountered in accident analysis is the lack of bicycle usage/trip data, which is needed to establish likelihoods or probabilities of bicycle accidents as well as the effects of safety improvements. A synthesis of the research up to 1995 in a publication on the topic began with the following comment (Clarke and Tracy 1995):

> *"Each year, the overall success of our national traffic safety effort is measured by the number of fatalities per 100 million miles traveled. Unfortunately, this means of determining progress, while perhaps useful in reporting safety of motoring, is woefully inadequate when applied to bicycling. We simply do not have adequate information on the amount of cycling being done. We know little about the actual number of people who ride, the time they spend on their trips, the distance they travel, as well as the number of trips they take in the course of a year."*

In other words, it is impossible to tell if an increase in bicycle accidents is due to an increase in bicycle trips or a decrease in safety for cyclists. In fact, safety improvements made to a bicycle facility could actually result in an increase in bicycle accidents if the improvements make the facility more appealing and increase the number of cyclists using it. The research team has been unable to locate a study produced since the 1995 report cited that integrates bicycle usage data and, based on the literature surveyed, it is doubtful that one exists. The immense resources required to gather such data discourages efforts to remedy this deficiency.

Despite the problems that the lack of bicycle usage data present, researchers have had some success in drawing conclusions through analysis of traffic, roadway, and cyclist factors observed in bicycle accidents and accident severities. However, like the issue of cyclists' frequency in the field, the distribution of traffic and roadway characteristics must also be considered. Most bicycle accidents occur on two-lane roads. This result may be based on the fact that this type of road forms the majority of all roads. Likewise, accident analysis may reveal a roadway or traffic feature that results in an abnormally high percentage of deaths and serious injury, but this type of analysis must also be tempered by related considerations. A four-lane road is much more likely to result in death or serious injury in the event of a motor-vehicle/bicycle accident when compared to a two-lane road with four-way stop intersections merely because of the motor vehicle operating speeds involved.

Notwithstanding the uncertainties summarized by Clarke and Tracy, significant trends or associations between roadway design, traffic volume, and the presence of cyclists factors may provide important clues. The data analysis presented in the following sections will highlight some of these trends.

3.2 Data Analysis

The data used in this analysis was generated by the Texas Department of Public Safety (TxDPS) and compiled by Dr. Ned Levine of the Houston-Galveston Area Council (H-GAC).[1] It includes 2,712 recorded bicycle accidents resulting in injuries or more than $1,000 in damage between the beginning of 1998 and the end of 2001 from the 13 counties (12,500 square miles) and over 5 million people represented by H-GAC. When possible, the statistics generated from this data are compared to those from the most recent comprehensive bicycle accident analysis in the United States by Hunter et al. (1990). A brief comment will follow each group of statistics regarding some of the confounding variables and/or limits of the analysis.

3.2.1 Severity of Accident for Cyclist

Fatal accidents accounted for 1.9 percent of all accidents and incapacitating injuries for 13.5 percent for known/recorded incidents. Using a nearly identical five-category ranking, Hunter et al. (1990) gave percentages of fatal accidents at 1.6 percent and serious (incapacitating) injuries—those where the cyclist were not simply able to walk or ride away—at 16.6 percent of total.

Comment: Fatalities form a reliable comparison, but differences in serious/incapacitating injury levels may be definitional. Both these percentages may be elevated because of underreporting in less serious or non-injury accidents.

3.2.2 Population Group

Rural areas accounted for 18.0 percent of all accidents and were responsible for 23.1 percent of fatal/incapacitating accidents. Towns over 250,000 residents were responsible for 57.3 percent and 47.0 percent of fatal/incapacitating accidents. Hunter et al. (1990) reported fatal/incapacitating accident contributions to be 21.8 percent in rural areas and 16.6 percent in areas of 100,000 plus people.

Comment: Rural areas are known to have high cyclist fatality percentages because of the higher motor vehicle speeds and the lack of bicycle facilities. A combination of high bicycle and motor vehicle volume is the most common cause for an increased number of accidents in more densely populated areas. Without data on bicycle volumes, a relative comparison of safety is not possible. Sampling techniques involved in the Hunter et al. (1990) report would cause some uncertainty in the comparison. For the urban comparisons, they gathered random samples of 500 accident records from small, medium, and large cities in each of the states surveyed, whereas the H-GAC data was not a random sample, but contained all accidents from TxDPS within H-GAC's borders. Furthermore, the difference in accident rates between the urban areas from the two sets of data is likely understated because Hunter et al. (1990) used a definition of *urban areas* as cities with 100,000 plus people compared to 250,000 plus people in H-GAC's study.

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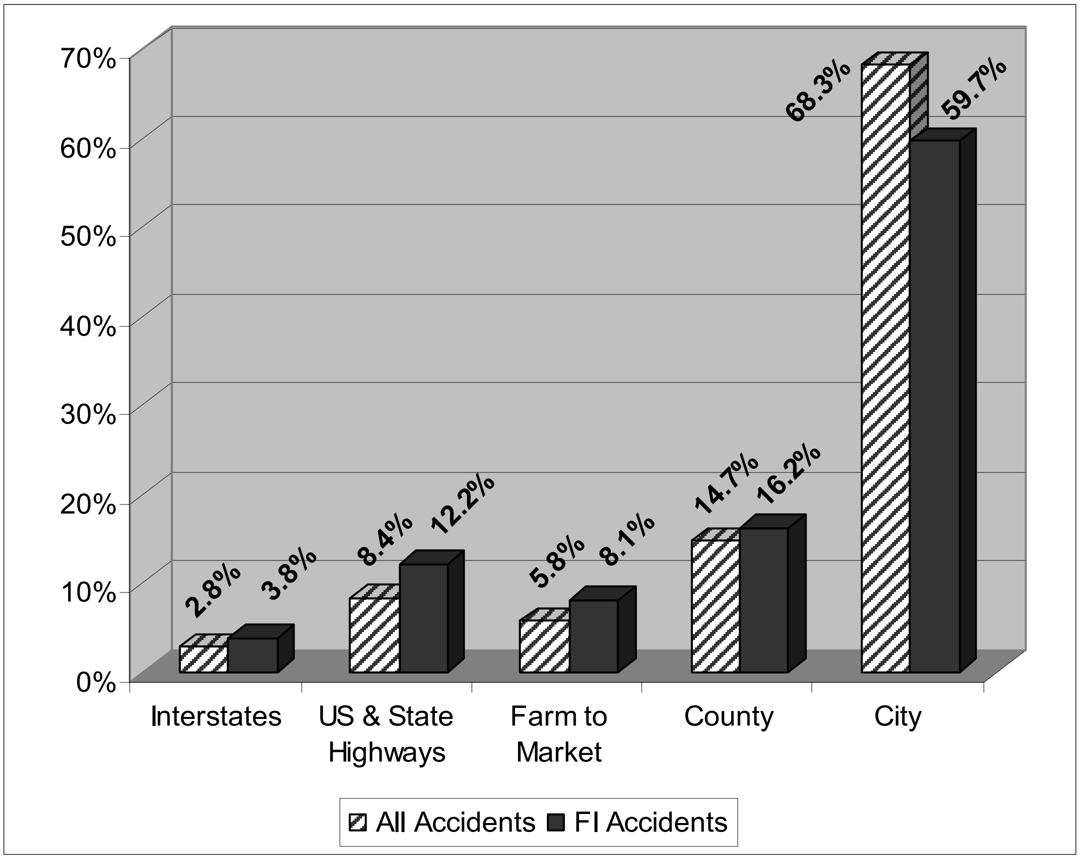
[1] The statements made in this document do not reflect the opinions or conclusions of Dr. Levine, H-GAC, or DPS.

3.2.3 Roadclass

Figure 3.1 presents the distribution of accidents and fatal/incapacitating (FI) accidents by roadway classification.



Note: "FI" refers to fatal/incapacitating accidents

Figure 3.1. Bicycle-car accidents by roadway classification in Houston-Galveston Area between 1998 and 2001

Comment: The relative quantities of each type of roadway classification and bicycle volumes (exposure) are needed to form conclusions about the relative safety considerations of each roadway classification. However, the speeds generally associated with each class of roadway seem to suggest that higher speeds produce a greater proportion of fatal/incapacitating accidents. Differences in road class definitions prevent comparison to the data of Hunter et al. (1990).

3.2.4 Month

The data exhibits above-average numbers of accidents in the months of April through October, excluding September. The proportion of fatal/incapacitating accidents, on the other hand, remained fairly constant across months. This pattern is consistent with Hunter et al. (1990).

Comment: These months are an excellent example of the bicycle volumes affecting the accident statistics as these months have been documented in other studies and Hunter et al. (1990) as having the highest numbers of cyclists.

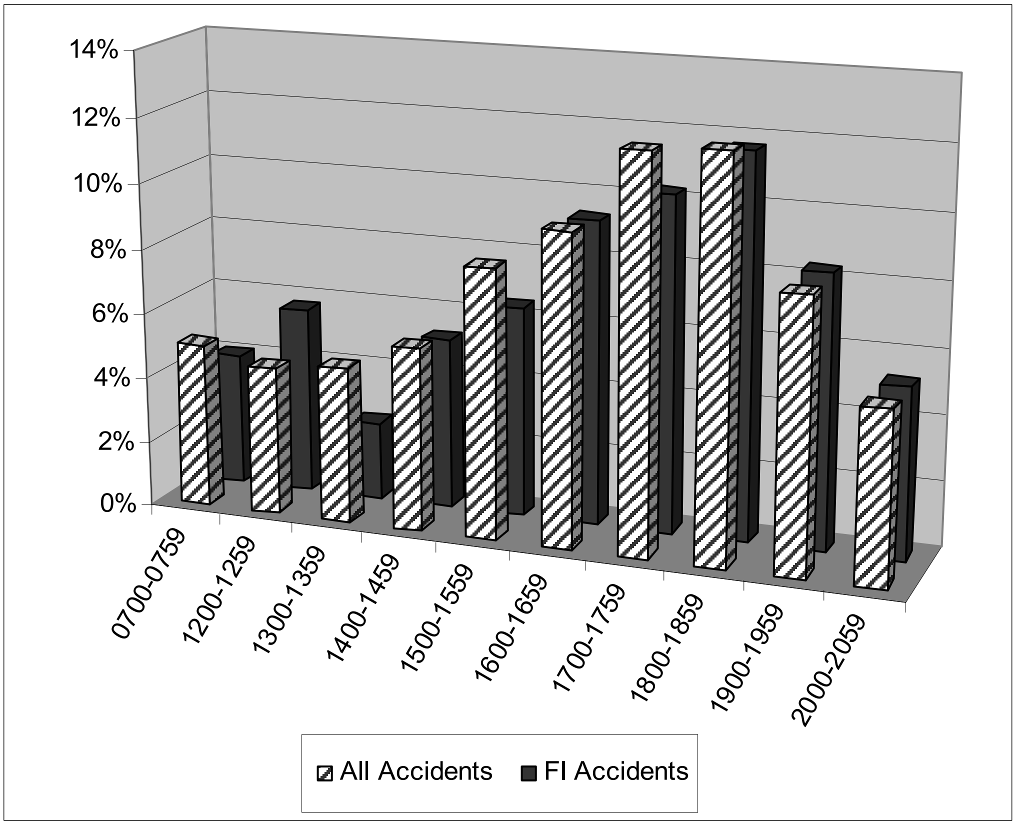
3.2.5 Day of the Week

The data exhibits above-average numbers of motor-vehicle/bicycle accidents during weekdays. fatal/incapacitating accidents as a proportion of total accidents were noticeably higher on the weekend than weekdays. For example, 10.8 percent of all accidents and 14.8 percent of all fatal/incapacitating accidents occur on Saturdays.

Comment: Bicycle accidents appear to be more severe on weekends, but the causes for this trend remain unknown. Possibilities include heightened substance abuse and increased nighttime operation on the part of both cyclists and motorists in the first hours of Saturday and Sunday.

3.2.6 Time

If accidents were distributed equally among all 24 hours of the day, then 4.2 percent of all accidents and fatal/incapacitating accidents should be observed each hour. The hours with an average or above average percentage of accidents can be found in Figure 3.2. The H-GAC data displays a greater number of accidents spread more evenly throughout the daylight hours with fewer accidents at night when compared to Hunter et al. (1991).



Note: "FI" refers to fatal/incapacitating accidents

Figure 3.2. Percent of total accidents by time of day (24-hour time format) for hours with average or above average rates from the Houston-Galveston Area between 1998 and 2001 (hours with lower-than-average accident rates not shown)

Comment: Distribution of accidents over time is another excellent example of how bicycle and motor vehicle volumes affect the data. However, there is no way to determine the contribution of each without data on both volumes. A peculiar trend occurs between 1200 and 1359 (12:00 a.m. and 1:59 a.m.). In the first hour of this period, percent of fatal/incapacitating accidents is relatively greater than the percent of all accidents and then is relatively fewer in the following hour. There are no obvious explanations for this pattern. Lastly, the hours listed here account for a below average percentage of fatal/incapacitating accidents. This means that the hours not referenced in Figure 3.2, mainly from 2300–0659 (11:00 p.m.–6:59 a.m.), witness above average fatal/incapacitating accidents. Light conditions (see following category) and substance abuse may be responsible for this observation.

3.2.7 Light Conditions

Daylight conditions witnessed 73.7 percent of all accidents, but only 65.1 percent of fatal/incapacitating accidents. Dark conditions with no artificial lighting contributed 7.2 percent of all accidents and 12.2 percent of all fatal/incapacitating accidents. The rest occurred in dark conditions with artificial lighting. Similar results for all accident statistics were found by Hunter et al. (1990).

Comment: These observations reinforce trends seen in the distribution of accidents over a 24-hour period given earlier; in general, accidents at night are more likely to be fatal.

3.2.8 Weather

Almost all accidents occurred in clear conditions (95.7 percent), but an even greater percentage of fatal/incapacitating accidents occurred during this period (96.2 percent). Surprisingly, sleet contributed to one accident, which was only one less than the number of accidents recorded in foggy conditions. Not surprisingly for the Houston-Galveston Area, snow was not associated with any accidents. Despite the fact that the Hunter et al. (1990) data was drawn from a wider geographical area, including states that regularly have snow, their results were very similar.

Comment: The confounding factor in this analysis is the relative occurrence of the different weather types. However, the data does suggest that inclement weather conditions significantly depress bicycle volumes. This has been shown explicitly in many other studies.

3.2.9 Surface Conditions

Defective shoulders were implicated in 6.8 percent of all accidents, but only 5.7 percent of all fatal/incapacitating accidents. It should be noted that this condition was the only one noted of nine possibilities; all other accidents occurred under conditions of no defects. Hunter et al. (1990) reported only 0.4 percent of accidents due to defective shoulders and had observations on four other conditions. The percentage of accidents in conditions of no defects was similar.

Comment: This variable is highly subject to the judgment and application of the officer reporting the event. The fact that Hunter et al. (1990) have observations on surface defects other than defective shoulders suggests that the contribution of these other defects in the DPS data is more likely unknown than absent.

3.2.10 Alignment

Almost all accidents occurred on straight, level sections (98.5 percent) with a fraction on level curves (1.5 percent) and a smaller fraction on straight hillcrests (0.04 percent). However, the level curves were responsible for 2.6 percent of all fatal/incapacitating accidents. The results were significantly different than those reported in Hunger et al. (1990).

Comments: The difference in results between Hunter et al. and the Texas Department of Public Safety's (TxDPS) data is surely a result of the wider geographical scope of the former study. The TxDPS data used in H-GAC's study presents a more localized geographic area providing an excellent example of how the distribution of roadway characteristics can confound bicycle accident analysis. The vertical and horizontal alignments (curves and straight sections) of the roadways in the H-GAC data are not comparable to those roads in the Hunter et al. (1990) study because of a lack of data on these characteristics. The comparison is further complicated by the uncertainty in bicycle volumes on each of the roadway sections.

3.2.11 Traffic Control Device Present

Approximately a quarter of all accidents (23.5 percent) were associated with a stop sign while 15.6 percent were associated with a traffic signal and 16.4 percent with no traffic control device. The remaining accidents were associated with traffic control devices that were not a stop sign or a traffic light. The contribution of each of these to fatal/incapacitating accidents was less than their contributions to all accidents. Hunter et al. (1990) reported nearly identical results.

Comments: This example again highlights the uncertainty introduced by the distribution of roadway and traffic factors. Certainly, the relative abundance of stop signs to traffic lights is contributing to these results, but to what degree is unknown.

3.2.12 Intersections

Approximately a third of all accidents (33.4 percent) occur at intersections while 18.1 percent are intersection-related. Of the 31.5 percent unaffected by an intersection, a significant percent of these accidents (17.0 percent) occur at a driveway access point. The classification of the remaining accidents is unknown. Hunter et al. (1990) report similar numbers for driveway accidents, but indicates that 46.8 percent of accidents occur at intersections while only 3.6 percent are intersection-related.

Comments: The difference in results between the two data sets is likely related to definitions of intersection and intersection-related accidents since the addition of intersection and intersection-related are similar for both data sets. Despite the confounding factors of intersection/driveway distribution and the lack of bicycle volume data, driveways appear to have an effect on cyclist safety.

3.2.13 Intersection Type

T-intersections witnessed 15.3 percent of all accidents while Y-intersections witnessed less than one percent. Four-way intersections accounted for 35.7 percent. These four-way intersections accounted for only 28.2 percent of all fatal/incapacitating accidents. Comparison with Hunter et al. (1990) was not possible.

