RESEARCH

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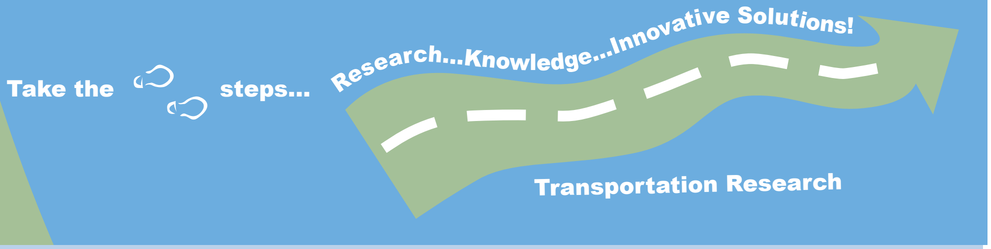
Cross Median Crashes: Identification and Countermeasures



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16. Abstract (Limit: 200 words)

The goals of this project were to first review the state-of-art with regard to identifying highway sections where median barriers would be most effective in preventing median-crossing crashes (MCC), and if necessary, develop remedies for any identified deficiencies. A statistical technique was developed for estimating the frequency and rate of MCCs on each of a set of highway sections, which required the analyst to review only a subset of hard-copy accident reports. This technique was applied to Minnesota's freeways and rural expressways, and highway sections were ranked with respect to estimated frequency of MCCs. A first version of a simulation model was developed for comparing the cost-effectiveness of barrier projects on different highway sections. The model uses Monte Carlo simulation to estimate the probability that an encroaching vehicle crosses a median with a specific cross-section, and collides with another vehicle traveling in the opposite direction. The model is implemented as a pair of linked Excel spreadsheets, with a companion macro written in Visual Basic for Applications.

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CROSS MEDIAN CRASHES: IDENTIFICATION AND COUNTERMEASURES

Final Report

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Executive Summary

An important crash type targeted for reduction in Minnesota's *Strategic Highway Safety Plan* is the median-crossing crash (MCC), where a vehicle departs its traveled way to the left, traverses the separation between the highway's directional lanes, and collides with a vehicle traveling in the opposite direction. The primary countermeasure for preventing MCCs, identified in *Roadside Design Guide* published by the American Association of State Highway and Transportation Officials, is placement of barriers in the median. Consequently, the Minnesota Department of Transportation (Mn/DOT) has embarked on a program of using median barriers, primarily cable guardrail, to reduce the frequency of MCCs.

The goals of this project were to review the state-of-art with regard to identifying highway sections where median barriers would be most effective, and if necessary, develop remedies for any identified deficiencies. The review concluded that, at present, no off-the-shelf method currently exists that adequately addresses this issue. A statistical technique was then developed for using crash records to estimate the frequency and rate of MCCs on each set of highway sections, which required an analyst to review only a subset of hard-copy accident reports. This technique was applied to Minnesota's freeways and rural expressways. Estimates which allowed highway sections to be ranked with respect to estimated frequency of MCCs, estimated density of MCCs, or estimated MCC rate were computed, and the results of one such ranking were reported. Finally, a first version of a simulation model was developed for comparing the cost-effectiveness of barrier projects on different highway sections. The model uses Monte Carlo simulation to estimate the probability that an encroaching vehicle crosses a median with a specific cross-section, and collides with another vehicle traveling in the opposite direction. The model is implemented as a pair of linked Excel spreadsheets, with a companion macro written in Visual Basic for Applications.

Chapter 1
Introduction

An important type of road crash, targeted for reduction in Minnesota's *Strategic Highway Safety Plan*, is the median crossing crash (MCC). In an MCC, a vehicle departs its traveled way to the left, traverses the separation between the highway's directional lanes, and collides with a vehicle traveling in the opposite direction. The primary countermeasure identified in the *Roadside Design Guide*, published by the American Association of State Highway and Transportation Officials (AASHTO), for preventing MCCs on divided highways, is the placement of barriers in the median separating the directions of travel. Consequently, the Minnesota Department of Transportation (Mn/DOT) has embarked on a program of using median barriers, primarily cable guardrail, on sections of divided highway in order to reduce the frequency of MCCs. At present though, in any given year, the cost of installing guardrail on all feasible locations exceeds the available funds, and it is desirable to have a rational method for identifying those guardrail projects that should be given a higher priority.

For relatively frequent types of crashes, such as those occurring at urban and suburban intersections, well-established statistical tools exist for screening large numbers of locations and identifying those that appear to show atypically high crash risk. For certain types of crashes that tend to be too infrequent to support application of statistical methods, such as road-departure collisions with fixed objects, simulation tools are available to help identify those improvement projects that should be given priority. Median-crossing crashes however appear to have fallen through the cracks. Statistical applications are difficult, partly because MCCs also tend to have a low spatial density, but even more because MCCs are rarely identified explicitly in computerized crash records. And the available simulation tools explicitly state that they do not apply to MCCs.