Comments: Again, the frequency of these different types of intersections is a confounding factor in the analysis of bicycle/motor vehicle accidents.

3.2.14 Movement of Vehicle

The majority of all accidents occurred with the motor vehicle proceeding straight (76.11 percent) while left and right turns contributed 9.96 percent and 11.43 percent, respectively. Backing up accounted for 1.59 percent of all accidents. Motor vehicles proceeding straight contributed to 85.92 percent of all fatal/incapacitating accidents while left and right turns contributed 8.11 percent and 5.01 percent, respectively. The categorization of motor vehicle movements in Hunter et al. (1990) does not provide for comparison.

Comments: These statistics likely show the potential contribution of speed to severity of accidents. A motor vehicle traveling in a straight line would most likely be traveling at a relatively higher rate of speed than a vehicle making a left turn, and both of these vehicles would likely be traveling faster than a right-turning vehicle because of the small turning radius associated with this action. However, the analysis is complicated by the lack of data on the frequency of bicycle interactions with cars traveling straight versus cars making a turn. The former is likely to be significantly more frequent than the latter.

3.2.15 Other Factors

More than 50 other factors were available in the accident descriptions, but only 32 were actually observed. Furthermore, only two factors—turns into a driveway and turns out of a driveway—contributed a noteworthy number of accidents at 2.40 percent and 8.15 percent of all accidents, respectively. Hunter et al. (1990) had similar results.

Comments: This data reinforces the hazards to cyclists from vehicles entering or exiting driveways.

3.2.16 Part of Roadway Involved

As expected, 70 percent of accidents occur in through lanes. Another 27.13 percent of accidents were not coded. The only other significant contributor to this category was frontage roads, which had 3.25 percent of all accidents with 4.32 percent of all fatal/incapacitating accidents. Hunter et al. (1990) do not list data on this topic.

Comments: Frontage roads appear to be more dangerous based on their disproportionate contribution to fatal/incapacitating accidents. Casual observation suggests that bicycle volume on them is extremely low. This might suggest that the crash statistics associated with them are quite severe, but without the data on bicycle volume, a firm conclusion about their relative safety cannot be reached.

3.2.17 Number of Vehicles Involved

Nearly all accidents with cyclists involve only one vehicle (98.38 percent), but there are also accidents involving a cyclist and two cars (1.55 percent). Hunter et al. (1990) do not list data related to this topic.

Comments: This data would be more informative if there were a way to know whether the accidents involving two cars occurred first between the two cars and subsequently involved a cyclist. This would suggest that cyclists should definitively avoid areas experiencing large numbers of motor vehicle accidents. However, since the second car may have been involved as a result of a motorist/cyclist accident, no firm inferences can be drawn from the data.

3.2.18 Vehicle Type

Just over 5 percent of the accidents were not coded for vehicle type. For the accidents that were thus coded, the breakdown was as follows: passenger cars (55.46 percent of all accidents, 49.64 percent of all fatal/incapacitating accidents), trucks (36.76 percent, 40.57 percent), semi-trailers (0.33 percent, 0.72 percent), and buses (0.66 percent, 0.72 percent). SUVs were included in the truck category. Hunter et al. (1990) give significantly different numbers with passenger cars involved in 70.8 percent of all accidents while vans and pick-ups only accounted for 20.1 percent. This could be a result of the assignment of SUVs to different categories, an increase in the percentage of SUVs in total vehicle fleet over time, or, perhaps, a greater prevalence of four-wheel trucks in Texas. In Hunter et al. (1990), semi-trailers and buses account for 1.3 percent and 0.8 percent of all accidents, respectively. In the case of semi-trailers, the figure is significantly higher than that of Texas.

Comments: As expected, deaths are more likely when a truck is involved compared to a passenger vehicle, and these deaths are likely due to differences in size of the two types of vehicles. Similarly, accidents with buses and semi-trailers may be rare, but the cyclist is much more likely to die (semi-trailers account for two times as many fatal/incapacitating accidents as they do all accidents). However, the relative risk of an accident with each type of vehicle, especially buses and semi-trailers, is confounded by the inability to know the composition of the vehicles in the traffic streams in which cyclists generally travel.

3.3 Observations from the National Bicycle Crash Data Set

Hunter et al. (1990) make some observations from their data that were not possible to duplicate with the H-GAC data, but are of interest to this study. All comments are based on 2,800-3,000 observations unless otherwise noted.

A bicycle lane was not present on the cyclist's side of the roadway in 97.2 percent of all accidents.

- A cyclist was in a bicycle lane when the accident occurred in only 2.2 percent of all accidents.
- A cyclist was in the through lane when the accident occurred in 68.2 percent of all accidents.
- Bike lane crashes tended to produce fewer than their share of fatal/incapacitating accidents.
- A cyclist involved in an accident while using a sidewalk composed 15.9 percent of all accidents while only 25.7 percent of all bicycle accident scenes actually had a sidewalk.

- Two motor vehicle lanes were present at 60.1 percent of all accident scenes while three lanes (presumably, two lanes with a center turn lane) were present in only 5.5 percent of all cases (2,474 observations).
- A median was not present at the scene of an accident in 98.3 percent of all cases (2,595 observations).
- A lane width of 9ft or less was implicated in 9.5 percent of all crashes, 10-11ft in 23.7 percent, 12ft in 23.5 percent, 13-14ft in 17.8 percent, and more than 14ft in 25.5 percent. With a standard road width recommendation of 12ft, the majority of accidents in terms of street width distribution should have occurred on these streets. Unfortunately, there are many other variables associated with street width like the presence of a bike route, design/travel speed, traffic composition, surrounding land use, and traffic volume.
- The cyclist was solely at fault in 49.8 percent of all accidents and at least partially responsible in 14.1 percent of all accidents. Motorists were solely at fault in only 27.2 percent of all accidents.

3.4 Discussion

The results from Hunter et al. (1990) and DPS/H-GAC suggest that roadway design and motor vehicle traffic factors have an influence on bicycle safety. The most notable factors appear to be presence/absence of a median, presence/absence of a bicycle lane, traffic volume, and density of intersections and access points. This conclusion is consistent with factors under study in this research project. The relative contribution of each to bicycle safety cannot be determined without knowing its distribution in the transportation network or the number of cyclists that encounter each factor during their trip. However, cyclists are solely at fault in an accident half of the time. This suggests that the installation of facilities that encourage proper bicycle operation in traffic and the education of cyclists about proper operating procedures can potentially significantly increase cyclist safety regardless of changes made to other design elements.

4. Field Observations of Motorist and Cyclist Position on Shared-Use Bicycle Facilities

4.1 Introduction

The objective of gathering field observations was to note the lateral positions of motorists and cyclists on a roadway as measured from the face of curb and to relate these positions to the geometric and traffic characteristics of the roadway. The observations were undertaken in two distinct situations: 1) when a vehicle was passing a cyclist and was immediately adjacent to the cyclist, hereafter referred to as a "passing event" and 2) when a vehicle was within the test segment and the motorist was determined to be uninfluenced by the presence of a cyclist, hereafter referred to as a "non-passing event." Accomplishing the objective of this study required thousands of observations at a variety of test sites and the formation of sophisticated multivariate regression models. The methods used to gather and analyze the observations are outlined in the following sections.

4.2 Site Selection

Bicycle facility retrofits exist mostly, if not entirely, in large metropolitan areas. For this reason, the 24 sites selected for this study were from three of the largest cities in Texas: Austin (9 sites), Houston (9 sites), and San Antonio (6 sites). These sites included roadways that were retrofitted to include designated bike lanes and wider outside lanes that have been signed as bike routes. Bicycle facility retrofits most often result in compromising the width of the roadway medians, motor vehicle lane widths, and bicycle facility widths (wide outside lanes and designated bicycle lanes). The site selection focused on representing a significant variation to consider these factors. Several sites were found to be asymmetrical with respect to motor vehicle lane widths and bike facility widths, which effectively increased the number of sites studied in the research. The segments of roadway studied, which were approximately 500 feet in length, had no vertical grades, horizontal curves, or influences from traffic control devices along the segment (motorists and cyclists traveled at free flow speeds). Visiting the sites at different times of the day produced variations in motor vehicle and truck traffic volume. Table 4.1 presents the range of roadway and traffic characteristics exhibited by the test sites. A list of the sites with their relevant characteristics can be found in Appendix A.

Table 4.1. Range values for site characteristics

Variable	Range
Motor Vehicle Lane Width (excluding wide outside lanes)	9.3–14.6 ft
Wide Outside Lanes (designated)	13.7–19.5 ft
Bike Lane Width	3.7–5.9 ft
Adjacent Space Type	• lane with opposing traffic • lane with same-direction traffic • two-way left-turn lane (TWLTL)
Traffic Volume	28–887 vehicles per hour
Percent Truck Traffic	0.0–16.2%
Average Observed Speed	27.1–48.7 mph

4.3 Field Data Collection

Each day, two paid cyclists accompanied the researchers to the test sites. The cyclists included males and females between the ages of 18 and 54 with varying levels of cycling experience. At each site, two video cameras were placed in opposing directions to capture the actions and reactions of bicyclists and motorists. The cyclists rode in a loop for 30 minutes at each test site, but avoided cycling simultaneously on the same side of the street. If one cyclist crossed the street early, he or she would wait for the other cyclist to finish the segment and cross to the other side before continuing to ride. The only other directions given to the cyclists were to ride on the right-hand side of the road and obey all traffic laws when crossing the street. Cyclists received a copy of the State of Texas bicycle statutes to ensure that their movements were in compliance with the law. Neither the researchers nor the Texas statutes indicated how close to the face of curb a cyclist should travel. Each cyclist participated in the study for only 1 day and in only own metropolitan area, visiting between 6 and 8 test sites and riding for 30 minutes continuously at each. A total of 30 paid cyclists were involved in the study (two cyclists each day for five days of field observations in each of the three metropolitan areas).

One video camera on each side of the road collected observations of both motorists and cyclists. The position of the cameras was approximately 150 feet downstream of the test sites. Motorists were unaware of the camera at distances greater than 150 feet because of the extremely small profile of the 8mm video camera and its tripod. The cameras captured images between approximately 225 feet and 375 feet away, ensuring that the motorist arrived after the cyclist established a position on the road and before the motorist discovered the camera. Camera operations on the other side of the road did not appear to distract the drivers, and the camera attendants hid themselves from sight. Attendants also gathered half-hour traffic counts for the curb lane on each side of the road.

4.4 Data Reduction

The field research generated approximately 60 half-hour video segments, each of which corresponded to the camera view on one side of the road during one site visit. Data generated from the video involved both passing events and non-passing events. The video analysis included three measures of motorist and cyclist position. Two were continuous variables, and one was a binary response variable (see following subsections). The recording of all observations also indicated whether the motor vehicle involved was a "truck" (any vehicle or vehicle towing a trailer that was wider than a sedan, pick-up, SUV, or passenger van). This did not include dual pick-ups (*duallies*), but included buses, semis, delivery trucks, and trucks with standard cabs and utility payloads. The observations did not include motorcycles.

The continuous variables had to be scaled from the television screen to produce actual measurements observed in the field. The scalar used was either the width of the bicycle lane or, if the bicycle facility was a wide outside lane, the width of the curb lane, both of which were known from measurements made in the field. Measurements from both the field and television screen were taken from the curb face to the outside edge of the appropriate lane stripe. For each video segment, a 1 PT. graphic art tape was applied to the television screen to mark each of these limits to ensure consistent measurements in the data reduction process. For every measurement taken on the screen with a ruler, the width of the bike lane or curb lane was noted at the same vertical level on the screen in order to apply the correct scalar to the data. Each of the data points taken from the video tapes is listed here along with a description of how it was collected.

4.4.1 Lateral Position of Bicyclist (LPB)

This variable is the distance in feet along the surface of the pavement between the cyclist's front wheel and the face of curb during a passing event. Aligning the cyclist's front tire with both of the motorist's front wheels at their respective points of contact with the pavement ensured that two vehicles were even at the moment of measurement. In particular, aligning the ruler with the contact points of both the motorist's front wheels and extending it across the screen ensured that the scalar was measured at the correct level and angle on the screen. Excluded were observations of cyclist position influenced by abnormalities in the environment such as mud puddles or other debris in the bikeway.

4.4.2 Lateral Position of the Motorist (LPM)

This variable is the distance along the surface of the pavement between the face of curb and the motorist's front wheel on the passenger side. The distance, in feet, was measured for one of two distinct moments: during a passing event at the same time the LPB was measured or during a non-passing event. In the former case, the measurement was taken according to the method developed for LPB. The latter case had a more complicated method.

A non-passing event was declared when a motorist approached the camera without first passing a cyclist nor shortly after a cyclist had passed the camera itself because, in this latter case, the motorist would be reacting to the cyclist even though the cyclist could not be seen by the camera. Despite the cyclists maintaining alternate sides of the streets, non-passing events could be captured when one of them was waiting for a break in traffic to cross. The periods of time when the cameras were running just before and after the cyclists began their laps also provided observations of a motorist's position not influenced by the presence of a cyclist, but could still be considered as having traffic conditions equal to those of the passing event observations. In all cases, the bicycle/motor-vehicle measurements were taken only when the entire front of the car was visible. This ensured that the ruler would be placed at the appropriate angle on the television screen by aligning it with the two front wheels, and the right scalar would be applied. It also ensured that the vehicle's position would not be influenced by downstream motorists: when in a tight platoon of cars, motorists tend to either follow in the path of the vehicle in front of them or drive so they are able to see around these vehicles. Observations were gathered until 95 percent of motorists were within three standard deviations of the iterative mean for the tape segment, but no less than twenty observations were gathered in any case. If the desired number of observations could not be gathered in the complete absence of cyclists, a slightly laxer standard was used. These observations could include moments when the cyclist was in the extreme foreground and the motorist in the extreme background of the camera's field of vision or vice versa.

The observations of the lateral position of motorists during passing events and in the absence of cyclists were used to form a measure of the change in lateral position of the motorist (CLP), a proxy for the average amount a motorist swerves to pass a cyclist sharing the roadway. This measure required the formation of a proxy because the camera view was not long enough to capture both the position of a motorist before or after a passing event and the passing event itself. Thus, motorists measured for each of the two conditions formed two mutually exclusive groups.

4.4.3 Encroachments (ENC)

This was a yes/no response to the question of whether or not the motorist's wheels crossed onto or over the inside curb lane stripe at any point during a passing event. This observation was gathered in the cueing of the correct video frame to make the measurements of LPB and LPM during a passing event. It was the result of observing several seconds of film rather than any one particular frame, especially when the inside curb lane stripe was dashed (as in four-lane cross sections). The observations excluded motorists who moved to an inside lane on four-lane roads to pass the cyclist, which was a regular occurrence.

4.5 Analysis

The analysis examined the contribution of several geometric and traffic characteristics (independent variables) to each of the dependent variables: lateral position of the bicyclist, change in lateral position of the motorist, and encroachment. The independent variables considered were:

Presence/absence of a bike lane

1. Bike lane width (if present)
2. Motor vehicle lane width
3. Total lane width: if bike lane present, the sum of bike lane width, motor vehicle lane width, and width of the stripe dividing the bike lane from the motor vehicle lane; if wide outside lane designated as a bicycle facility, total lane width equaled motor vehicle lane width

4. Presence/absence of lane with opposing traffic
5. Presence/absence of lane with same-direction traffic
6. Presence/absence of two-way, left-turn lane (TWLTL)
7. Hourly volume of all vehicles in the curb lane*
8. Hourly volume of trucks in the curb lane*
9. Truck percentage of total vehicle volume in curb lane*
10. Hourly volume of vehicles per hour in the adjacent motor vehicle lane (zero if two-way left-turn lane; equal to the figure for item 8 of this list if lane carries same-direction traffic, and also for the other side of the road if lane carries opposing traffic)*
11. Average observed speed
12. Presence/absence of residential development (traffic less than 150 vehicles per hour and all roadside buildings are residential dwellings)
13. Cyclist was/was not a "casual recreationalist" (at least 70 percent of cycling trips made for recreation and exercise)

* *Values generated from the half-hour session in which the observation occurred.*

Separate regression models used these independent variables to explain the variation witnessed in each of the dependent variables. Random effects were incorporated into these models to account for test site or cyclist specific influences. After generating several variations of each model, variables with coefficient estimates where $p>.05$ were eliminated. The p-value indicates the probability that the coefficient estimate generated is the result of random variation. An exception to this process was the generation of regression models for the lateral position of motorists during the passing event and in the absence of cyclists. In this case, researchers wished to generate two explanatory models with the same independent variables so that the change in lateral position (CLP) of the motorists could be described using the same characteristics. (CLP is a measure of how much motorists are expected to swerve.) The results for each model are located in the following subsections.

4.5.1 Lateral Position of the Bicyclist (LPB)

The only variables found to have a statistically reliable effect on the lateral position of the bicyclist were the presence of residential development, whether cyclist was a casual recreationalist, the presence of a bike lane, and the width of the bike lane, if present. The magnitudes of these effects and their statistical significance in a model excluding variables with unreliable effects are given in Table 4.2.

Table 4.2. Multivariate regression results for LPB

Variable	Coefficient Estimate (ft)	*p*-value
Intercept	1.7	<0.01
Residential Development	0.5	<0.01
Casual Recreationalists	-0.3	<0.01
Presence of Bike Lane	-0.8	0.01
Bike Lane Width (if present)	0.3	<0.01

The bike lane widths examined in this study ranged from 3.8 to 5.9 feet, yielding a change in LPB between 0.3 to 1.0 feet (a synthesis of the estimates in the last two rows of Table 4.2).

4.5.2 Lateral Position of the Motorist (LPM)

Some roadway and traffic variables have a clear effect on the lateral position of the motorist during both passing and non-passing events. However, several variables are only statistically significant in one of these cases. One regression model may include a variable that is statistically insignificant if it is significant in the other in order to maintain the same independent variables among the two events and to ultimately generate a measure for the change in lateral position of the motorist. CLP represents the change in the predicted position of non-passing events at a site to the predicted position during a passing event at the same site. For the variables that meet this criteria, the regression results are shown in Table 4.3.

Table 4.3. Multivariate regression results for LPM

	Non-Passing Events		Passing Events	
Variable	Coefficient Estimate (ft)	*p*-value	Coefficient Estimate (ft)	*p*-value
Intercept	-5.7	<0.01	1.7	0.14
LPB	N/A	N/A	0.5	<0.01
Residential Development	0.5	0.19	0.9	<0.01
Presence of Bike Lane	-0.9	0.33	-2.6	<0.01
Bike Lane Width (if present)	0.3	0.11	0.4	<0.01
Total Lane Width	0.8	<0.01	0.4	<0.01
Adjacent Space Is Lane with Opposing Traffic	-1.0	<0.01	-0.4	0.07
Percentage of Trucks	0.02	0.10	0.03	<0.01

4.5.3 Encroachments (ENC)

A logistic regression model was used to predict the probability of a motorist encroaching on an adjacent motor vehicle lane to move away from a cyclist. Table 4.4 presents the changes to the log-likelihood of an encroachment resulting from a one unit increase in a given variable determined to be statistically significant. Estimates of these changes do not have a convenient interpretation, but their magnitude and sign give an indication of the effect and importance of each roadway and traffic characteristic.

Table 4.4. Multivariate regression results for ENC

Variable	**Coefficient Estimate (log-likelihood)**	***p*-value**
Intercept	5.1	0.01
LPB	0.4	<0.01
CR	-0.5	0.01
Bike Lane Presence	-4.2	<0.01
Bike Lane Width (if present)	0.6	0.03
Total Lane Width	-0.3	<0.01
Adjacent Space Is Two-Way Left-Turn Lane	1.0	0.02
Percentage of Trucks	0.1	<0.01

It should be noted that the probability of encroachment for nearly any road, even the most ample ones, will be around 50 percent or more. This observation is the result of the definition of an encroachment—both driver-side wheels of a vehicle making any contact with the inside adjacent curb lane stripe—which creates a very low threshold for the occurrence of this behavior. For this reason, this measure functions better as a relative value than an absolute indication of the suitability for motorists of a particular roadway with cyclists. Considering the encroachment in conjunction with the change in lateral position (CLP) of the motorist is needed to evaluate this subject. In general, when a larger CLP value is observed in combination with a high probability of ENC, the results tend to indicate that the encroachment was significant in contrast to an incident where two wheels briefly skim the adjacent lane line.

4.6 Discussion

The multivariate regression models identify the major determinants, and their effects on, the lateral placement of both motorists and cyclists when the two share the same roadway. Cyclist position on the roadway is most influenced by the presence or absence of a designated bike lane, the width of the bike lane if present, and the experience level of the cyclist.

During non-passing events, motorists are most affected by the total outside width and the type of vehicular traffic in the adjacent space, which is well documented in traffic engineering literature. Once a cyclist is added to the scenario, these same factors are important, but to them are added the lateral position of the cyclist, the type and characteristics of the bike facility present, and the type of roadside development. Since a motorist cannot encroach without a change in lateral position, it is not surprising that this behavior is tied to the same geometric and traffic characteristics.

Because it is not desirable for a motor vehicle to leave its intended lane of travel, the probability of an encroachment has obvious implications for the operational level of a roadway in accommodating both motorists and cyclists. However, the other measures in this study—lateral position of the bicyclist and the change in the lateral position of the motorist—do not generate such direct conclusions about the performance of a roadway. The conclusions developed in this study stem from two assumptions about the meaning of motorist and cyclist position on the roadway:

Assumption 1: Cyclists move laterally away from objects that cause discomfort or are considered to be dangerous. In this way, lateral position can indicate the comfort level of a cyclist, which also determines the suitability, or operational level, of a shared roadway.

Assumption 2: Motorists place themselves on a roadway in a lateral position that provides the greatest comfort and operational level. Temporary deviations from this path that can be attributed to the presence of an object or situation— in this case, a cyclist— indicate a reduction in the level of comfort and operational level caused by it. The magnitude of the deviation indicates the magnitude of this reduction.

With these assumptions and the results of the multivariate regression models, several important conclusions can be developed from the field observations of cyclists and motorists in this study.

1) Designated bike lanes of four feet or more are operationally superior to wide outside lanes for both cyclists and motorists.

On a nonresidential street without a bike lane, the cyclist's wheels (the center of the bike) are only 1.7 feet from the curb face based on the regression model described in Section 4.5.1. The operating space of a cyclist is 3.3 feet (AASHTO 1999), which includes 2.5 feet for the width of the bicycle and about a foot for the meandering that naturally occurs during cycling. Half of this distance is slightly less than 1.7 feet. Thus, the cyclist is riding at the immediate edge of his/her operating space and is in danger of contacting a roadside object with the handlebars or pedals, which could easily result in loss of control and greater harm. A casual recreational cyclist is predicted to ride even closer to the curb. However, this may physically be impossible, and anecdotal observations from the field indicate that these riders would either be on the sidewalk next to the road or absent from the roadway altogether. An exception to this case develops in residential areas, where significantly lower traffic levels and roadside activity seem to increase the comfort of cyclists and allow them to ride a half-foot farther from the curb, providing a reasonable buffer for the cyclists from roadside objects regardless of the type of bike facility.

In the case of the motorist, the change in lateral position and probability of an encroachment is much higher on a roadway without a bike lane, even when total outside width is held constant. For example, adding a 4-foot-wide bike lane to a 25-foot-wide curb lane without any additional width added to the road will decrease CLP by 1.3 feet. This decrease in CLP coincides with a decline of nearly 20 percent in the probability of encroachment in the same scenario. Thus, cyclists ride as close as possible to the face of curb or outside edge of the road, and motorists swerve and encroach significantly to avoid the cyclist on a street without a bike lane. This indicates a high level of discomfort for both motorists and cyclists and puts both in more dangerous situations, each of which decreases the operational level of the roadway.

2) The type of space adjacent to the outside curb lane significantly affects the behavior of a motorist during a passing event.

In the results of the regression model regarding the lateral position of the motorist (Table 4.3), the presence of an adjacent lane with opposing traffic has a significant effect. This type of adjacent lane causes an increase of 0.6 feet in the change in lateral position of the motorist (lateral position of motorist during passing events minus that of non-passing events). The greater change in lateral position reflects a non-passing position of the motorist closer to the curb in order to minimize the possibility of contact with oncoming traffic. Thus, a greater lateral movement is needed by the motorist to create a comfortable buffer from the cyclist when compared to situations where there is either a TWLTL or a lane with same-direction traffic. This passing event places the motorist closer than desirable to oncoming traffic. Motorists tend to travel towards the inside of their lane: 1) when next to a TWLTL because it is most often empty and 2) when next to a same-direction lane because it does not present the same danger as an opposing traffic lane. Already near the inside of the lane, the passing event does not place the motorist far from his/her intended path of greatest comfort and results in a lower value for CLP, which can be interpreted as a higher level of comfort and operational performance. The small effects of TWLTL and same-direction lanes on CLP resulted in statistically insignificant coefficients and their elimination from the final regression model.

On the other hand, the presence of a TWLTL is the most significant contributor to an increase in the probability of an encroachment. Even on roads with motor vehicles lanes 12-feet wide and bike lanes 5-feet wide, the probability of an encroachment on roads with a TWLTL was upwards of 70 percent. This appears related to the relatively high availability of this lane compared to a through lane for encroachments. The decision of a motorist to encroach on this space also appears to be relatively simple, because there should not be a motorist traveling alongside another in this area and the TWLTL can be easily monitored for oncoming motorists while maintaining visual contact with the cyclist to be passed. For this reason, and unlike the case of higher encroachments with a bike lane absent, it is not necessarily appropriate to evaluate a high encroachment probability on roads with a TWLTL next to the curb lane as having a lesser operational or comfort level. Anecdotal observations from the field did not reveal any conflicts associated with this higher rate of encroachment and one site with a very constrained total outside width generated not atypical passing clearances and lateral placement of cyclists because of the TWLTL. Curb lanes with an opposing or same-direction traffic stream adjacent had significantly lower encroachment rates, because there is little time in these cases where motorists do not run a high risk of contact. On two lane roads, vehicles approach each other too fast to encroach without a possibility of collision. On four-lane roads, adjacent vehicles travel at roughly the same speed and must make significant adjustments to their speed in order to encroach into the adjacent lane without a collision. The unique behavior of motorists on curb lanes next to a TWLTL means that comparisons of CLP and ENC at these sites to those without a TWLTL may not be useful. However, comparisons of CLP and ENC on streets with the same-lane configuration are immediately applicable.

> ***3) Residential areas—those areas with less than 150 vehicles per hour in the curb lane and only residential dwellings—witness differences in motorist and cyclist placement on the road compared to all other areas.***

In a residential area, cyclists ride 0.5 feet farther from the curb face regardless of the bike facility type that is present, and motorists swerve 0.4 feet more even when holding the position of the cyclist constant. In the case of the cyclist, the observation surely reflects a greater comfort level resulting from reduced traffic volume, reduced traffic speed, and reduced activity along the roadside. The increased swerving, or change in lateral position of the motorist, is likely not a reflection of reduced operational or comfort level, but actually the opposite, as extremely low volume levels and reduced activity in the area allow motorists to offer cyclists more room out of courtesy. Most importantly, the results indicate that bike facility and roadway designs and guidelines for residential areas may be different than roadways with higher traffic volumes and speeds and where the adjacent land is mixed-use.

5. Alternative Pavement Treatment

5.1 Introduction

This part of the field research addressed the effect of an 8-inch stripes separating the bike lane from the curb lane on the same dependent variables examined in Chapter 4: lateral position of the bicyclist; change in lateral position of the motorist; and probability of encroachment. Most cities use a 4-inch stripe for this purpose, which is minimum width according to AASHTO (1990). However, other cities use either a 6-inch or, as in Houston, an 8-inch stripe.

5.2 Methods

Three previously studied sites in Austin with bike lanes and fairly narrow curb-to-curb widths—Oltorf Street, North Loop Boulevard, and Hancock Drive—served as test sites. Four-inch, foil-back, temporary pavement tape was applied immediately next to and parallel with the existing painted bike lane stripe, except at one site where faded paint required the application of two vertically contiguous lines to create the appearance of an 8-inch bike lane stripe. The lines were laid between breaks in the pre-existing painted lane lines to avoid an immediately obvious transition from 4-inch lane lines to 8-inch lane lines. This resulted in the application of 0.25 to 0.5 miles of tape in each direction at each site. To isolate the impact of the 4-inch loss of space to either the motor vehicle or the bike lane, the tape was applied to the inside of the original stripe on one side of the street and to the outside of the line on the other. Appropriate corrections were made to the curb lane and bike lane width data for this variation on the otherwise symmetrical street segment. The testing employed the same method of gathering field observations as the previous section. However, the observations included only seven riders who rode at the site under observation both before the installation of the wider stripes and afterwards for analysis.

5.3 Analysis and Discussion

Observations of passing events originated from the seven cyclists riding at each of the three test sites before and after the application of the 8-inch stripes and numbered 532 in total. A dummy variable for the presence of 8-inch stripes at the test sites—zero for the time before their application and one thereafter—provided a statistical test for the effect of the wider lines using the same multivariate analysis from Chapter 4 minus the site- and cyclist-specific random effects. The LPB model yielded a coefficient estimate of -0.001 with a p-value of 0.99. The LPM model for passing events yielded a coefficient estimate of -0.24 with a p-value of 0.13. Lastly, the ENC model indicated a log-likelihood estimate of 0.20 with a p-value of 0.41. No analysis of LPM during non-passing events was undertaken because the coefficient for the 8-inch lines was statistically insignificant during passing events. The analysis did not reinsert random effects into the model because they would have further exacerbated the statistical unreliability of the results.

Houston currently uses the 8-inch bike lane stripe and the influence of this feature was also tested by adding a dummy variable to the data developed in the first set of field observations on the six sites in that city with bike lanes. The coefficient for this dummy variable failed to achieve statistical significance. The results of this analysis may require further studies based on the limited before-and-after comparisons suggesting that an 8-inch stripes may not have an effect on the lateral position of either cyclists or motorists.

However, the results do not suggest that 8-inch stripes have *no* effect on motorist or cyclist behavior, only that this study looked at the significance of lateral placement on the roadway. The stripes are significantly more noticeable and may serve to raise awareness of the probability that cyclists may be present and to warn motorists to watch cyclists on these roads. The wider stripe may also help prevent motorists from mistaking the bike lane as an additional motor vehicle lane, especially as the bike lane approaches 6 feet of width or more. Effects related to 8-inch and 4-inch stripes would have to be identified with a survey or other types of research methodology.

6. Conclusion

6.1 Goals of Research

The Texas Department of Transportation (TxDOT) has experienced an expanded role in approving bicycle facilities proposed by local government entities as they seek federal funding from several programs administered by TxDOT such as the Statewide Transportation Enhancement, Congestion Mitigation and Air Quality, and Safe Routes to School programs for which the state has oversight. An increasing number of bicycle facilities are being planned to provide alternative modes of transport and as mitigation projects in air-quality non-attainment regions, which are characterized by highly developed, urbanized environments where expansion of the street right-of-way to incorporate bicycle facilities is difficult. These conditions prompted TxDOT to search for clear guidelines on the acceptability of bicycle retrofit designs. Such guidelines should ideally address both the safety and operational impacts of a design for both cyclists and motorists. In the event that no acceptable design could be chosen for a given roadway, there was also a desire for a mechanism to choose alternate locations for a bicycle facility among a set of streets in a corridor.

Video documentation of several thousand passing events illustrated the effects of roadway and traffic characteristics on existing retrofit bicycle facilities and the facilities' performance for both cyclists and motorists. The change in lateral position of the motorist and encroachment rate allowed conclusions to be made concerning comfort and operational level of varying roadway designs for these users. Statistical analysis demonstrated a clear response to particular geometric and traffic characteristics, including bicycle facility type. Similar observations were made for the lateral position of bicyclists thereby producing quantifiable results used to evaluate operational and comfort levels.

At the same time, many empirical limitations prevented the research from being as definitive and encompassing as originally desired. The effects of roadway design elements, such as motor vehicle lane width and median treatment on safety and operation, are often confounded with the effects of other variables. This generates a lack of consensus on the effects of changes to a roadway and makes the outcome of a bicycle retrofit in terms of motor vehicle capacity loss or accident rates difficult to predict. Adding to the difficulty of predicting the safety outcomes is a lack of data on the volume of bicycle trips. The field research methodology used for this study was not conducive to filling this gap. The field research generated valuable information on operational aspects of facilities for cyclists; however, this research did not identify specific responses to several variables, such as traffic volume and motor vehicle speed, which are found to affect cyclists in other investigations.

These difficulties prompted two general strategies in formulating the final product of this research, a guide for retrofitting bicycle facilities in Texas. The first strategy was to abandon a prescriptive tone to the guide and present the multivariate regression models based on the field research as predictive tools that would aid the decision making processes challenging designers, planners, and engineers considering on-street bikeways as part of the roadway plan. However, this decision was not just the result of research limitations. It was assumed to have several advantages: generating more transparent decision making, incorporating rather than excluding local knowledge, and avoiding resistance and mistrust among potential users of the guide. The second general strategy was to incorporate other research project results into the final guide to augment the conclusions of this research project.

6.2 Final Product

The final product of this research, the *Texas Guide for Retrofit and Planned Bicycle Facility Design*, allows the user to input basic roadway and traffic data into a Microsoft Excel workbook and generate two measures to identify the operational performance of an on-street bicycle facility. The first measure provides a rating from 1 to 6 of a cyclist's comfort level on a given roadway segment, as well as a descriptive label of the comfort rating. This comfort rating is based on a translation of Highway Capacity Manual methodologies to cycling. This set of measures came directly from Harkey et al.'s (1998) *Development of the Bicycle Compatibility Index: A Level of Service Concept*, which was based on rigorous statistical analysis of a video-based survey administered to hundreds of cyclists across the U.S. The second measure developed from this research project allows users to predict the physical location of both cyclists and motorists during passing events: the lateral position of the bicyclist, the change in the lateral position of the motorist, and the encroachment rate of the latter.