The objectives of this project were to first review that state-of-art with regard to these issues, and if deficiencies were identified, develop remedies. To this end, Chapter 2 reviews recent literature on criteria for assessing locations with regard to MCC risk, and concludes that, at present, no off-the-shelf method exists that adequately addresses these issues. Chapter 3 then takes up the problem of using observed crash data to rank locations with regard to MCC risk. A new statistical technique, which only requires the analyst to review a subset of hard-copy accident reports, is developed and applied to Minnesota's freeways and rural expressways. Estimates which allow highway sections to be ranked with respect to estimated frequency of MCCs, with respect to estimated density of MCCs, or with respect ot estimated MCC rate, are computed and the results of one such ranking are reported. Finally, Chapter 4 describes a simulation model for comparing the cost-effectiveness of barrier projects on individual highway sections. The development of this model drew heavily on the median encroachment data collected by Hutchinson and Kennedy (1966). The model uses Monte Carlo simulation to estimate the probability an encroaching vehicle crosses a median with a specific cross-section, and collides with another vehicle traveling in the opposite direction. The model is implemented as a pair of linked Excel spreadsheets and companion macro written in Visual Basic for Applications.

Chapter 2
Selecting Sites for Median Barriers: A State of Practice Review

In a median-crossing crash (MCC) a vehicle departs its traveled way to the left, traverses the separation between the highway's directional lanes, and collides with a vehicle traveling in the opposite direction. The primary countermeasure for preventing MCCs on divided highways is placing barriers in the median. Task 1 for this project was to conduct a state-of-art review regarding how highway sections are, or should be, selected for such median barrier installation. Our overall finding is that MCCs are currently an active topic for research, with several national and state-based projects that were either recently completed or are in progress. The products of these projects have included summaries of practices regarding median barriers, so it is not our intention to duplicate this existing work. Rather, we will summarize this work where appropriate, and focus on the main issue at hand, determining the degree to which any of these methods might help decision-making in Minnesota.

To begin then, rational decision-making regarding median barrier placements can be regarded as a special case of a problem frequently confronting safety engineers. At any given time the list of locations where safety treatments could be administered outstrips the resources available, so that some selectivity is required. This selection problem is often usefully divided into two subtasks: (1) screening the hundreds, or even thousands, of possible locations for those most in need of intervention, and (2) designing and evaluating treatment plans for a smaller number of selected locations. For crash types that tend to be relatively frequent, such as multiple-vehicle crashes at intersections, statistical procedures for addressing each of these component tasks continue to be developed and refined, and the *Highway Safety Manual* being developed by the Federal Highway Administration and the Transportation Research Board, is expected to present a relatively mature methodology for implementing this (Hughes et al 2004). However, roadway departure crashes in general, and cross-median crashes in particular, tend to be relatively infrequent, and statistical methods for these crash types tend to be less well-developed. Over the past several years a number of states have shown interest in using median barriers as a MCC countermeasure, and this interest has highlighted weaknesses in the existing methods for identifying promising locations, and for evaluating the effects of barrier placement. Reflecting this interest, over the past 10 years a not inconsiderable literature has been generated on these issues, including recently completed efforts funded by the Pennsylvania Department of Transportation, by the National Cooperative Highway Research Program, and by the Texas Department of Transportation.

Screening for Sites Most in Need of Treatment

The goal here is identify, from a large number of locations, those which appear to be especially at risk for MCCs. Roughly speaking there are two general methods for doing this, one based on statistical analysis of crash histories, and one based on warrants.

AASHTO Roadside Design Guide

A warrant-based method is given in AASHTO's *Roadside Design Guide* (RDG). In the 2006 edition, this guideline is summarized in the RDG's Figure 6.1. A median barrier is recommended for a highway section with an average daily traffic volume (ADT) greater than 20,000 vehicles/day and a median width less than 30 feet. Barriers should be considered for sections with ADTs greater than 20,000 vehicles/day and median widths between 30 and 50 feet, and barriers are optional for sections with medians wider than 50 feet. One advantage of this warrant is that it is based on readily obtained data and so is easy to apply.

NCHRP 17-14

One objective of NCHRP Project 17-14, "Improved Guidelines for Median Safety," was to review current practice regarding median barrier placement and compare these to the AASHTO warrant. A draft copy of the project report was loaned to the PI by the NCHRP, for the purposes of this review. A major component of NCHRP Project 17-14 was a survey of state departments of transportation (DOT), to which 35 state DOTs responded. California and Maryland reported using barrier warrants, based on combinations of median width and ADT, that were different in their details from the AASHTO warrant, the general effect being to allow barriers on roadways with median widths greater than 50 feet. California and Florida also reported use of warrants based on crash history. NCHRP Study 17-14 also reviewed cross-median crash data from North Carolina, where it appeared that over half of MCCs occurred on highway sections with ADTs and/or median widths falling outside AASHTO's "barrier recommended" region.

Statistical Methods

An alternative to warrant-based methods is to use crash data to identify locations that appear to be atypically dangerous when compared to other, ostensibly similar, locations. The primary data needed for this are counts of crashes of a given type at each location in the population, which are usually obtained by searching and tabulating computerized crash records. The oldest of these methods is known as the rate quality control method, where crash rates are estimated for each individual site and then compared to an aggregate estimate. Those sites whose individual estimated rates are significantly higher than the aggregate estimate are then identified. More recently, empirical and hierarchical Bayes methods have also been applied to this task, these methods having the advantage that site features other than exposure can be included in the analysis. One first develops a statistical model which relates expected crash frequency to observable site characteristics, such as traffic volume, section length, or median width, and then computes, for each site, an estimate of its expected crash frequency. This estimate is essentially a weighted combination of the model's prediction and the actual crash count. This allows the analyst to identify sites where the expected crash frequency is high compared to sites with similar characteristics. A detailed application of this approach to the problem of identifying potentially hazardous stop-controlled intersections on Minnesota expressways has been described in Davis et al (2006).