Each of the measures have strengths that compensate for the other's weaknesses, producing a stronger tool to aid TxDOT and others to evaluate both retrofit and planned bicycle facilities. The measures from the Bicycle Compatibility Index respond to minor variations in a large number of roadway and traffic variables but are based only on cyclist perceptions of these variables, which some transportation authorities view as too distorted. The measures developed in this study address both the cyclist and the motorist and indicate how each will physically respond to specific changes in roadway design. However, these observations of physical responses cannot convey all reactions to a given roadway; there is little a cyclist can change about his/her lateral placement to mitigate increased motor vehicle volumes or observed speeds. For these situations, the results from the Bicycle Compatibility Index can indicate the effects on the cyclist's comfort level and whether or not a cyclist is likely to use the facility. The measures developed in the *Texas Guide for Retrofit and Planned Bicycle Facilities* determine the suitability of a bicycle facility, for both retrofitted and planned, for both the motorist and the cyclist. The results produced when using the Excel Workbook should be used in conjunction with local knowledge of the roadway and sound engineering judgment. The guide is presented as the next and final chapter of this report.

6.3 Future Research

The research in this study along with the studies reviewed or incorporated in this report did not address two particular areas of bicycle facility design: intersections and the influence of parking. A Bicycle Compatibility Index is currently being constructed for intersections, and the Bicycle and Pedestrian Subcommittee of the Transportation Research Board has called for more work on this topic. The results from such research should be combined with the guide in Chapter 7 to provide a more comprehensive guide to bicycle facility retrofits that address the entire length of a roadway. The research methodology for this project was not suitable to address parking issues, because parking-related factors would likely affect cyclist route choice rather than their lateral position.

7. Texas Guide for Retrofit and Planned Bicycle Facilities

7.1 Introduction

This guide is designed for anyone interested in considering on-street bicycle facilities for both existing and planned roadways. This guide may be used by roadway designers, planners, and engineers with technical expertise or bicycle advocates with front-line experience. This guide will familiarize readers with two tools for evaluating and designing on-street bicycle facilities. The first tool, the Bicycle Compatibility Index (BCI), was developed for the Federal Highway Administration (FHWA) in 1997 and rates the cyclist comfort level on mid-block roadway segments, the technical term referring to streets exclusive of their intersections with other roadways.[i] The BCI was derived from rigorous statistical analysis of the responses to a large-scale survey of cyclists. The second tool, the Passing Event Model (PEM), was developed for TxDOT. The Passing Event Model also focuses on mid-block roadway segments, and provides indicators of operational suitability in the form of predicted cyclist and motor vehicle lateral position. **The PEM was derived from statistical analysis of more than 8,000 field observations in which the lateral position of the cyclist and motor vehicle have been measured in relationship to the roadway width and striping.**[ii] By introducing these tools in combination, this guide enables the user to maximize the comparative advantages of both studies, as shown in Table 7.1.

Table 7.1. Description and comparison of the Bicycle Compatibility Index (BCI) and Passing Event Model (PEM)

	BCI	PEM
Developed by	University of North Carolina at Chapel Hill's Highway Safety Research Center for Federal Highway Administration	University of Texas at Austin's Center for Transportation Research for Texas Department of Transportation
Measures	cyclist comfort level	behavior of cyclists and motorists during passing events
Based on	survey of cyclists' perceptions of roadway and traffic characteristics	field observations of motorists' and cyclists' physical responses to roadway and traffic characteristics
Output	rating from 1 to 6	measurements of cyclist and motorist lateral position
Strengths	responds to minor variations in many roadway and traffic characteristics	quantitative; addresses comfort and operational level of bike facility for both cyclists and motorists
Weaknesses	qualitative; addresses only cyclists, does not indicate how cyclists will react to roadway and traffic conditions	responds to a narrower set of roadway and traffic characteristics

Readers will learn to use the models by entering basic roadway data into the Microsoft Excel Workbook on the accompanying CD-ROM and to interpret the indicators produced. The results will have three potential applications:

1) Bicycle Facility Retrofits (On Street). To retrofit is to add an on-street bicycle facility to an existing roadway where the right-of-way and/or curb-to-curb width is constrained. Adding a bikeway requires adjustments to existing geometric and traffic characteristics, which may include narrowing of motor vehicle lanes or median. Retrofits vary in type and extent of adjustments made; this guide allows users to examine the suitability of various alternative designs.

2) Evaluation of Existing Roads. Readers can use this guide to evaluate mid-block roadway segments with and without designated bicycle facilities. A thorough evaluation of existing roadway conditions will support the selection of a bicycle route among alternative streets within a corridor, produce documentation to form the basis of a bike map or inventory of bicycle-friendly streets, or provide input to a community assessment.

3) Planning Bikeways. When a new roadway or reconstructed roadway is in the planning stage, careful consideration of all modes of transportation during design can help achieve target levels of service for cyclists and motorists under present and future traffic conditions. This guide provides a valuable tool for use in the design process.

The strength of this guide lies in the communication of empirically based and unbiased information on both cyclists' and motorists' reactions to specific geometric and traffic conditions. At the same time, certain omissions from this guide should be noted. The level of cyclist safety is not quantified. Cyclist-motorist crashes are under-reported, making data on these events scarce and unreliable at this time. Indeed, field studies of bicycle facilities have yet to observe a single collision, let alone a sufficient number of them, that would allow researchers to predict or determine the probability of such an event. Moreover, the lack of data on bicycle traffic volumes makes it all but impossible to determine if a rise or fall in accident rates is merely reflecting a change in the number of cyclists traveling on a particular roadway or bikeway. Another omission from this guide is information to support the design or evaluation of intersections to accommodate cyclists.[iii] To meet the need for more information on this unsettled question, the Transportation Research Board and TxDOT's Office of Research and Technology Implementation have called for additional research.

Section 7.2 explains how to use the Excel Workbook provided with the program guide, including a discussion of the needed input and interpretation of the output. Section 7.3 presents an example of how the accompanying Excel Workbook can be used to retrofit a bikeway on an existing roadway. Section 7.4 discusses important roadway design elements to consider when retrofitting bicycle facilities.

7.1.2 Use of the Excel Workbook

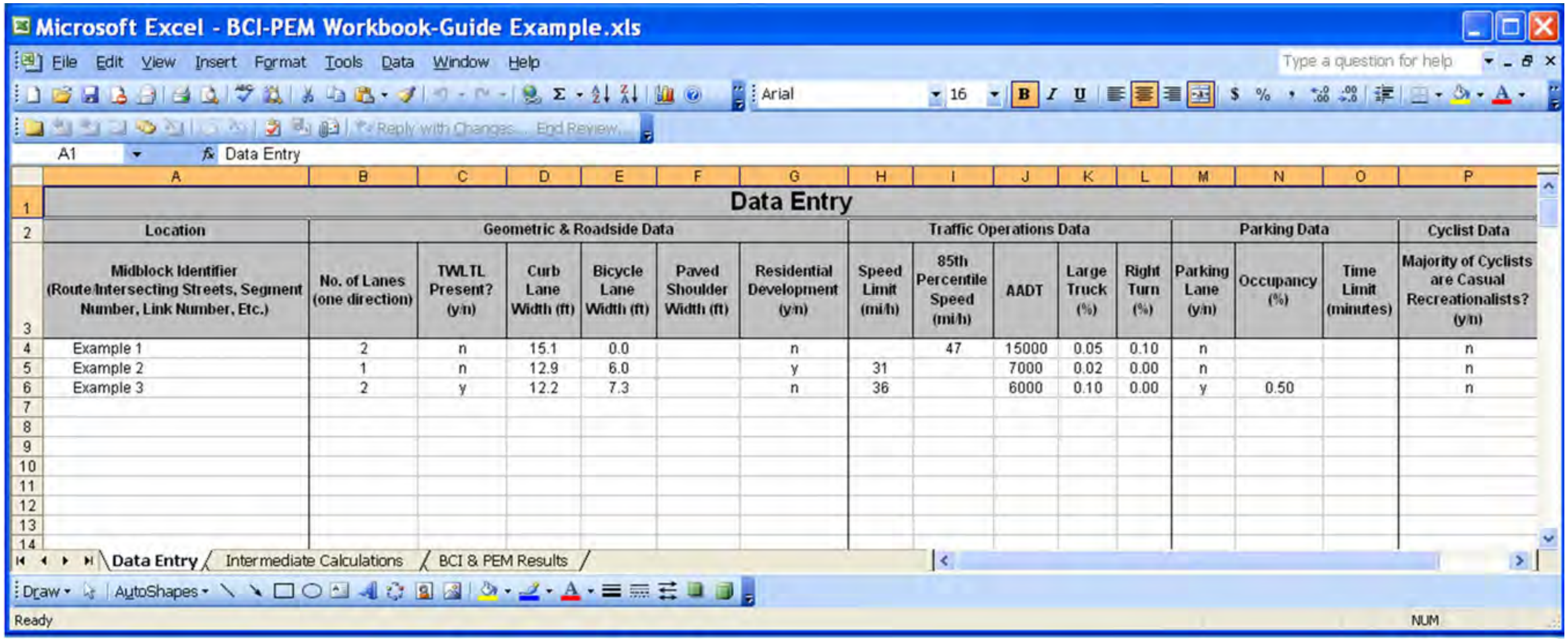
In preparing to generate the BCI and PEM values identified in the Excel Workbook, users must obtain data on roadway geometric and traffic characteristics. These data are usually available from state and local governments, which regularly collect traffic data for transportation planning. For certain characteristics of a roadway segment, users can choose between alternative measures and enter corresponding data. This flexibility is valuable when data for one of the measures are unavailable. For example, when data on observed speeds is not available, the posted speed can substitute for the 85th percentile speed, and the program will automatically make the necessary adjustments. For other characteristics, the measures incorporated into the Workbook have been designed with the limitations of available data in mind. For example, the input for percentage of right-turning vehicles in the Excel Workbook is simply used to decide whether right-turn volume exceeds 270 vehicles per hour or not. If this data is unavailable, the user will learn how to input a value above and below this threshold to test its effect on the results. These efforts minimize data requirements needed to run the Workbook. Notwithstanding, some of the required data may prove unobtainable for particular roadway segments, and the user will have to make educated guesses. In other situations, data may be available but problematic, and the user will need to exercise professional judgment to enter data and interpret results.

It is imperative that the user read this entire chapter for specific directions on entering data into the worksheet and interpreting the results before using the Excel Workbook.

Following are the categories of data required to run the Workbook:

1. Number and Type of Motor Vehicle Lanes
2. Outside Lane Width
3. Bike Lane or Shoulder Width
4. Motor Vehicle Speed
5. Traffic Volume
6. Percentage of Trucks
7. Right-turn Volume
8. Parking
9. Area Type
10. Cyclist Experience Level

To enter data into the Excel program file, press the *Data Entry* tab at the bottom of the screen and enter the data into the appropriate columns of that worksheet. An example of the “Data Entry” worksheet appears as Figure 7.1.

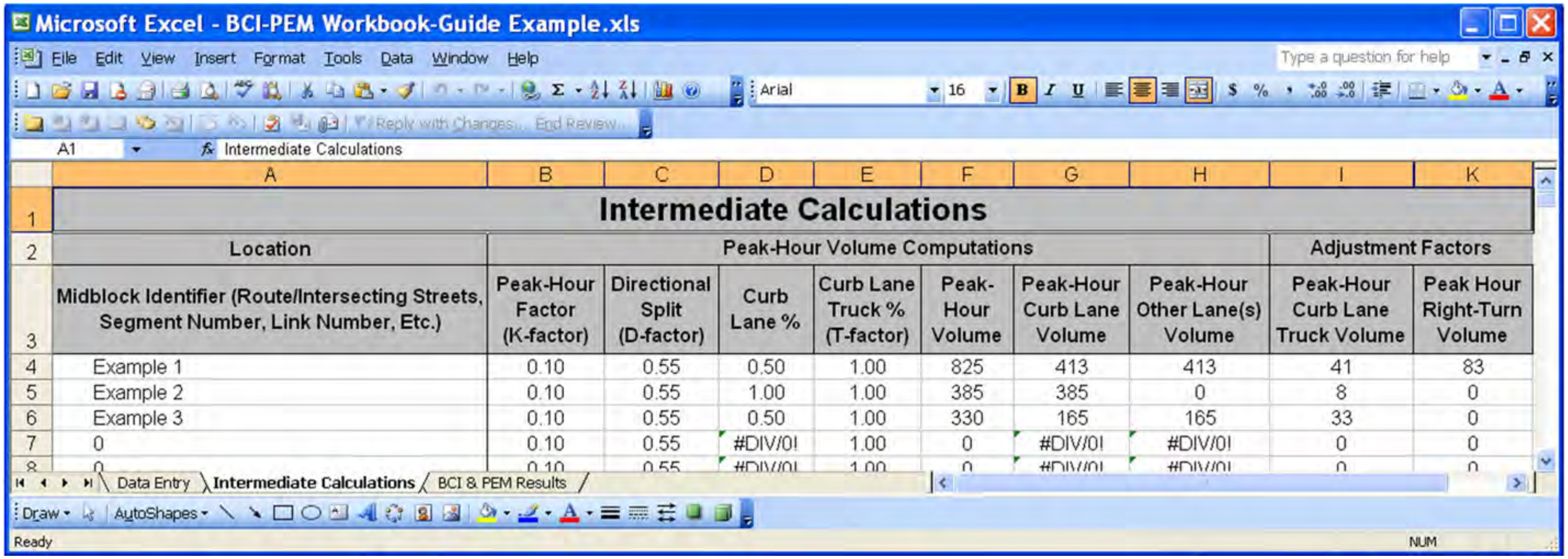


Data Entry

Location	Geometric & Roadside Data						Traffic Operations Data					Parking Data			Cyclist Data
Midblock Identifier (Route/Intersecting Streets, Segment Number, Link Number, Etc.)	No. of Lanes (one direction)	TWLTL Present? (y/n)	Curb Lane Width (ft)	Bicycle Lane Width (ft)	Paved Shoulder Width (ft)	Residential Development (y/n)	Speed Limit (mi/h)	85th Percentile Speed (mi/h)	AADT	Large Truck (%)	Right Turn (%)	Parking Lane (y/n)	Occupancy (%)	Time Limit (minutes)	Majority of Cyclists are Casual Recreationalists? (y/n)
Example 1	2	n	15.1	0.0		n		47	15000	0.05	0.10	n			n
Example 2	1	n	12.9	6.0		y	31		7000	0.02	0.00	n			n
Example 3	2	y	12.2	7.3		n	36		6000	0.10	0.00	y	0.50		n

Figure 7.1. Sample Data Entry worksheet from the Excel Workbook

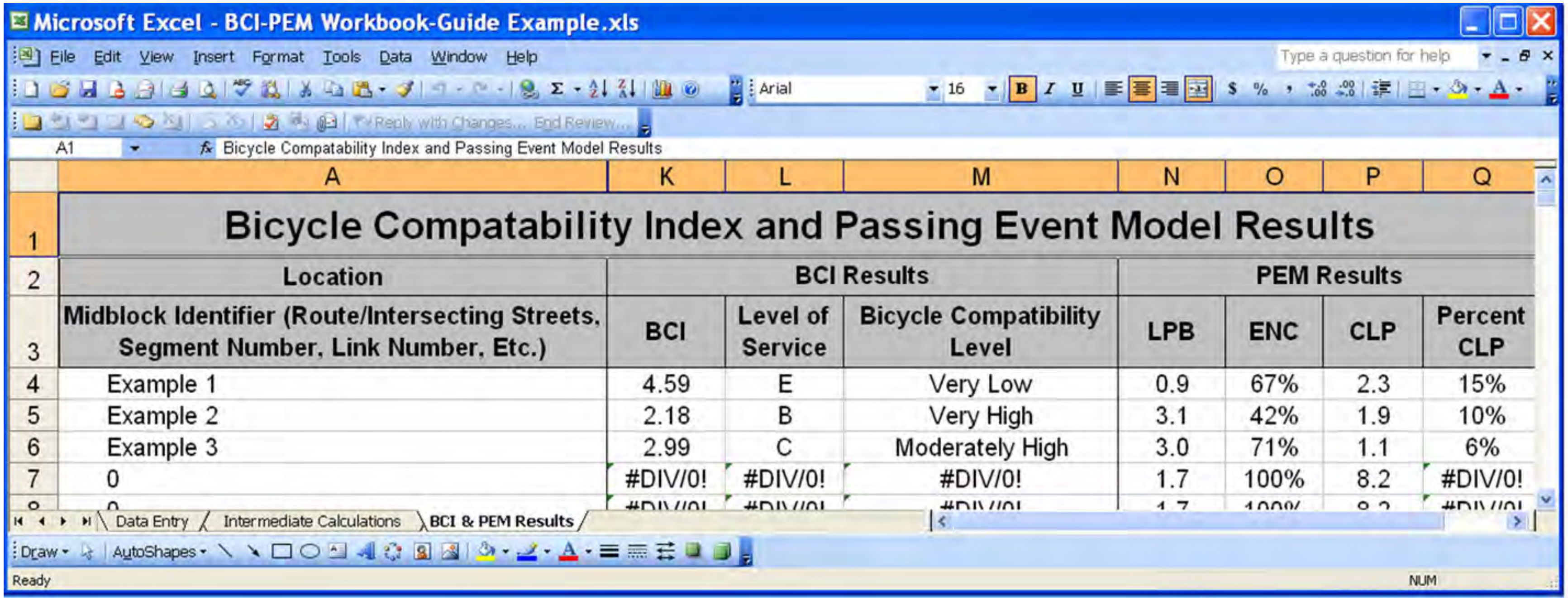
The Excel program file allows users to change the default values used in the program's calculations and to enter some of the required input data using alternative measures. To exercise these options, click on the *Intermediate Calculations* tab at the bottom of the Excel program window. Many of the columns of data will have little meaning before the user reads the rest of this chapter, but for reference, Figure 7.2 provides an example of this worksheet:



	A	B	C	D	E	F	G	H	I	K
1	Intermediate Calculations									
2	Location	Peak-Hour Volume Computations							Adjustment Factors	
3	Midblock Identifier (Route/Intersecting Streets, Segment Number, Link Number, Etc.)	Peak-Hour Factor (K-factor)	Directional Split (D-factor)	Curb Lane %	Curb Lane Truck % (T-factor)	Peak-Hour Volume	Peak-Hour Curb Lane Volume	Peak-Hour Other Lane(s) Volume	Peak-Hour Curb Lane Truck Volume	Peak Hour Right-Turn Volume
4	Example 1	0.10	0.55	0.50	1.00	825	413	413	41	83
5	Example 2	0.10	0.55	1.00	1.00	385	385	0	8	0
6	Example 3	0.10	0.55	0.50	1.00	330	165	165	33	0
7	0	0.10	0.55	#DIV/0!	1.00	0	#DIV/0!	#DIV/0!	0	0
8	0	0.10	0.55	#DIV/0!	1.00	0	#DIV/0!	#DIV/0!	0	0

Figure 7.2. Sample Intermediate Calculations worksheet from the Excel Workbook

The program output appears on the third and final worksheet of the Excel file, including both the BCI & PEM Results. To view this worksheet, select the tab named *BCI & PEM Results* at the bottom of the Excel program window. The BCI results include: (i) the cyclist comfort index value, (ii) a corresponding indicator for level of service, and (iii) a verbal description of the compatibility of the facility with cycling activity. For the mid-block roadway segment being evaluated, the PEM provides predicted values for: (i) the lateral position of a bicyclist (LPB), (ii) the probability of motor vehicle encroachment (ENC), and (iii) the change in lateral position (CLP) of a vehicle, provided as both a figure and a percentage. The last section of this chapter discusses the significance and interpretation of these outputs from the BCI and PEM. The output example in Figure 7.3 serves to acquaint readers with the program's final step.



A1 Bicycle Compatability Index and Passing Event Model Results

	A	K	L	M	N	O	P	Q
1	Bicycle Compatability Index and Passing Event Model Results							
2	Location	BCI Results			PEM Results			
3	Midblock Identifier (Route/Intersecting Streets, Segment Number, Link Number, Etc.)	BCI	Level of Service	Bicycle Compatibility Level	LPB	ENC	CLP	Percent CLP
4	Example 1	4.59	E	Very Low	0.9	67%	2.3	15%
5	Example 2	2.18	B	Very High	3.1	42%	1.9	10%
6	Example 3	2.99	C	Moderately High	3.0	71%	1.1	6%
7	0	#DIV/0!	#DIV/0!	#DIV/0!	1.7	100%	8.2	#DIV/0!

Figure 7.3. Sample BCI & PEM Results worksheet from the Excel Workbook

7.1.3 Filling in the Data Entry worksheet[iv]

This section contains instructions for inputting information into the Data Entry worksheet and, where applicable, the Intermediate Calculations worksheet.

Geometric and Roadside Data

Number of Motor Vehicle Travel Lanes in One Direction

This value is used in combination with annual average daily traffic (AADT) and other data to generate peak curb lane (outside lane) volume per hour.

- Value to enter: number of lanes in one direction

TWLTL Present?

The Excel Workbook also requires the user to indicate if there is a two-way left-turn lane (TWLTL)—this is a flush center turn lane without raised curbs or other barriers preventing the entrance of a motor vehicle.

- Value to enter: Y or N

Curb Lane Width

The curb lane shall be identified as the right-hand motor vehicle lane closest to the face of curb in the direction of travel. This measurement is taken from the face of curb to the center of the stripe that separates the inside motor vehicle lane from the outside motor vehicle lane. In the case of a bicycle lane or on-street parallel parking, this measurement is taken from the center of the inside curb lane line to the outside curb lane line. Figure 7.4 provides an example measurement in the case of a wide outside lane.

- Value to enter: width in feet

Figure 7.4. Example measurement from a roadway with a wide outside lane

Uneven Gutter Pan-Road Seam—If the gutter seam between the face of curb and the street does not allow a half-inch-wide bicycle tire (a common width on many current road and hybrid bicycles) to easily cross back and forth between the two, then the measurement should stop at the gutter seam; the gutter pan is not usable space in this situation (see Figure 7.5). Figure 7.6 provides an example of a smooth seam, the width of which would be included in the lane measurement.

Figure 7.5. Example of an uneven seam between the gutter pan and roadway (grass is covering the curb face)

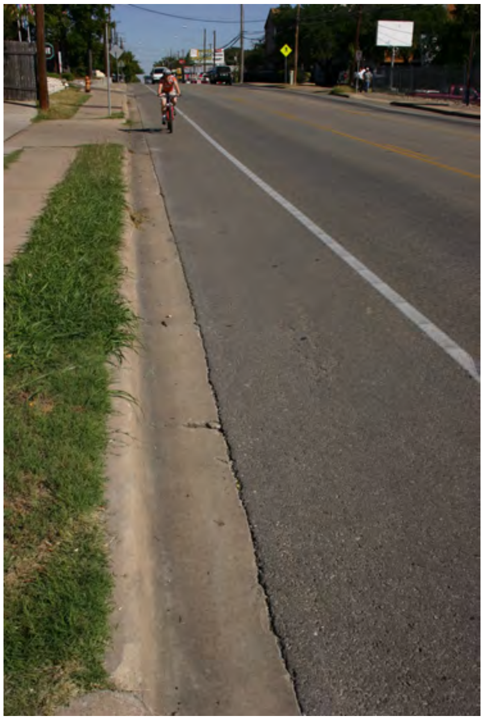


Figure 7.6. Example of a smooth seam between a gutter pan and roadway

Bike Lane Width

If a bike lane is present, the measurement is taken from the face of curb to the edge of the stripe between the bike lane and the adjacent motor vehicle lane (Figure 7.7). In the case of on-street parallel parking, the measurement is taken from the center of the outside curb lane line to the outside bike lane line.

- ○ Value to enter: number of feet

- **Combined parking and bike lane**—If the bicycle lane is not separated from on-street parallel parking with an outside line, subtract 8 feet from this combined bike and parking lane.

- **Uneven gutter pan-road seam**—If a half-inch-wide bicycle tire cannot easily cross the gutter seam between the face of curb and the street, the measurement should stop at the gutter seam; in this situation, the gutter pan is not usable space.

Figure 7.7. Example measurements for a roadway with a bicycle lane

Paved Shoulder Width

If there is no bike lane but a paved shoulder is available, enter its measurement; the program will treat it as a bicycle lane. The shoulder should be composed of smooth, near-level pavement free of cracks, rumble strips, debris, sand, and vegetation. Research has shown such paved shoulders and bike lanes to be operationally equivalent (Harkey et al. 1996). Paved shoulders should be measured from the middle of the outside curb lane line to the edge of the road.

- Value to enter: number of feet

Is the Area Part of a Residential Development?

If the mid-block segment is composed entirely of residential buildings and the hourly curb lane volume is less than 150, it is classified as residential (Figure 7.8). Segments with non-residential development or residential sections with higher hourly volumes are not classified as residential.

- Value to enter: Y or N

Figure 7.8. Example of a residential type of development

Traffic Operations Data

Speed Limit

Input the posted speed limit for the mid-block section if 85th percentile speed─the speed at which 85 percent of motorists are traveling at or under─is not available. The program will then add 9 miles per hour to the posted limit as a proxy measure for 85th percentile speed.[v]

- ○ Value to enter: number of mph or leave blank

85th Percentile Speed

If the 85th percentile speed is available, enter it into the column with this heading on the *Data Entry* worksheet and leave the column for Speed Limit blank.

- ○ Value to enter: number of mph or leave blank

AADT

The Excel Workbook converts average annual daily traffic (AADT), the most readily available traffic measure, to peak-hour volume of the curb lane. The conversion takes into account the number of lanes[vi], a peak-hour factor, and a directional split factor.

- ○ Value to enter: number of vehicles

- **Peak-hour factor**—The default value for this factor in the program is 0.10, meaning that ten percent of the AADT travels during the peak hour. The factor can range, however, from 0.07 (7 percent; traffic very evenly distributed throughout the day) to 0.15 (15 percent; traffic with a very pronounced rush hour). Users of the guide can change this factor in the Intermediate Calculations worksheet.

  - Value to enter: percentage as decimal (e.g., 0.07 rather than 7 percent)
  - Default value is 0.10

- **Directional split factor**—This figure represents the percentage of vehicles on the roadway during the peak hour that are traveling in the peak direction. The default value of this factor is 0.55 (55 percent), but would need to change to 1.00 in the case of a one-way street. The factor used in the Excel Workbook can be changed in the Intermediate Calculations worksheet, but should not be less than 0.50, because the analysis should address maximum flow conditions for any given period of time. If the side of the road under observation is carrying 40 percent of the traffic, then the other side of the road is carrying 60 percent of the traffic and is presumed to be the more pressing condition to analyze if cyclists are using both sides of the road.
  - Value to enter: percentage as decimal (e.g., 0.60 rather than 60 percent)
  - Default value is 0.55

Although peak-hour volume is the recommended measure of curb lane traffic volume, users can substitute other measures, such as average hourly curb lane volume, that they deem more appropriate for the roadway segment under consideration.

- **Hourly curb lane volume**—If the volume of the curb lane is known for the peak hour, or another measure of this traffic volume is deemed more appropriate, the AADT column on the Data Entry worksheet can be skipped. The user would then enter the information directly into the Peak Hour Curb Lane Volume column of the Intermediate Calculations worksheet along with an estimate of the Peak Hour Other (same direction) Lane(s) Volume.
  - Value to enter: number of vehicles or leave blank

Percentage of Large Trucks

Although FHWA considers sport-utility vehicles, pickup trucks, duallies, etc. to be trucks, this guide classifies these vehicles as cars. For this application, trucks are semi-trailers, school buses, public buses, delivery trucks, vehicles with wide trailers, and even standard pickups with oversized utility kits (e.g., telephone/electric service trucks). See Figure 7.9. The Excel Workbook will use the percentage of large trucks, along with the volume of curb lane traffic and the truck factor (see next paragraph), to determine the volume of truck traffic for other calculations in the Workbook; the only essential input to run the Workbook is some value for the percentage of large trucks. If data on the truck percentage of traffic are not available, the user can derive a value through professional judgment or use the following default range values: less than 1.0 percent for local streets, 0.4-2.6 percent for collectors, 0.5-3.9 percent on minor arterials, 1.4-5.4 percent for non-freeway principal arterials (Harkey et al. 1998).

- Value to enter: percentage as decimal (e.g., 0.01 rather than 1 percent)

- **Truck factor (T-factor)**—This is the proportion of all trucks traveling in the same direction that are in the curb lane. On a two-lane, bidirectional facility, with or without a median, this t-factor should be changed to 1.00, because there is only one lane traveling in the peak direction. Otherwise, the default is 0.80 (80 percent).vii The user can change this default value in the Intermediate Calculations worksheet.

- ○ Value to enter: percentage as decimal (e.g., 1.00 rather than 100 percent)
- ○ Default value is 0.80

Figure 7.9. Truck passing a cyclist on a wide outside lane

Right-Turn Percentage
With the right-turn percentage value entered by the user, the Excel Workbook generates a right-turn volume (Figure 7.10). The results of the Workbook are only affected when the volume of right turns exceeds 270 per hour. If the right-turn percentage is unknown, users can skip this input on the *Data Entry* worksheet and enter an actual right-turn volume from field observations or an artificial value using professional judgment above or below the 270 turns-per-hour threshold in the *Intermediate Calculations* worksheet.

- ○ Value to enter: percentage of right-turning vehicles as a decimal (0.20 rather than 20 percent)

Figure 7.10. Motor vehicle turning right in front of a cyclist

Parking Data

Three factors determine the effect of parking on the BCI and PEM.

Parking Lane: Presence of on-street parking facilities

- ○ Value to enter: Y or N

Occupancy: the percentage of spaces occupied during the selected hour of analysis[viii]

- ○ Value to enter: percentage as a decimal (e.g., 0.50 rather than 50 percent)

Time Limit: the time limit placed on users of the parking facilities *or* the average amount of time a space is used[ix]

- ○ Value to enter: number of minutes

Cyclist Data

Are Majority of Cyclists Casual Recreationalists?

The term *casual recreationalists* has been used to describe cyclists who make at least 70 percent of their bicycle trips for recreation and exercise. Since this group favors riding off-road bike paths, they may be less experienced and less skilled at riding on major streets. Selecting *yes* to indicate that this group forms the majority of the cyclists on a particular roadway will cause the Excel program to rate the facility less favorably for both the BCI and the PEM. This means that additional measures will be needed to provide the same level of service as a similar facility ridden by more advanced cyclists.

- ○ Value to enter: Y or N

7.1.4 Valid Range of Input Values

Lastly, it is important to keep in mind that the program's calculations are based on a range of values developed from actual observations. The reliability of the BCI and PEM results is questionable when user-inputted values fall outside this range, becoming more uncertain the farther the input exceeds pre-set ranges indicated in Table 7.2. For example, if a user has data for a street with vehicle speeds of less than 25 mph or faster than 60 mph, results of the program's calculations will be less reliable than if those values fell within the valid range of 25 to 60 mph.

Table 7.2. Range in inputs for which the predictions from each model are statistically valid

Valid Range of Inputs		
Variable	**BCI Range**	**PEM Range**
Curb Lane Width (no wide outside lanes)	10.0–18.5 ft	9.5–18.0 ft
Wide Outside Lane Width	unknown	13.75–18 ft
Bicycle Lane / Paved Shoulder Width	3.0–8.0 ft	3.8–6.0 ft
Curb Lane Volume	90–900 vehicles/hour	60–700 vehicles/hour
Percentage of Trucks	0.0–10.0%	0.0–12.0%
Speed	25–55 mph	30–60 mph

7.1.5 Interpreting the Output: BCI

BCI

The Bicycle Compatibility Index predicts the relative comfort level of an average cyclist on a scale from 1 to 6, with lower numbers indicating higher levels of comfort. The index considers the traffic volume and type in conjunction with geometric characteristics of the roadway.

Level of Service

This measure is an adaptation of the Highway Capacity Manual's Level of Service (LOS) measure for motor vehicles (Harkey et al. 1998):[x]

> For other modes of transportation, however, the term LOS is used to characterize the operational conditions of a roadway with six designations (LOS A through LOS F). The descriptive terms in the written definition of LOS include speed and travel time, comfort/convenience, traffic interruptions, and freedom to maneuver. While this concept and the subsequent defining terms were originally developed for motor vehicle

> applications, the qualitative descriptors of comfort/convenience and freedom to maneuver are most applicable to bicyclists traveling on the roadway in the presence of motor vehicles. The LOS definition also states that it is the user's perception of the operational conditions within the traffic stream that dictates the ranges of qualitative measures included in each LOS designation. The perceived comfort level of bicyclists within a given set of operating conditions on the roadway is exactly what the BCI model produces. Thus for bicycle LOS, the measure of effectiveness should be the BCI. Subsequently, each LOS designation should be defined by a range of values produced by the model.

The relationship between BCI score and LOS designation is given in Table 7.3.

Table 7.3. Level of service (LOS) and BCI score relationship

LOS Designation	BCI Range
A	≤ 1.50
B	1.51–2.30
C	2.31–3.40
D	3.41–4.40
E	4.41–5.30
F	> 5.30

Bicycle Compatibility Level

This is a verbal description of the BCI rating: A, extremely high; B, very high; C, moderately high; D, moderately low; E, very low; and F, extremely low.

7.1.6 Interpreting the Output: PEM

Lateral Position of Bicyclist (LPB)

AASHTO's *Guide for the Development of Bicycle Facilities* (1999) indicates that the operating space of a cyclist is identified as 40 inches wide (see Figure 7.11 for this and other key measurements). Any time the tire of the bicycle passes within 20 inches (1.7 ft) of a roadside object, the cyclist's operating space is violated and the possibility exists that his or her pedal or handlebars could strike an object, causing loss of control or injury. Thus, this distance (1.7 feet) becomes a benchmark from which to evaluate the lateral position of a cyclist on a roadway segment and that segment's suitability as a bicycle facility. Since cyclists generally try to avoid passing cars by moving towards the face of curb, increases in lateral distance between the cyclist and the curb face are interpreted as an increase in comfort for the cyclist along the given roadway segment. The only exception to this pattern would be if the movement away from the face of curb occurred due to a roadside obstacle such as a parked car, debris, or a mud puddle.