A search of existing literature failed to turn up an application of either the rate quality control method or a Bayesian method for identifying or ranking locations with regard to

MCC risk. This is probably due, at least in part, to the fact that most crash reporting systems do not explicitly identify MCCs as a separate crash type on computerized crash records. Determining an observed frequency of MCCs on a road section must then be done by reviewing the narratives provided on the original crash report forms, and this need for manual review severely limits the usefulness of statistical screening methods.

Overall then, there appears to be some diversity in the practices used by the states regarding placement of median barriers. Warrant-based methods are at present the primary tools for identifying situations where median barriers may be required. Overall, roads with medians narrower than 30 feet are most likely to satisfy warrants, while for roads having medians wider than a threshold, which ranges from 50 feet to 80 feet depending on the actual warrant, the risk of MCCs is considered low enough to not normally require a barrier. Roads with intermediate median widths may or may not satisfy a warrant, depending on their traffic volume. An analysis of MCC data from North Carolina indicated however, at least in that state, that MCCs do occur on roads with medians wider than these thresholds, so the warrants alone are not sufficient to prevent MCCs.

Statistical Modeling of MCCs

Arguably, a warrant for median barriers should have a relation with expected risk for MCCs. Those locations where a barrier is recommended should, other things equal, be more likely to experience MCCs, while at those locations where the warrant indicates that a barrier is optional MCCs should be relatively infrequent. The existing warrants rely primarily on traffic volume and median width, but a quantitative connection between these variables and expected MCCs was not made explicit, and so it is difficult to compare different warrants, or to evaluate the effect of changing a warrant. Several recent efforts have sought to remedy this lack through statistical modeling of MCC frequency.

Pennsylvania Study

The Pennsylvania study (Donnell et al 2002) was led by researchers at the Pennsylvania State University, and funded by the Pennsylvania Department of Transportation and the Federal Highway Administration. This study focused on cross-median crashes on Pennsylvania freeways and expressways. Computerized crash records and road inventory data for the years 1994-1998 were compiled, with totals of about 2500 miles for freeways, and 1400 miles for expressways. Since Pennsylvania's computerized crash records did not identify median-crossing crashes explicitly, hard copies of crash reports for candidate crashes were studied. 267 cross-median crashes were identified, with 52% of these being on Interstate highways, and 48% on expressways. It was also determined that about 57% of the MCCs occurred on roadway sections with median widths greater than 50 feet, where the RDG indicates "barrier optional," while only 12% occurred where the current RDG indicates "barrier recommended."

Generalized linear modeling was used to relate the average daily traffic and median width of a road section to the expected number of MCCs. Two models were developed, which for interstate highways, took the form:

$$N1_{MCC} = \left(\frac{1}{5}\right) e^{-10.308}(L)(ADT)e^{-.0216W}$$
$$N2_{MCC} = \left(\frac{1}{5}\right) e^{-18.203}(L)(ADT)^{1.770}\, e^{-.0165W} \tag{2.1}$$

where

N_{MCC} = expected number of MCCs per year per direction, all severity levels,
L = section length (miles),
ADT = directional average daily traffic (vehicles/day),
W = median width (feet).

In the first model, the expected number of MCCs is proportional to the average daily traffic on a section, while for the second model the expected number of MCCs is disproportionately higher for sections with high ADTs. On a 5-mile section of freeway with a directional ADT of 15000 and a median width of 60 feet, one would expect, for that direction, about 0.137 MCCs per year using the first model, or 0.114 MCCs per year using the second.

The authors also assessed the goodness of fit provided by these models, and reported that it was relatively poor. That is, after accounting for ADT, section length and median width, a substantial amount of variability remained in the MCC frequency data. This suggests that unmeasured, site-specific variables may also be contributing to MCC frequency.

NCHRP Project 17-14
As indicated earlier, the National Highway Cooperative Research Program funded a major effort to review state practices regarding median barriers, and to recommend possible changes in the RDG median barrier warrant. *A draft copy of the project report was obtained for the purposes of this review. However, the report is still under revision, and the material described in the report has not yet been approved for dissemination by the NCHRP.*

Texas Study
As part of the trend toward reevaluating practices regarding median barriers, the Texas Department of Transportation funded a team at the Texas Transportation Institute to investigate this issue (Miaou et al 2005). The research team identified 52 Texas counties where a preponderance of potential MCCs occurred, and requested hard copies of crash reports for 791 potential MCCs, for the years 1998-1999. Inspection of the crash reports identified 443 apparently genuine MCCs. Roadway inventory data were also compiled, but data limitations prevented separate directional analyses. Generalized linear modeling was used to relate MCC frequency to measured site features, and the result was a model with the form

$$N_{MCC} = \left(\frac{365(ADT)(L)}{1000000}\right)\exp(-3.779 + (1.163)year - (.011)W - (.293)nlane + speed) \quad (2.2)$$

where

N_{MCC} = expected number of MCCs per year, both direction, all severity levels
ADT = total (not directional) ADT (vehicles/day)
L,W are as defined above
year = 0 for 1998, 1 for 1999,
nlane = number of lanes,
speed = -.139 for 60 mph speed limit
.5, for 65 mph speed limit
.284, for 70 mph speed limit.

Setting year =0.5, on a 5-mile, four-lane section to highway with 60-foot median, a total ADT of 30000 vehicles/day, 4 lanes and a speed limit of 60 mph we would expect about 0.312 MCCs per year, or about 0.156 MCCs per direction per year, which is roughly comparable with what the Pennsylvania models produce. Note though that for 65 mph and 70 mph speed limits, the Texas model gives predicted MCC frequencies of 0.296 and 0.238 MCCs per direction per year, respectively.

The models described above identify traffic volume and median width as important predictors of MCC frequency. The Texas study also found that the number of lanes and the speed limit were useful, and appears to have detected a time trend in MCC frequency. The models can differ by as much as a factor of 2 with respect to the MCC frequencies predicted for approximately similar conditions. This last tendency is troubling, and it is not clear if it is due to actual differences in crash tendencies in the different states, to differences in how MCCs were identified and counted, or to some other difference. This means though that none of the models should be naively applied to Minnesota highways with an expectation of producing reliable results.

Evaluating Proposed Designs

The second major subtask in selecting locations for median barrier treatments is evaluation of actual designs for a limited number of selected sites. For other crash types and other types of countermeasures, a commonly-used method for accomplishing this is to compare the benefits resulting from a reduced number of crashes to the costs associated with the countermeasure. For situations where crashes are frequent enough to justify statistical approaches, the crash reduction effect of a countermeasure can be predicted by multiplying the number of crashes expected without the countermeasure by a crash reduction factor (CRF). The methodological issues that arise when estimating CRFs are now reasonably well-understood (Hauer 1997), and this approach is the backbone of the *Highway Safety Manual* methodology.

Our review turned up several published reports comparing MCC experience before and after installation of median barriers, the general trend being that MCC counts tended to be lower after barrier installation, while barrier collisions tended to increase. (Johnson 1966; Murthy 1992; TRB 1992; Strasburg and Crawley 2005). However, none of these studies appeared to have used the controls generally regarded as necessary for estimating causal effects from observational before-after studies, so their results, although suggestive, cannot be used to predict reductions in MCCs. The authors of the Texas study indicated that reliable estimation of median-barrier CRFs was one of the objects of their effort, but that the experience with barrier installations in Texas was not yet extensive enough to support this.

Simulation Models

Statistical models such as those described earlier require crash frequencies high enough so that estimates of reasonable accuracy can be obtained with a reasonable amounts of data. As indicated above, using a large number of sites, regression-type models can be developed which relate expected MCC frequencies to observable site features, such as ADT and median width. Because MCCs tend to be infrequent, obtaining reliable estimates at individual sites is rarely feasible, and evaluation of site-specific improvement plans requires an alternative methodology. This situation characterizes road-departure crashes in general, especially on rural roadways, and over the past 40 years, increasingly sophisticated versions of encroachment/collision models have been developed to address this situation. A detailed review of the history of these modeling efforts has been provided by Mak and Sicking (2003). Highlights of the modeling effort include Glennon's (1974) graphical method, the DOS-based program ROADSIDE, which was included in the 1996 edition of the *Roadside Design Guide*, and the Roadside Safety Analysis Program (RSAP), which is currently included with the 2006 edition of the RDG. It should be noted that all these efforts have focused on modeling collisions between vehicles and objects on the roadside, and that none directly address the problem of modeling MCCs. Since RSAP is the most advanced routine available to date, we will briefly outline its workings.

RSAP's method can be summarized by the following equation,

$$E(C) = VP(E)P(C|E)P(I|C)C(I) \qquad (2.3)$$

where

$E(C)$ = estimated cost of collisions with severity level I,
V = traffic volume during design life,
$P(E)$ = probability a vehicle traversing the section of interest encroaches onto the roadside,
$P(C|E)$ = probability an encroaching vehicle collides with an object on the roadside,
$P(I|C)$ = probability a collision has a severity level I,
$C(I)$ = estimated cost of collisions with severity level I.

In RSAP, the encroachment probabilities P(E) are based on estimates derived from Cooper's (1980) study of vehicle encroachments on Canadian highways. The collision probabilities P(C|E) are determined by randomly assigning each simulated encroaching vehicle a point of departure, an angle of encroachment, and a distance to be traversed. These three characteristics, together with the vehicle's size, then determine the swath tracked by the vehicle during its encroachment, and if an object lies in that swath the simulated encroachment results in a collision. Monte Carlo simulation of a large number of such encroachments then gives an estimate of P(C|E). The severity probability P(I|C) is based on assigning the colliding vehicle an impact speed, which in turn is based on empirical work by Mak et al (1986). Probabilities of collisions resulting in fatalities, severe, moderate, or slight injuries, or two levels of property damage, are essentially found by table look-up. Each of these injury severities is then assigned a cost based on another table look-up.

RSAP is arguably the state-of-art tool for weighing the costs and benefits of roadside improvement projects. Nonetheless, in its current form, it is not designed to evaluate the need for median barriers. The RSAP *User's Guide* states "The RSAP program is intended for ran-off-road crashes and cannot handle cross-median, vehicle-to-vehicle type crashes. Thus, you cannot evaluate the need for a median barrier directly" (p. 97). The *User's Guide* then outlines an approximate procedure where a cross-median crash is simulated in RSAP as a fixed object collision at the far edge of a median. This approximation requires the user to have an estimate of the probability that an encroachment results in a median-crossing collision, P(C|E), and estimates of the probability distribution over severity levels, for MCCs.