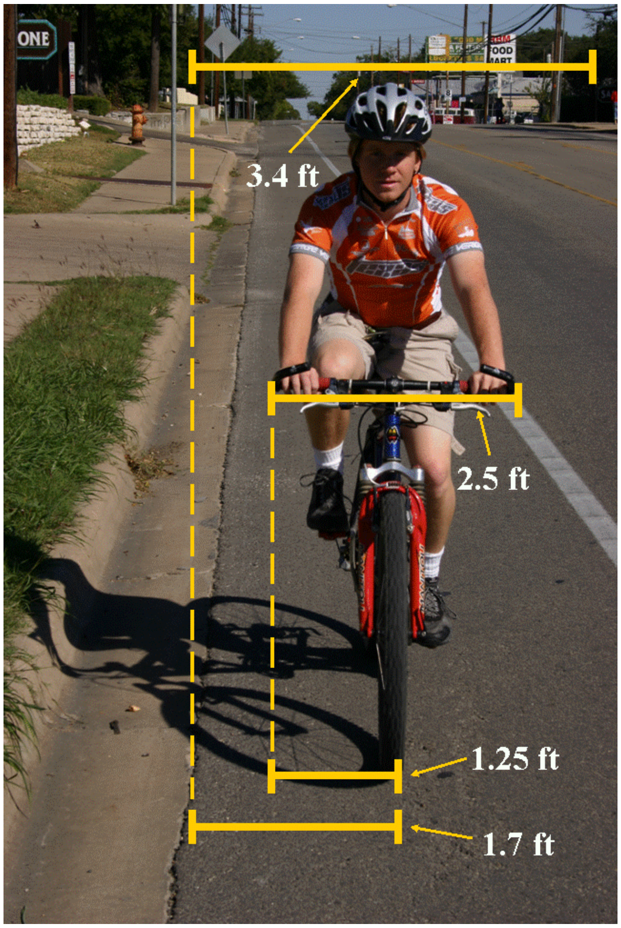


Figure 7.11. Operating space of a cyclist
(2.5 ft is the profile of an average cyclist while 3.4 ft represents the space occupied by a cyclist when his/her natural meanderings are considered)

Encroachment (ENC)

Encroachment is a response to circumstances that reduce the motorist's level of comfort with the driving environment. Encroachment occurs when a motor vehicle—seeking to avoid a cyclist—moves leftward from the curb lane and two or more wheels make contact with the lane line dividing the vehicle's original curb lane from the neighboring motor vehicle lane or a TWLTL. Encroachment is a response to circumstances that reduce the motorist's level of comfort with the driving environment. Figures 7.12-14 depict instances of encroachment. In reviewing the encroachments measured for this project, the precipitating circumstance is overwhelmingly that proximity to a cyclist was the cause for the encroachments based on the fact that the test sites excluded other causes for this behavior (e.g., parked cars, debris, etc.). It should be noted that the probability of encroachment for nearly any road, even the most ample ones, will be around 50 percent or more. These high probability levels primarily result from this guide's definition of an encroachment as both driver-side wheels of a vehicle making any contact with the inner stripe of a curb lane. Additionally, a large number of encroachments may result from extremely cautious or courteous motorists giving as wide a berth to a passing cyclist as circumstances permit (e.g., presence of oncoming traffic). For these reasons, this measure functions better as a relative value in comparisons than an absolute indication of suitability for motorists of a particular roadway with cyclists. Considering this measure in conjunction with the change in lateral position (CLP) of the motorist may also be helpful. In general, large CLP values combined with a high probability of ENC tend to indicate that the encroachment was significant, in contrast to a mild occurrence in which two wheels briefly skim the inside lane line. When entering values in the Excel Workbook, users can always enter ideal widths for vehicle and bicycle lanes to establish a best-case benchmark for the encroachment rate on a given roadway.

Two-lane streets with a TWLTL exhibit above average encroachment rates because the TWLTL is often vacant, and motorists can easily assess its availability for encroachment. Although research undertaken to develop the PEM revealed no conflicts associated with opportunistic encroachments, users of this guide can decide for themselves whether such maneuvers are problematic.

Figure 7.12. Motorist encroachment on a roadway with a TWLTL

Figure 7.13. Motorist encroachment on a four-lane roadway with median

Figure 7.14. Motorist encroachment on a two-lane roadway

Change in Lateral Position of Motorist (CLP)

Motorists who swerve around a passing cyclist do so because the proximity of the cyclist reduces their level of comfort, particularly in terms of safety. The amount of the swerve is the change in the motorist's lateral distance from the position before and after the passing event to that during the event. Large changes in lateral position clearly signify lower levels of motorist comfort.

An important example of this concept involves two-lane streets. Motorists generally travel closer to the edge of the road to avoid the possibility of a head-on collision, and these roadways witness large changes in motorists' lateral position during passing events with bicyclists traveling in the same direction. Clearly, the maneuver around the cyclist is pushing the motorist closer to oncoming traffic, which causes the motorist discomfort. Thus, CLP is a good indicator of the motorist's level of discomfort with on-road bicyclists. As in the case of encroachments, users of the Excel Workbook can input ideal widths for both motor vehicle and bicycle lanes to create a minimum level of CLP. This baseline level of CLP can then be compared with the predicted levels under conditions more applicable to bicycle facility retrofits.

Percent Change in Lateral Position of Motorist

The extent to which a motorist swerves around a cyclist reflects not just the driver's level of discomfort, but also the amount of room available for shifting the vehicle leftward. The amount of room available is, in turn, related to the total outside width of the roadway—the distance from the inside line of the curb lane to the edge of the road or face of curb. To facilitate comparisons between roadways with differing outside widths, the Excel Workbook includes as an output the predicted change in motorist lateral position as a percentage of the outside width. The primary use of this measure would be in route selection, rather than in designing retrofits for a given same roadway segment (where the outside width often remains the same).

Before using the guide, the user should also have an idea of how the various geometric and traffic variables affect the BCI and PEM measures. This information is summarized in Table 7.4.

Table 7.4. Effect of changes in roadway and traffic characteristics on the outputs of the BCI and PEM

Traffic/Geometric Variables (Increase/Presence)	BCI/LOS/ Compatibility Level	Lateral Position of Bicyclist (LPB)	Percentage of Encroachments (ENC)	Change in Lateral Position of Motorist (CLP)
Curb Lane Width	**improves**	**no effect**	**decreases**	**decreases**
Bike Lane	**improves**	**improves**	**decreases**	**decreases**
Bike Lane Width (if present)	**improves**	**improves**	**decreases**	**decreases**
TWLTL Adjacent to Curb Lane	**no effect**	**no effect**	**increases**	**no effect**
Opposing Traffic Adjacent to Curb Lane	**no effect**	**no effect**	**no effect**	**increases**
Motor Vehicle Speed[xi]	**degrades**	**no effect**	**no effect**	**no effect**
Traffic Volume in Curb Lane	**degrades**	**no effect**	**no effect**	**no effect**
Parking	**degrades**	**degrades (not quantitatively)**	**increases**	**increases**
Trucks	**degrades**	**no effect**	**increases**	**increases**
Right-Turn Volume	**degrades**	**degrades**	**no effect**	**no effect**
Residential Area	**improves**	**improves**	**no effect**	**increases**
Majority of Cyclists are Casual Recreationalists	**no effect (current version)**	**degrades**	**decreases**	**no effect**

Note: Text size indicates relative magnitude of effects.

7.2 Example of a Bicycle Facility Retrofit Design

To illustrate potential applications of this guide and its accompanying software, this chapter considers two competing proposals for retrofitting a bicycle facility onto a hypothetical roadway. The first proposal involves re-striping to provide a wide outside lane, and the second proposal involves re-striping to provide a bike lane. Because the general practice in retrofit design is to minimize any loss in the roadway's functionality for motorists, several factors remain unaltered.

For the characteristics that are assumed to remain unaltered, the following values have been assigned:

- AADT: 8,000 (assume default peak-hour and directional split factor values)
- Percentage of trucks: 8 percent (assume default t-factor)
- Right-turn volume: 20 percent
- 85th percentile motor vehicle speed: 37 mph
- Number of lanes in one direction: 2
- Two-way left-turn lane (TWLTL) present?: no
- Parking?: no
- Residential area?: no
- Majority of cyclists are casual recreationalists?: no

7.2.1 Existing Roadway to be Retrofitted (Base)

To generate the BCI and PEM values for the existing roadway, the only remaining input data needed is the curb lane width, which is 13 feet. As the illustration in Figure 7.15 shows, the existing roadway has neither bike lanes nor paved shoulders, and the gutter pan seam is very smooth.

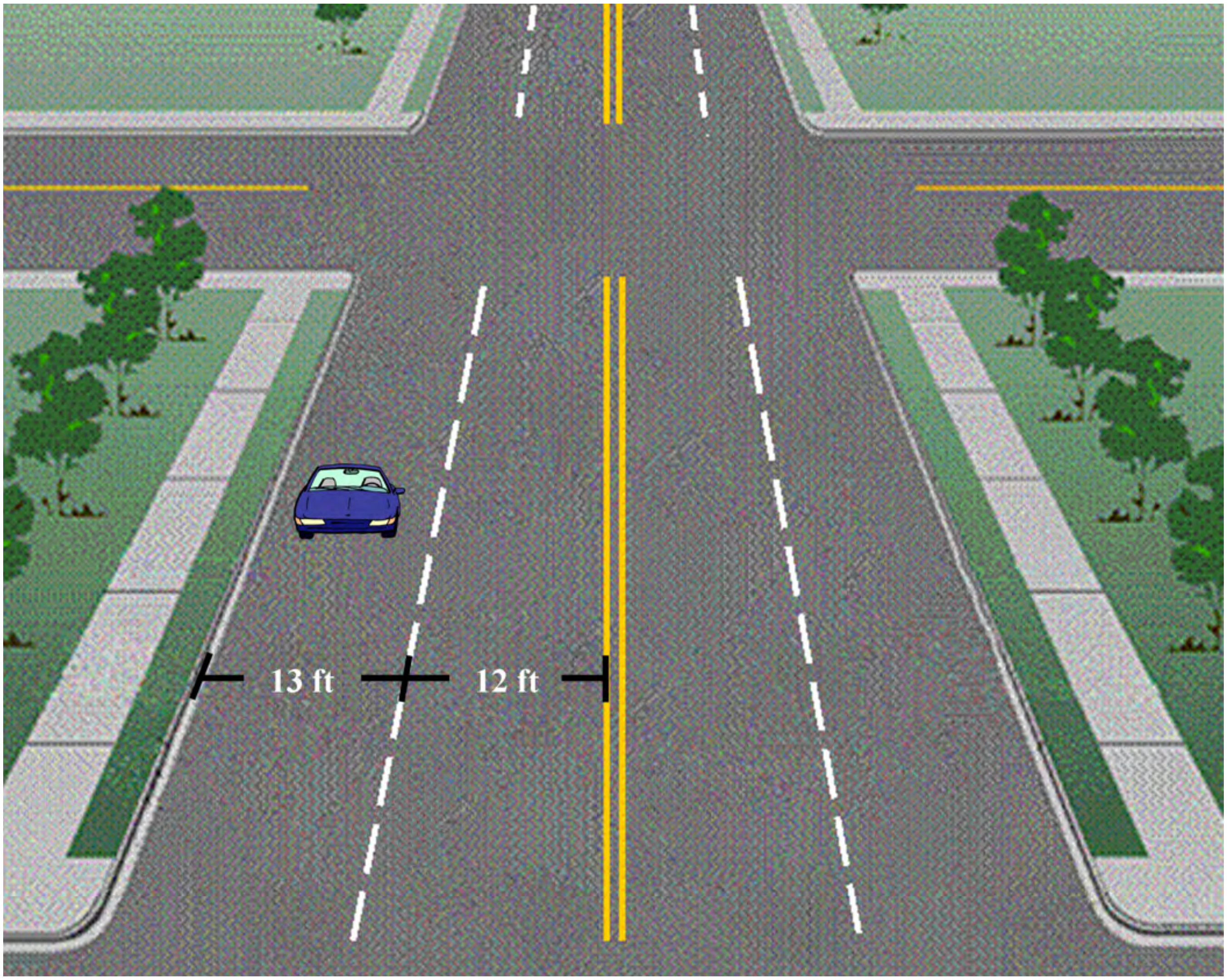


Figure 7.15. An illustration of the existing roadway to be retrofitted with a bicycle facility (Modified from Harkey et al. 1998)

7.2.2 Retrofit Proposal I: Wide Outside Lane

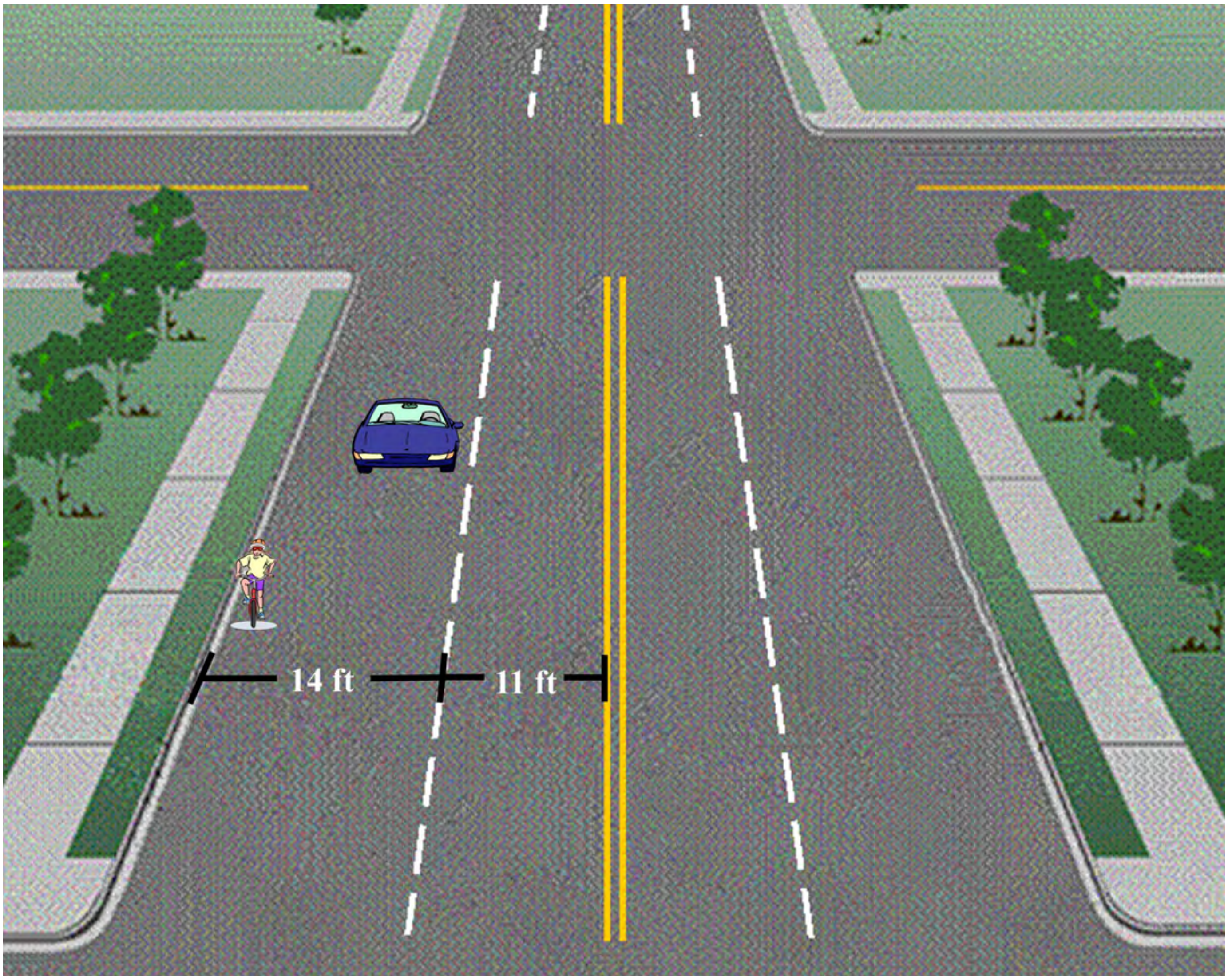


Figure 7.16. A wide outside lane configuration
(Modified from Harkey et al. 1998)

The first retrofit alternative, creating a wide outside lane, is often called a *line swapping exercise.* For each directional pair of motor vehicle lanes, this retrofit moves the dashed line separating the lanes towards the center of the road to create an 11-foot inside lane and a 14-foot curb lane (Figure 7.16). The 14-foot curb lane then functions as a wide outside lane accommodating both cyclists and motorists.[xii] Apart from adjusting the lane widths, representing this retrofit in the Excel program requires only an adjustment to the t-value, which describes the distribution of trucks between the inside lanes and curb lanes. In the new configuration, the 11-foot inside lane will be especially unattractive to trucks relative to the 14-foot curb lane. Accordingly, the user of the program should increase the t-value from the default value of 0.8 (80 percent of all trucks travel in curb lane) to 1.0 (100 percent of all trucks travel in the curb lane). [xiii]