Conclusion

The main object of this review was to assess the current practice for identifying which highway sections ought to receive median barriers as a countermeasure for cross-median crashes. Compared to practices regarding other crash types and countermeasures, it seems clear that the situation for MCCs and median barriers is less well-developed. For example, when considering installation of a traffic signal at an intersection as a safety countermeasure, well-developed statistical procedures exist for identifying intersections with atypically high crash experience, and defensible estimates of crash reduction factors, for different collision types, are available (McGee et al. 2003). On the other hand, when considering fixed object collisions on roadsides, encroachment envelope models are available for estimating the costs and benefits of particular designs. Neither of these approaches is, at present, available for evaluating the effectiveness of median barrier placements. In part this is due to methodological features peculiar to MCCs. This crash type is not often explicitly identified on computerized crash records, and MCCs tend to be infrequent on any given section of road, so that routine application of statistical methods is difficult. On the other hand, simulating a MCC requires not only modeling encroachment and traversal of the median, as is done for fixed object collisions, but modeling the interaction of the encroaching vehicle with opposite direction traffic.

In summary then, there does not appear to be a method for programming median barrier placements that can be adopted without qualification in Minnesota. However, the relation between MCCs and median barriers is an active topic of research, and it is expected that this situation will be different in a few years.

Chapter 3
Estimated Frequency of Median-Crossing Collisions on Freeways and Rural Expressways

Tasks 2 and 3 of this project call for using statistical methods to identify locations showing atypically high tendencies for median-crossing collisions (MCC). The traditional approach to doing this is the rate quality control method, where each location's estimated crash rate is compared to a mean or aggregate value estimated for a population of sites. Those locations having an estimated crash rate significantly higher than the aggregate value are flagged as potentially high risk sites. More recently, empirical Bayes and hierarchical Bayes methods have also been applied to this problem. When crashes at the individual sites tend to be frequent, the rate quality control and Bayesian approaches tend to identify the same locations as high risk, but unlike the rate quality control method, the Bayesian methods do not employ large-sample approximations, and so are more justified in situations where crashes tend to be rare. In what follows we will use Bayesian statistical methods to estimate the frequency of median-crossing crashes when it is not possible to identify this crash type from computerized crash records, and for each site in a population, compute a probability that that site has an atypically high rate of median-crossing collisions.

Freeways

Data analysis began with a request to Highway Safety Information System (HSIS) for crash, roadway, and traffic data relevant to this project. The request was restricted to data from the years 2001-2005, inclusive, restricted to roadway segments classified as ISTH, USTH, or MNTH highways, and where the roadway segments was identified as divided, with either a raised or lowered median, and where no median barrier was present. The resulting request produced data on approximately 8900 roadway segments and 20,000 crashes per year.

Because there is evidence in the literature that MCC characteristics can differ for limited access and non-limited access facilities (Donnell et al 2002) it was then decided to conduct separate analyses for freeways and non-freeways. From the HSIS database, roadway segments classified as either rural or urban freeway segments were selected, together with the crash and traffic data associated with these sections. The majority of these sections were on the ISTH system, but some were USTH of MNTH highways if they were coded as functioning as limited access facilities. The number of freeway road segments for each year ranged between 921 and 967, with a total mileage of about 790 miles. The number of freeway crash records for each year ranged between 7817 and 9055. An additional selection was then done on the crash records to eliminate those crashes not likely to have been MCCs. Records for those crashes involving only one vehicle, or where the accident diagram code indicated it was either a rear-ending crash, or a crash where a vehicle ran-off the road to the right, were eliminated. Finally, since recent safety emphases have been on reducing fatal and severe crashes, only those crash records with severity categories of K,A, or B were retained. This resulted in between 135 and 187 crash records for each year.

Table 3.1. Database Size for Minnesota Freeway Sections.

Year	Road Segments	Crash Records Before Selection	Crash Records After Selection
2001	961	7817	155
2002	967	7582	174
2003	958	7959	168
2004	937	9055	187
2005	921	8595	135

Data Preparation and Preliminary Analyses

Ideally, median-crossing crashes would be identified explicitly in computerized crash records with a special code. Well-established methods for screening roadway locations for those showing atypically high risk or frequencies of median-crossing crashes, based on computerized crash records, could then be applied. However, Minnesota's crash records, like those of many other states (e.g. Donnell et al 2002; Miaou et al 2005), do not make this identification explicit. Determining whether or not a crash was a MCC then requires that a copy of the original accident report form be obtained, so that the investigating officer's narrative description of the event can be studied. This requirement for manual review of individual accident reports severely restricts the ability to apply computer-based screening methods to median crossing crashes.

To work around this problem, it was decided to apply an idea originating in epidemiology (Carroll et al 1993), where alternative tests for the presence of disease differ as to their cost and accuracy. Here, a smaller training sample of cases, where both an expensive but accurate test, and a less expensive but less accurate test have been applied, is used to characterize the accuracy of the less-expensive test. These results in turn can be used to estimate the fraction of cases testing positive on the less accurate test that actually have the disease. Similarly, if there exists information in a computerized crash record that shows a clear association with whether or not the crash was a median-crossing collision, this information can play the role of the less accurate test for a disease, while a smaller sample of crash reports can play the role of the training sample. To this end, data files containing the computerized crash records of the possible severe freeway MCCs for 2001 and 2004 were prepared, and copies of their crash reports were requested from Mn/DOT. These crash reports were studied to identify those which actually involved median-crossing collisions, and an additional data field indicating whether or not a crash was an MCC was added to the data files. Exploratory analyses were then carried out to identify which, if any, of the data fields appearing in the HSIS crash records were reliable identifiers of median-crossing collisions.

For the 2001 crashes, whether or not the accident diagram field was coded as '4,' which indicated a run-off to left, turned out to be the single most reliable predictor. Examination of other fields on the HSIS crash record, both separately and in combination with the accident diagram field, failed to produce better predictions. However, a case by case comparison of the crash reports and the computerized crash records revealed that in many cases the accident diagram code on the report differed from what finally appeared in the HSIS crash record. In particular, for many of the median-crossing collisions, the diagram code ‘4’ did not appear on the crash report even though it did appear in the computerized record. A similar case by case comparison of the 2004 crash reports and records did not reveal a similar discrepancy. Since significant changes were made to the state’s crash report form, which took effect in 2003, it was decided to restrict further analysis to data from 2003-2005, with the 2004 data being used as the training sample.

For the 2004 crash data, the most reliable predictor of whether or not a crash was a median-crossing collision was again the accident diagram field, but with a code of ‘8,’ which indicated a ‘head-on’ collision. Again, exploratory analyses using different fields from the HSIS crash record, separately or in combination with the diagram field, failed to produce a better predictor. Table 3.2 summarizes the relation between median-crossing collisions and the accident diagram code.

Table 3.2. Cross Tabulation of Potential Median-Crossing Collisions for 2004.

		Diagram Code=8?		
		Yes	No	Totals
Median-Crossing?	Yes	20	21	41
	No	14	132	146
	Totals	34	153	187

Of the 187 possible serious MCCs from 2004, 41 turned out to involve median crossing collisions, and of these, 20 we recorded as head-on collisions in the accident diagram field (i.e. coded as ‘8’). For the crashes that did not turn out to involve median-crossing collisions, 14 we coded as ‘head-on’ in the accident diagram field. A test for association produced a log odds-ratio statistic of 2.195, with an estimated standard error of 0.42. The corresponding z-statistic was 5.22, with a significance level of $p<0.001$.

Data files suitable for input into statistical analysis routines were then prepared from the 2003-2005 crash, roadway, and traffic files. It turned out that the definition of roadway sections varied somewhat from year to year, so the first task was to construct a consistent set of section definitions, and this ultimately produced a set of 915 sections. The resulting data files contained, for each section, its ADT values for 2003-2005, its length in miles, its HSIS median width information, and eight fields containing crash counts. Four of these fields were for 2004 data, with counts of the crashes with each combination of being a median-crossing collision, and having or not having an accident diagram code of ‘8’ were entered. For 2003 and 2005, only counts of the number of crashes with, and the number without, diagram codes of ‘8’ were entered.

It also turned out that a substantial fraction of the roadway sections had median width codes of ‘VR,’ the HSIS indicator that the median width varied within that section, but that no further information was available. Preliminary analyses using the year 2004 data indicated that while ADT and section length were reliable predictors of the number of median crossing crashes, median width was not, most likely due at least in part to the low variability in median widths for this sample. Since other studies have found median width to be a reliable predictor of MCC frequency, this result should *not* be interpreted as showing that median width is unimportant.

Statistical Model and Estimation Results

Based on the preliminary analyses, the following statistical model was then used to identify potentially high-risk sections. First, the number of median-crossing collisions in section number k was assumed to be the outcome of a Poisson random variable rate $\lambda_{1,k}$, while non-median crossing collisions were assumed to Poisson with a rate $\overline{\lambda}_0$. Next, median-crossing crashes were assumed to be classified as ‘head-on’ (i.e. with accident diagram code equal to ‘8’) with a probability p_1, while non median-crossing collision are classified as ‘head-on’ with a possibly different probability p_0. Finally, at each site the median-crossing crash rate was assumed to take the form

$$\lambda_{1,k} = \overline{\lambda}_1 \tilde{\lambda}_k \tag{3.1}$$

where $\overline{\lambda}_1$ denotes a mean collision rate for the population of sections, while $\tilde{\lambda}_k$ denotes site k’s deviation from the mean rate, due to unobserved, site-specific factors. Assuming that the $\tilde{\lambda}_k$ are independent, identically-distributed gamma random variables with expected values equal to 1.0 then leads to a version of the negative-binomial statistical model.

Table 3.3. Estimates of Freeway Model Population Parameters, Rate Units are Collisions/10 million VMT.