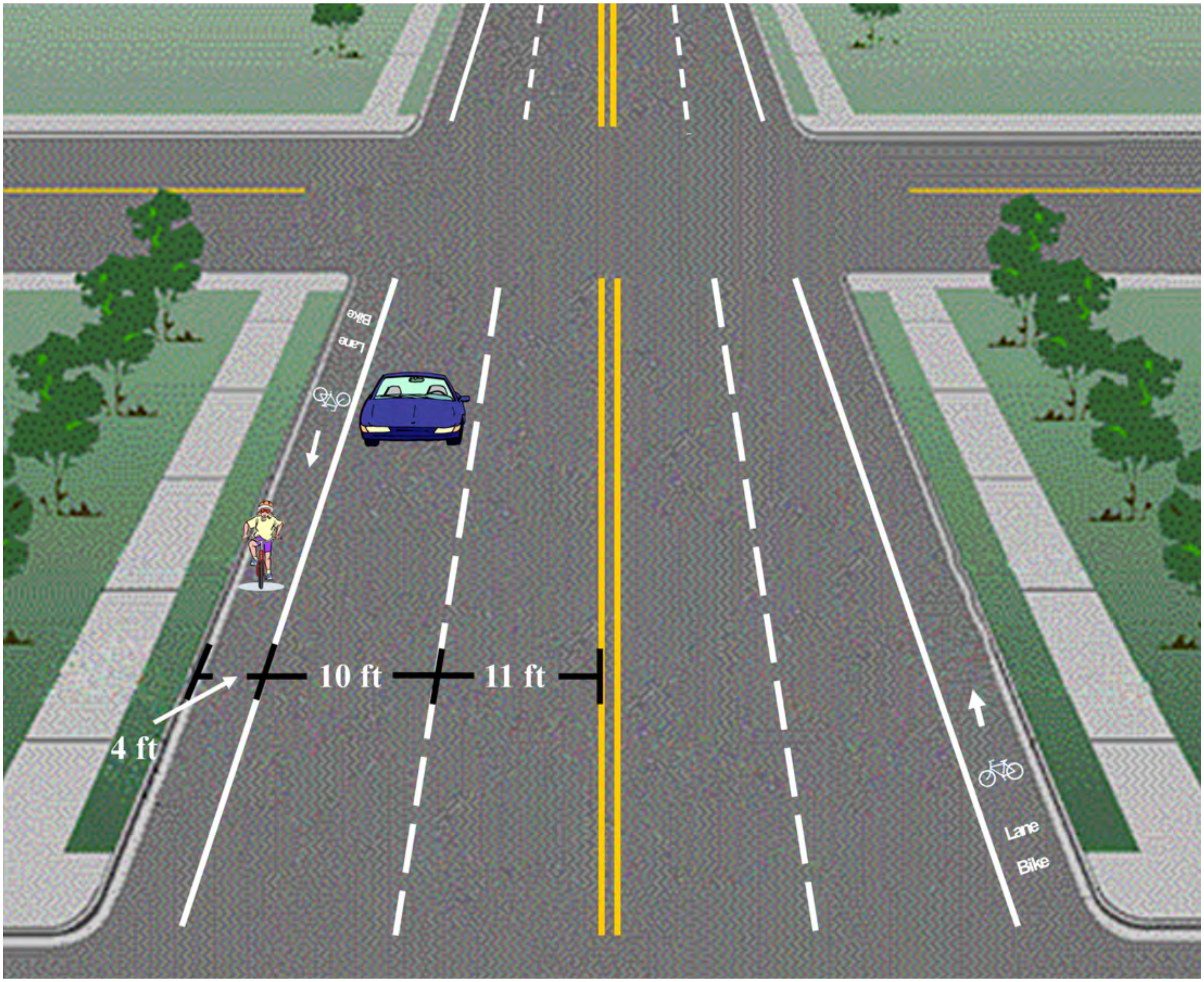


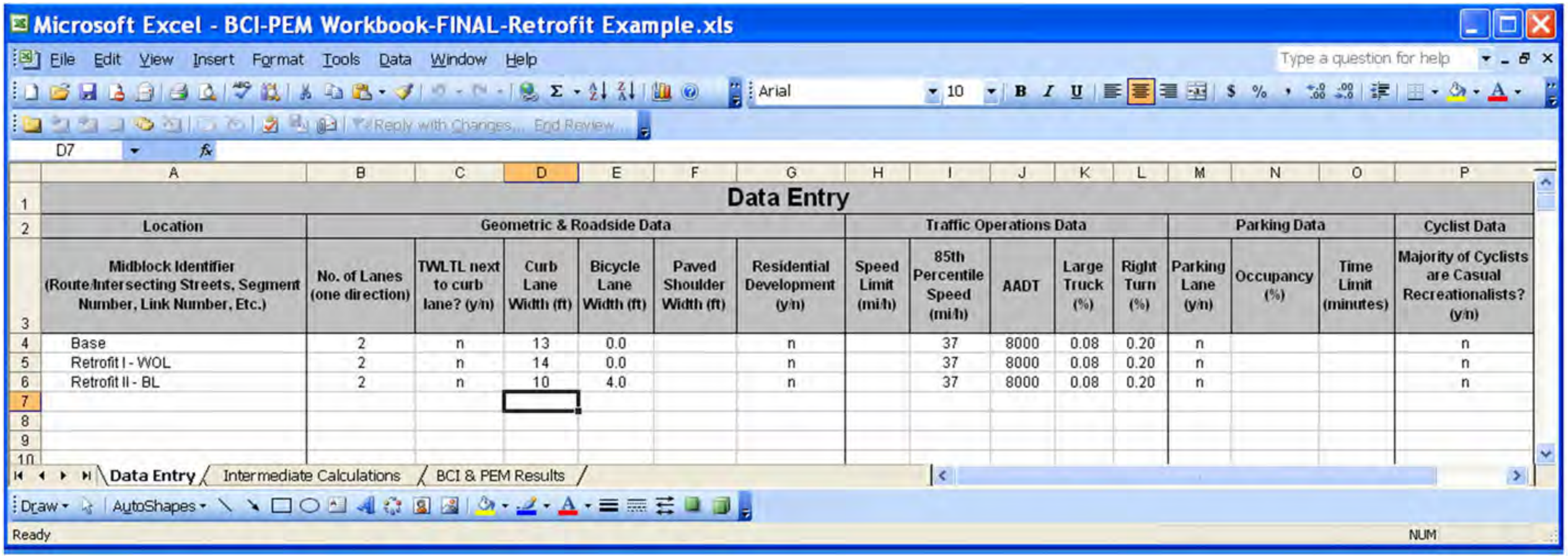
Figure 7.17. A bicycle lane configuration
(Modified from Harkey et al. 1998)

7.2.3 Retrofit Proposal II: Bike Lane

The second retrofit alternative adds a 4-foot bike lane in each direction to the outside of the roadway adjacent to the outside curb. Space for the bike lanes is made by narrowing each motor vehicle lane as shown in Figure 7.17. The t-factor should again be increased somewhat above the default value, because the bike lane provides a 4-foot buffer when no cyclist is present, which strengthens the inclination of truckers to travel in the curb lane. An appropriate value for the t-factor might be about 0.9.

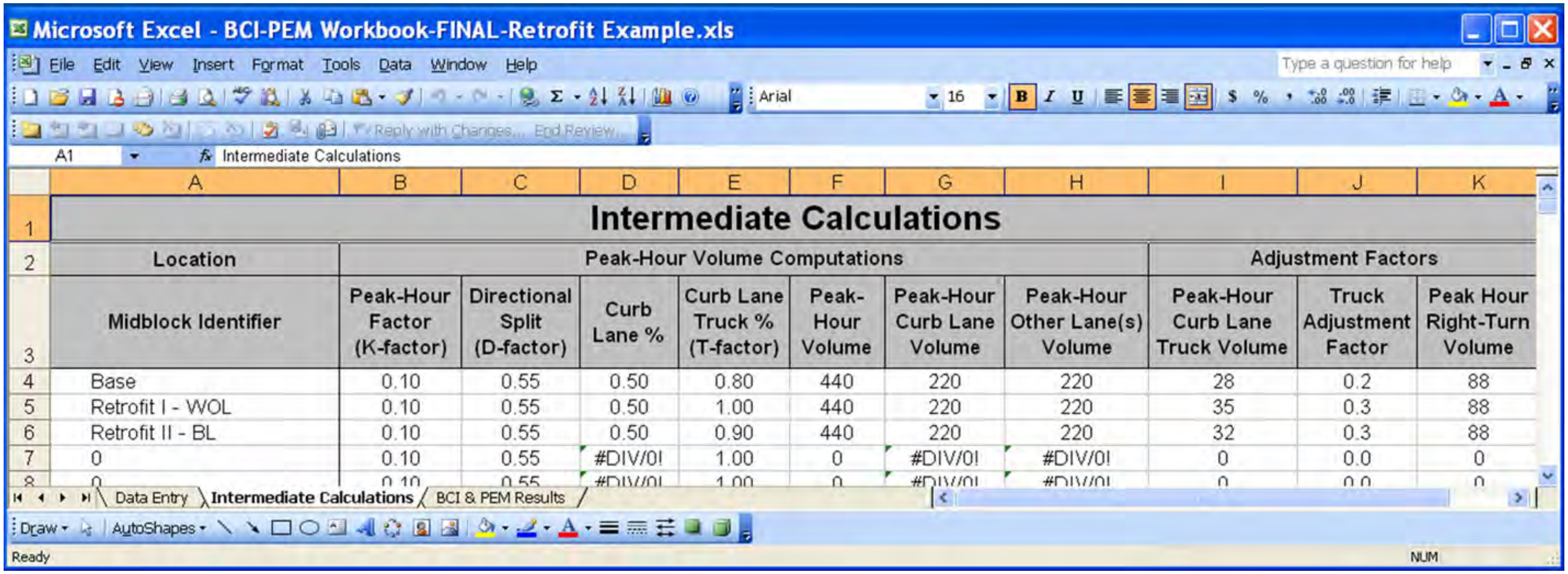
7.2.4 Data Entry and Results

For the three scenarios just described—the base case, the wide curb lanes, and the bike lanes—Figures 7.18 and 7.19 show how users of the Excel program would enter the data inputs. Figure 7.20 shows the outputs that would be obtained—the results for the BCI and PEM.



Data Entry															
Location	Geometric & Roadside Data						Traffic Operations Data					Parking Data			Cyclist Data
Midblock Identifier (Route/Intersecting Streets, Segment Number, Link Number, Etc.)	No. of Lanes (one direction)	TWLTL next to curb lane? (y/n)	Curb Lane Width (ft)	Bicycle Lane Width (ft)	Paved Shoulder Width (ft)	Residential Development (y/n)	Speed Limit (mi/h)	85th Percentile Speed (mi/h)	AADT	Large Truck (%)	Right Turn (%)	Parking Lane (y/n)	Occupancy (%)	Time Limit (minutes)	Majority of Cyclists are Casual Recreationalists? (y/n)
Base	2	n	13	0.0		n		37	8000	0.08	0.20	n			n
Retrofit I - WOL	2	n	14	0.0		n		37	8000	0.08	0.20	n			n
Retrofit II - BL	2	n	10	4.0		n		37	8000	0.08	0.20	n			n

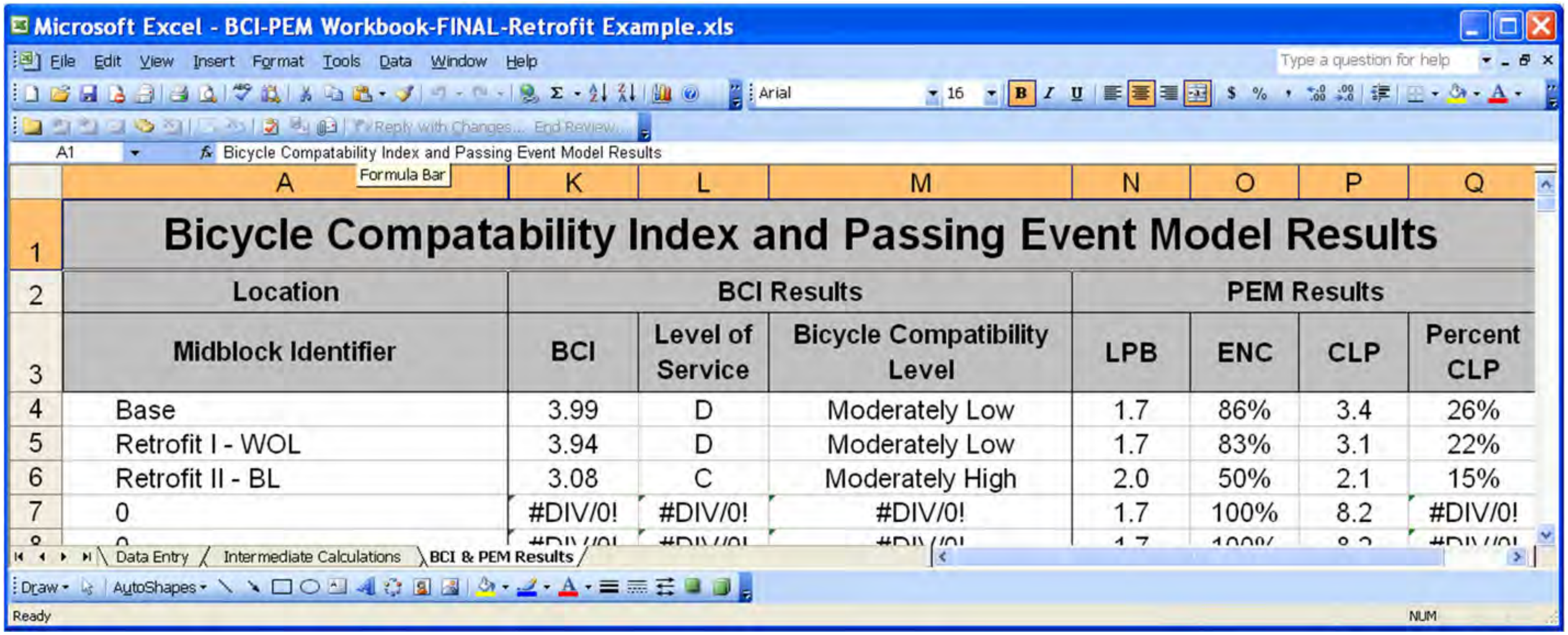
Figure 7.18. Data Entry worksheet for the existing roadway (base) and two bicycle facility retrofit proposals —wide outside lane (WOL) and bike lane (BL) configurations.



Intermediate Calculations

Location	Peak-Hour Volume Computations							Adjustment Factors		
Midblock Identifier	Peak-Hour Factor (K-factor)	Directional Split (D-factor)	Curb Lane %	Curb Lane Truck % (T-factor)	Peak-Hour Volume	Peak-Hour Curb Lane Volume	Peak-Hour Other Lane(s) Volume	Peak-Hour Curb Lane Truck Volume	Truck Adjustment Factor	Peak Hour Right-Turn Volume
Base	0.10	0.55	0.50	0.80	440	220	220	28	0.2	88
Retrofit I - WOL	0.10	0.55	0.50	1.00	440	220	220	35	0.3	88
Retrofit II - BL	0.10	0.55	0.50	0.90	440	220	220	32	0.3	88
0	0.10	0.55	#DIV/0!	1.00	0	#DIV/0!	#DIV/0!	0	0.0	0
0	0.10	0.55	#DIV/0!	1.00	0	#DIV/0!	#DIV/0!	0	0.0	0

Figure 7.19. Intermediate Calculations worksheet for the existing roadway (base) and two bicycle facility retrofit proposals —wide outside lane (WOL) and bike lane (BL) configurations. Note the changes to Curb Lane Truck % (T-factor).



Bicycle Compatability Index and Passing Event Model Results

Location	BCI Results			PEM Results			
Midblock Identifier	BCI	Level of Service	Bicycle Compatibility Level	LPB	ENC	CLP	Percent CLP
Base	3.99	D	Moderately Low	1.7	86%	3.4	26%
Retrofit I - WOL	3.94	D	Moderately Low	1.7	83%	3.1	22%
Retrofit II - BL	3.08	C	Moderately High	2.0	50%	2.1	15%
0	#DIV/0!	#DIV/0!	#DIV/0!	1.7	100%	8.2	#DIV/0!

Figure 7.20. BCI & PEM Results worksheet for the existing roadway (base) and two bicycle facility retrofit proposals —wide outside lane (WOL) and bike lane (BL) configurations.

7.2.5 Discussion

Base Case

The existing roadway generates a bicycle compatibility level of Moderately Low with a level of service D and a BCI score of 3.99. A cyclist on this road would be predicted to travel just within his or her operating space and dangerously close to the curb face. To avoid the cyclist, nearly nine out of every ten motorists will encroach on the adjacent left motor lane, and the average motor vehicle would swerve about 3.4 feet (about half the width of a typical car). The data for the existing roadway were entered with the assumption that all cyclists ride in the curb lane (as in the case of a wide outside lane). At only 13 feet, the curb lane width falls outside the valid range of inputs specified in Table 2 for the PEM and probably outside the valid range for the BCI as well. The results obtained are thus only rough indications, but they help to establish that, in the base case, before any bicycle facility retrofit, the comfort and operational levels on this street are poor for both cyclists and motorists passing cyclists.

Retrofit Proposal I: Wide Outside Lane

The first retrofit alternative, a 14-foot-wide wide outside lane, leaves the BCI comfort rating in the same moderately low range (level of service D) as in the base case. The results from the PEM indicate that cyclists would still travel dangerously close to the curb; in fact, an extra foot of curb lane width has not changed the predicted position of the average cyclist.[xiv] Motorists would likely swerve one-half foot less than before, but eight of ten drivers would continue to encroach on the adjacent lane. Although the retrofit meets AASHTO's bikeway guidelines and the lane widths might not need a special design exception, the resulting bicycle facility appears to operate poorly for both motorists and cyclists.

Retrofit Proposal II: Bike Lane

The second retrofit alternative, the addition of a 4-foot bicycle lane, scores significantly better. The BCI rating moves up to Moderately High (level of service C). A physical indication of this increased level of comfort is that the cyclist would likely move away from the curb face even as the combined space for the motorists in the adjacent lane and the bike lane remains at 14 feet (as in the case of the first retrofit alternative, a proposed 14 feet outside curb lane). Motorists, too, would be more comfortable with the bike lane retrofit than with the wide outside lane alternative: they would swerve approximately 33 percent less, and only five of ten motorists would encroach on the adjacent motor vehicle lane.