	Posterior Summary			
Parameter	Mean	Stand. Dev.	2.5%ile	97.5%ile
$\overline{\lambda}_1$	0.0336	0.0051	0.0245	0.0447
$\overline{\lambda}_0$	0.1229	0.0072	0.1093	0.1371
p_1	0.4223	0.0689	0.2904	0.5591
p_0	0.0863	0.0183	0.0531	0.1243
r	9.343	13.08	0.604	46.26

For 2004, each section’s counts of median-crossing and other collisions, broken down by whether or not the diagram code was ‘head-on’ provided the dependent variables, while to 2003 and 2005 the counts of crashes with and without ‘head-on’ codes were the dependent variables. Independent variables were the average ADT for each section and its length. Estimation of the model parameters was carried out using the Bayesian statistical software WinBUGS (Lunn et al 2000). WinBUGS produced Bayes estimates of the population parameters $\overline{\lambda}_1$, $\overline{\lambda}_0$, p_1, and p_0, and summaries for these estimates are given in Table 3.3. For each section, WinBUGS also produced an estimate of the number of median-crossing collisions experienced by that section during 2003-2005, and the probability that section's median-crossing collision rate is higher than the population mean. The results for the ten freeway sections with the highest estimated MCC frequencies are shown in Table 3.4, and a more comprehensive list is given in Appendix A.

Overall, median-crossing collisions that result in serious or fatal injuries appear to happen at a rate of 0.0336 collisions per 10 million vehicle-miles of travel, while the other collisions happen at about 0.1229 collisions per 10 million vehicle-mile of travel. A median-crossing collision will be coded as a head-on collision with probability 0.4223, while the other collisions are coded as head-on with probability 0.0863.

Table 3.4. 10 Freeway Sections with Highest Estimated 2003-2005 MCC Frequencies.

ID	E[mu]	E[mu]/length	P[lambda>1]	2003 aadt	2004 aadt	2005 aadt	length	width
626	2.919	0.62532134	0.6833	71260	71500	72215	4.668	VR
415	2.796	0.38353909	0.6848	34071	39000	39195	7.29	60
445	2.318	0.42917978	0.5043	95834	96792	94940	5.401	VR
757	1.889	0.48041709	0.5441	85767	84500	85345	3.932	30
125	1.795	0.31624383	0.6634	17895	22100	22210	5.676	54
653	1.759	1.19254237	0.6631	72278	72000	72720	1.475	40
569	1.686	0.63550697	0.5938	75332	76000	76760	2.653	VR
725	1.63	0.43259023	0.5918	44635	46250	46481	3.768	34
194	1.626	3.23904382	0.7025	55990	55000	55550	0.502	VR
365	1.367	0.25124058	0.6171	15266	15000	15075	5.441	54

Only 181 of the freeway sections experienced at least one potential serious MCC during 2003-2005, and so only those 181 sections had a possibility of non-zero expected MCCs during that time period. That is, if no relevant crashes occurred on a section, then the subset of median crossing collisions necessarily equaled zero. Listed in Appendix A are results from all freeway sections where the estimated number of median-crossing collisions during 2003-2005 was greater than zero. These are listed in descending order of expected crash frequency, and range from a high of about 2.92 median-crossing collisions to a low of about 0.113.

Freeway Results

The Table 3.4 lists, for each site, three clues as to its risk for median-crossing collisions. The first, E[mu], is the estimated number of such collisions occurring during 2003-2005. This estimate consists of a count of the actual number of MCCs occurring during 2004, together with appropriately weighted contributions of head-on and non head-on collisions from 2003 and 2005. The second is the crash density, E[mu]/length, which is obtained by dividing the estimated crash frequency by the section length. The third clue, P[lambda>0], is the probability that a site's $\tilde{\lambda}_k$ is greater than 1.0, which is equivalent to that site having a rate of median-crossing collisions that is greater than the overall population value of about 0.0336 collisions per 10 million vehicle miles of travel. A probability value greater than 0.5 can be interpreted as meaning that it is more probable than not that this site has an atypically high MCC rate.

The freeway section with highest estimated frequency of MCCs was number 626, with about 2.9 MCCs over three years. The estimated crash density for this section is about 0.63 crashes/mile, and the probability that this section has a MCC rate greater than the population mean is about 0.68. The section with the second highest estimated MCC frequency is number 415, with about 2.8 MCCs during the three-year period, and the probability this section has an atypically high MCC rate is about 0.685. Of the sections listed in Table 3.4, number 194 has the highest estimated crash density, about 3.2 MCCs/mile.

Rural Expressways

As noted above, there is evidence in the literature that MCC characteristics can differ for limited access and non-limited access facilities (Donnell et al 2002) and so it was decided to conduct separate analyses for freeways and rural expressways. Mn/DOT personnel provided a list of trunk highway sections classified as either rural or non-rural expressways, which included the system classification, route number, and milepost range for each section. These descriptors were then used to extract from the HSIS database roadway and accident data associated with the rural expressway sections. Accidents that were not likely to have been MCCs were then deleted from further consideration. This first selection eliminated records for those crashes involving only one vehicle, or where the accident diagram code indicated it was either a rear-ending crash, or a crash where a vehicle ran-off the road to the right, or where the severity code indicated possible injury of property damage only.

Copies of accident reports for the remaining potential 2004 MCCs were provided by Mn/DOT, and these were then inspected to determine if the crash was actually an MCC. Unlike freeways, the majority of these crash reports described angle and left-turn crashes occurring at intersections, so crashes with Location_Type codes of 4,5,6, or 7 were also removed from consideration. After also removing those crashes where the accident report was insufficient to determine whether or not a crash was an MCC, this left a total of 60 possible MCCs on rural expressways for 2004. Exploratory analysis then revealed that the most reliable predictor of whether or not a crash was a median-crossing collision was whether or not the accident diagram field contained a code of ‘4’ or ‘8’, which indicated either a ‘run-off road left’ or a ‘head-on’ collision. Table 3.5 summarizes the relation between median-crossing collisions and the accident diagram code.