Conclusion

The bike lane is the better option for adding a retrofit bicycle facility to the existing roadway.

7.3 Roadway Design Considerations When Retrofitting Bicycle Facilities

If bicycle facility retrofits involve providing space for cyclists on a roadway where the curb-to-curb width is unchanged, the question immediately arises: From where is the space for cyclists gained? In the retrofit example of Section 7.2, space came from narrowing one or more motor vehicle lanes. Other retrofits may carve space for cyclists from the median, from space dedicated to on-street parking, or in relatively rare cases, by eliminating a motor vehicle lane. Selecting among these alternative design options will require knowledge about the roadway to identify possible options in conjunction with sound engineering judgment. Users would need to know: 1) the applicable state and local standards; 2) the safety and operational consequences of each alternative; and 3) anticipated population growth and roadway usage. Readers experienced in roadway design may be more familiar with the standards and much of the relevant research, including the lack of consensus on the magnitudes and even the directions of some of the traffic engineering relationships. For the benefit of lay readers, this chapter summarizes the standards in national reference materials on roadway design and the findings from this project's review of the research literature. Since the standards are taken from national reference sources, they may fall outside what some states and localities allow. Nothing in this chapter should be construed to supersede state or local standards.

7.3.1 Motor Vehicle Lane Width

Motor vehicle lane widths are generally between 10 feet and 12 feet, although 9-foot lanes may be used in residential areas (AASHTO 2001). Industrial areas with high volumes of trucks should have 12-foot-wide lanes, but 11 feet is tolerable. Lane widths in excess of 15 feet tend to function as a double motor vehicle lane at all but minimal traffic volumes.

Studies on the effects of lane width normally focus on a 12-foot lane as standard. In general, reductions in width are known to cause decreases in motor vehicle speed and roadway capacity, as well as increases in accidents rates (Harwood 1986, Fitzpatrick et al. 2000, Zeeger et al. 1987, Harwood 1990). Over the 10–12 foot range, estimates of these effects per foot of reduced width have been in the ranges 0.6mph to 2.9mph for decreases in speed, 3–4 percent for lost capacity, and 3–5 percent for increases in the accident rate. While small, such effects could prove critical on roads already near capacity or with high accident rates.

7.3.2 Median Width

The appropriate width for a median depends on the median's primary function. For a paint-striped or raised-curb median intended only to separate oncoming traffic, 2 to 6 feet is sufficient (AASHTO 2001). Medians providing left-turn lanes, including the two-way left-turn lane (TWLTL), require widths of 10 feet to 16 feet and, on high-volume roads, 18 feet (a 12-foot-wide left turn bay and a 6-foot medial separator) to ensure safe separation of left-turn vehicles from oncoming traffic. When necessary, however, the width for such medians on high volume roads can be reduced to a minimum of 12 feet (10 foot left turn bay and 2 foot medial separator). If a median also provides room for passenger cars to pause perpendicular to the roadway in the median as they cross the street, the width should be 18-25 feet.

Medians serve numerous functions: barriers to oncoming traffic, recovery areas for errant vehicles, stopping areas in case of emergencies, space for acceleration and deceleration, storage for turning or crossing vehicles, width for future lanes, refuge for pedestrians, traffic calming, road beautification, roadway delineation, etc. Because these functions are so varied and complex, evaluations of retrofits that involve anything beyond marginal changes to the median require a specialist's expertise.

7.3.3 Elimination of Motor Vehicle Lanes or Medians

Elimination of motor vehicle lanes is rarely a feasible way of making room for a bicycle facility. Generally, the roadways that are candidates for retrofitted bicycle facilities are near capacity at current traffic levels or at the traffic levels forecast for the near future. Only in the rare situations where the current and forecast traffic volumes are significantly under capacity would elimination of a motor vehicle lane make sense in a bicycle facility retrofit.

Elimination of medians is equally unlikely. Studies have shown that medians with left turn lanes reduce accident rates between 11-44 percent and substantially reduce delays by removing turning vehicles from the through lanes (Bowman and Vecellio 1994, Bonneson and McCoy 1997). These benefits would also be lost in converting one of these medians to 2–6 ft paint-striped or raised-curb median. Eliminating a non-traversable median would permit oncoming vehicles to collide and allow cross-traffic to traverse the street at any point.

In some scenarios, however, elimination of a motor vehicle lane or a median may warrant some consideration in designing a bicycle facility retrofit. One such scenario is a four-lane, undivided road with high left-turn volume. On these roads, some local transportation authorities have implemented *road diets* that eliminate one through lane in each direction to make room for a two-way left-turn lane and allocations of space for other uses (see Figure 7.21). These other uses include landscape and facilities for bicycles, parking, and pedestrians. Diets have been applied on roads with average daily traffic levels ranging from 8,000–24,000, and the before-after reductions in accident rates have been between 17–62 percent (Huang et al. 2002, Knapp et al. 1999, Sallaberry 2000). A road diet in San Francisco undertaken specifically to add bicycle facilities witnessed an increase in bicycle traffic of 144 percent. The criterion for a successful execution of a road diet appears to be relatively simple: the street must function as a de facto three-lane segment because left-turn volumes are sufficiently high as to block travel in the inner two lanes for most of the day.

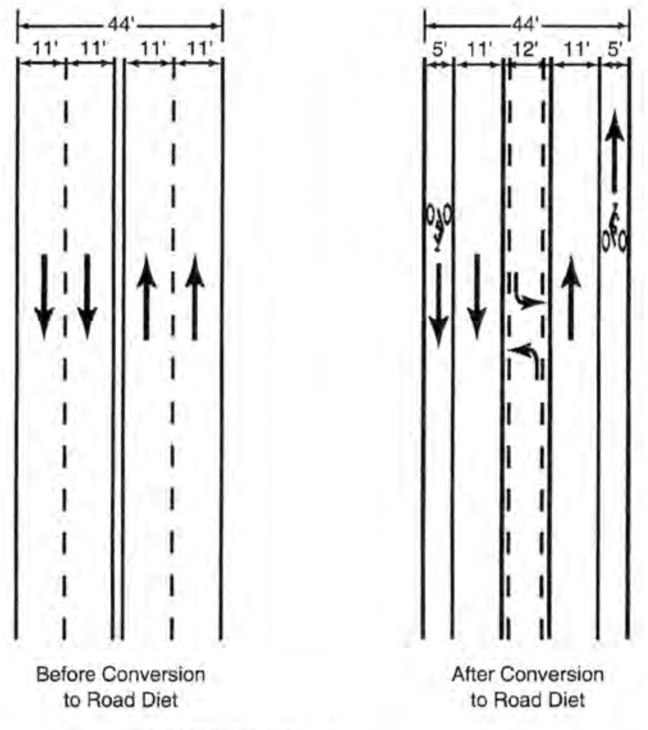


Figure 7.21. Before/after illustration of a road diet to provide bike lanes (From Huang, Stewart, and Zegeer 2002)

7.3.4 Bicycle Facility Type

Compared to wide outside lanes, bike lanes provide higher operational and comfort levels under all conditions, except perhaps very low traffic volumes on exclusively residential streets. The retrofit design example with the Excel Workbook in Section 7.2 displayed this pattern, which additional trials will corroborate. On wide outside lanes, cyclists ride extremely close to the curb, and motorists encroach on the adjacent lane quite frequently. Figures 7.22 and 7.23 depict this occurrence. Both behaviors indicate low operational and comfort levels. In addition, wide outside lanes usually score one point higher (less comfortable) on the BCI than do comparable bike lane facilities. Nonetheless, it is important to know the range of widths available for both types of facilities for the process of preparing retrofit proposals.

Figure 7.22. Typical cyclist and motorist lateral position on a wide outside lane (14 ft wide outside lane)

Figure 7.23. Typical cyclist and motorist lateral position on a roadway with a bicycle lane (10 ft motor vehicle lane and 4 ft bicycle lane)

7.3.5 Wide Outside Lane Width

TxDOT requires a minimum width of 14 feet for wide outside lanes, the standard recommended by the American Association of State Highway and Transportation Officials (AASHTO). For roadways where cyclists need more room for maneuvering, 15 feet of width is preferred; such roadways can include those with steep uphill grades, roadside objects such as drainage grates, and on-street parking (AASHTO 1999). On roadways without such problems, outside lanes with continuous stretches wider than 14 feet will often prompt sharing of the lane by two cars. For these roadways, the creation of a bike lane should receive serious consideration.

7.3.6 Bike Lane Width

In 1994, TxDOT adopted AASHTO's *Guide for the Development of Bicycle Facilities* for use when considering bicycle accommodations. The guidelines for bike lane width in this publication can be somewhat confusing and complicated, but the following sentences will summarize their essential indications, which are much simpler. A cyclist needs 5 feet of operating space free of roadside obstacles like curb faces, guard rails, and parked cars (AASHTO 1999).[xv] Within this operating space, there should be at least 4 feet of pavement contiguous with the outside motor vehicle lane. If the seam between the gutter pan and the road is smooth, the entire width can be counted as pavement width to ride as long as a minimum of 3 feet of this width is provided by the road. This requirement prevents cyclists, who generally travel in the middle of the pavement designated as a bike lane, from repeatedly traversing the seam of the gutter pan and roadway in the natural meandering that occurs in cycling. Additional width beyond 4 feet of roadway pavement for riding and 5 feet of operating space is always preferable where motor vehicle speeds exceed 50 mph and substantial truck traffic is present. However, it is important that in the process of providing additional width, the purpose of the lane remain clear and not be perceived as a through or turn lane for motor vehicles. Lastly, if the bike lane is not segregated from on-street parking facilities by an outside line or parking stalls, 11 feet of width should be allotted to this combined facility in the absence of a curb face and 12 feet in the presence of one.

7.3.7 Parking

Design features such as added width for bicycle lanes (see previous paragraph) can mitigate the potential traffic conflicts between cycling and vehicle parking (AASHTO 1999). Inherently, however, angled on-street parking is extremely dangerous for cyclists. Converting angled parking to parallel parking can create additional width for bicycle facilities and provide a safer parking situation for cyclists. However, this conversion will decrease parking capacity and thus may be politically or economically unpalatable.

In other situations, reducing or eliminating parking to create space for bicycle facilities can also make traffic engineering sense. But in many cases, economic and political factors effectively rule out this option.

7.4 Conclusion

The *Texas Bicycle Facility Retrofit Guide* represents the synthesis of much information regarding the design of bicycle facilities. Almost a dozen individuals from TxDOT and the Center for Transportation Research, several of whom commute by bike daily, met to evaluate research findings for the purpose of forming an effective final product. The field research component represented nearly 200 hours of observations and the hard work of many cyclists, both activists and casual riders. The research team exhausted literature on the topic and probed local sources of information such as crash records for all that could be gleaned from them and used in retrofit operations. The incorporation of the BCI and the help of its authors were invaluable. The addition of information regarding cyclist and motorist behavior from the PEM to the BCI greatly increased the efficacy of both. Without exaggeration, the creation of the Texas Bicycle Facility Retrofit Guide represents a bold move forward in incorporating rigorous research into the process of providing better bicycle facilities for the sake of all road users.

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Appendix A: Test Site Characteristics

City	Site	Facility Type	Lane Width (ft)	Bike Lane Width (ft)	Adjacent Space	Average Speed (mph)	Traffic Volume (veh/h)	Truck Traffic (%)
Austin	Barton Springs	BL	9.8	4.3	Same-Direction Lane	34	234-376	2-8
			10.2	3.9				
Austin	Oltorf	BL	9.7	5.0	Same-Direction Lane	46	140-346	1-5
			9.7	4.6				
Austin	Congress	BL	11.3	5.6	Same-Direction Lane	39	458-887	3-8
			11.6	6.3				
Austin	Hancock	BL	10.0	4.3	Opposing Lane	38	148-502	1-4
			11.6	5.8				
Austin	Woodrow (North)	BL	14.0	4.8	Opposing Lane	34	124-314	1-4
			14.6	4.7				
Austin	Woodrow (South)	WOL	19.5	N/A	Opposing Lane	33	82-156	2-7
Austin	Manor (East)	BL	10.0	6.0	TWLTL	34	142-588	4-13
			10.4	5.8				
Austin	Manor (West)	BL	11.5	5.8	Opposing Lane	31	200-516	5-15
San Antonio	Henderson Pass	BL	9.8	5.0	TWLTL	35	346-732	0-7
			9.5	5.0				
San Antonio	Encino Rio	BL	11.6	5.0	TWLTL	35	214-460	1-8
			11.6	4.7				
San Antonio	Zarzamora	WOL	18.2	N/A	Opposing Lane	31	236-536	2-5
San Antonio	Ingram	BL	10.6	4.7	Same-Direction Lane	41	322-514	1-3
			10.8	3.9				
San Antonio	Callaghan (North)	WCL	15.0	N/A	Same-Direction Lane	44	112-192	0-14
San Antonio	Callaghan (South)	BL	10.5	4.7	Same-Direction Lane	49	28-190	0-11

Test site characteristics (continued)

City	Site	Facility Type	Lane Width (ft)	Bike Lane Width (ft)	Adjacent Space	Average Speed (mph)	Traffic Volume (veh/h)	Truck Traffic (%)
Houston	Memorial	WOL	13.7	N/A	Same-Direction Lane	40	51-500	0-6
Houston	Blalock	BL	9.6	4.0	Same-Direction Lane	40	218-366	1-10
Houston	Westview	WOL	13.8	N/A	Opposing Lane	33	208-466	2-12
Houston	Westpark (East)	BL	10.1	4.7	TWLTL	36	280-665	1-4
Houston	Westpark (West)	BL	10.1	4.3	Same-Direction Lane	37	250-362	1-4
Houston	Richmond	BL	9.5	3.8	Same-Direction Lane	40	224-552	1-8
Houston	Crosstimbers	BL	9.5	3.8	Same-Direction Lane	38	174-226	7-16
Houston	Morningside	BL	10.1	6.0	Opposing Lane	28	64-212	0-3
Houston	Lyons	BL	12.8 12.0	4.8 5.0	Opposing Lane	32	180-284	2-14

End Notes

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[i] The BCI was developed by David L. Harkey, Donald W. Reinfurt, Matthew Knuiman, J. Richard Stewart, and Alex Sorton at the University of North Carolina Chapel Hill's Highway Safety Research Center for the Federal Highway Administration (FHWA Report Number: FHWA-RD-98-072). Permission to use the BCI, adapt the BCI Excel Workbook, and use material/examples from associated publications was granted by David Harkey.

[ii] The PEM was developed by Randy Machemehl, David Luskin and Ian Hallett at The University of Texas at Austin's Center for Transportation Research for the Texas Department of Transportation (Project Number: 0-5157).

[iii] The Highway Safety Research Center at University of North Carolina, Chapel Hill, is currently working on a BCI applicable to intersections that should be incorporated in future modifications of this guide.

[iv] Much of the material following this point is summarized from Harkey et al. (1998) as the PEM was adapted to work within the Excel Workbook designed for the BCI. However, important differences exist in how data is used in this synthesis of the BCI and PEM. Following input procedures from the BCI literature would result in mistaken results from the Excel Workbook accompanying this guide.

[v] "Prior research has shown that 85th percentile speeds for vehicles traveling on many urban and suburban streets (including arterial, collector, and local classifications) generally exceed the speed limit by 6mph to 14mph" (2).

[vi] The distribution of traffic among lanes traveling in the same direction is assumed to be equal in this guide because the myriad of factors that influence this distribution like number and location of access points, type of development, traffic composition, speed, volume, and local driving habits make it hard to calculate. To the extent that actual traffic distribution between lanes in the same direction is known, it should be incorporated into the inputs.

[vii] While data is not available from urban arterials and collectors, data collected on freeways indicates that approximately 80% of trucks travel in the curb lane.

[viii] Research undertaken for the BCI determined that 30% or more of the parking spaces had to be filled to affect the comfort level of cyclists. The PEM does not respond to the influence of parking at this time.

[ix] Parking turnover was found to negatively influence cyclist comfort in the BCI research. It does not affect the PEM measures.

[x] For a complete discussion of the method used to correlate BCI with LOS designations, see pages 33-36 of Harkey et al. (1998).

[xi] Motor vehicle speed is an example of a traffic characteristic that can causes changes in comfort level without affecting cyclist or motorist behavior. An increase in speed makes both uneasy, but there is not much the either can change in his or her lateral position to mitigate this affect. The same observation is true for curb lane volume.

[xii] It should be noted that fourteen feet is the minimum acceptable width by TxDOT for a wide outside lane bicycle facility and is two feet wider than the minimum width suggested by AASHTO.

[xiii] This adjustment to the t-factor exemplifies the type of professional judgment and holistic thinking on which the successful implementation of this guide depends.

[xiv] This is an excellent example of how a change in cyclist comfort level does not predict how the cyclist will actually behave on the roadway. The comfort level could, however, indicate how likely a cyclist is to use the retrofit facility, but this has not been addressed in either tool or associated research study.

[xv] The directions regarding measurements of bike lane and shoulder width presented in chapter two should not be construed to indicate acceptable widths. The Excel Workbook makes adjustments unseen by the user in generating results that depend on these measures.