Table 3.5. Cross Tabulation of Potential Median-Crossing Collisions for 2004.

		Diagram Code=4 or 8		
		Yes	No	Totals
Median-Crossing?	Yes	6	3	9
	No	7	44	51
	Totals	13	47	60

Of the 60 possible serious MCCs from 2004, 9 turned out to involve median-crossing collisions, and of these, 6 were recorded as ‘head-on’ or ‘run-off left’ collisions in the accident diagram field. For the crashes that did not turn out to involve median-crossing collisions, 7 were coded as ‘head-on’ or ‘run-off left’. A test for association produced a log odds-ratio statistic of 2.53, with an estimated standard error of 0.816. The corresponding z-statistic was 3.10, with a significance level of $p<0.01$.

Data files suitable for input into statistical analysis routines were then prepared from the 2003-2005 crash, roadway, and traffic files. As with the freeways, the definition of roadway sections varied somewhat from year to year, so the first task was to construct a consistent set of section definitions, and this ultimately produced a set of 528 sections, with a total mileage of about 770 miles. The average daily traffic on these sections varied between about 2900 and about 62000 vehicles/day. The resulting data files contained, for each section, its ADT values for 2003-2005, its length in miles, its HSIS median width information, and eight fields containing crash counts. Four of these fields were for 2004 data, with counts of the crashes with each combination of being a median-crossing collision or not, and having or not having an accident diagram code of ‘4’ or ‘8’, were entered. For 2003 and 2005, only counts of the number of crashes with, and the number without, diagram codes of satisfying the above condition were entered.

Statistical Model and Estimation Results

Based on the preliminary analyses, the following statistical model was then used to identify potentially high-risk sections. First, the number of median-crossing collisions in section number k was assumed to be the outcome of a Poisson random variable rate $\lambda_{1,k}$, while non-median crossing collisions were assumed to Poisson with a rate $\bar{\lambda}_0$. Next, median-crossing crashes were assumed to be classified as ‘run-off left’ or ‘head-on’(i.e. with accident diagram code equal to ‘4’ or ‘8’) with a probability p_1, while non median-crossing collision are so classified with a possibly different probability p_0. Finally, at each site the median-crossing crash rate was assumed to take the form

$$\lambda_{1,k} = \bar{\lambda}_1 \tilde{\lambda}_k \qquad (3.2)$$

where $\bar{\lambda}_1$ denotes a mean collision rate for the population of sections, while $\tilde{\lambda}_k$ denotes site k’s deviation of the mean rate, due to unobserved, site-specific factors. Assuming that the $\tilde{\lambda}_k$ are independent, identically-distributed gamma random variables with expected values equal to 1.0 then leads to a version of the negative-binomial statistical model.

For 2004, each section's counts of median-crossing and other collisions, broken down by whether or not the diagram code was 'run-off left' or 'head-on' provided the dependent variables, while to 2003 and 2005 the counts of crashes with and without the appropriate codes were the dependent variables. Independent variables were the average ADT for each section and its length. Estimation of the model parameters was carried out using the Bayesian statistical software WinBUGS (Lunn et al 2000). WinBUGS produced Bayes estimates of the population parameters $\overline{\lambda}_1$, $\overline{\lambda}_0$, p_1, and p_0, and summaries for these estimates are given in Table 3.6. For each section, WinBUGS also produced an estimate of the number of median-crossing collisions experienced by that section during 2003-2005, and the probability that section's median-crossing collision rate is higher than the population mean.

Table 3.6. Estimates of Rural Expressway Model Population Parameters, Rate Units are Collisions/10 million VMT.

	Posterior Summary			
Parameter	Mean	Stand. Dev.	2.5%ile	97.5%ile
$\overline{\lambda}_1$	0.0267	0.0086	0.0131	0.0468
$\overline{\lambda}_0$	0.1162	0.0115	0.094	0.139
p_1	0.629	0.127	0.367	0.861
p_0	0.143	0.0376	0.075	0.222
r	1.141	1.093	0.262	4.11

Overall, on the rural expressways, median-crossing collisions that result in serious or fatal injuries appear to happen at a rate of 0.0267 collisions per 10 million vehicle-miles of travel, while the other collisions happen at about 0.1162 collisions per 10 million vehicle-mile of travel. A median-crossing collision will be coded as a head-on or run-off left collision with probability 0.629, while the other collisions are so coded with probability 0.143.

Rural Expressway Results

Of the 528 rural expressway sections, only 80 of them experienced at least one serious potential MCC during 2003-2005, and so only those 80 sections had a possibility of non-zero expected MCCs during that time period. That is, if no relevant crashes occurred on a section, then the subset of median crossing collisions necessarily equaled zero. Listed in Appendix A are results from all rural expressway sections where the estimated number of median-crossing collisions during 2003-2005 was greater than zero. Table 3.7 lists the results from the 10 rural expressway sections with the highest estimated MCC frequencies.

Table 3.7. Ten Rural Expressway Sections with Highest Estimated MCC Frequencies.

ID#	E[mu]	E[mu]/length	P(lambda>1)	2003_ADT	2004_ADT	2005_ADT	length	Width
472	3.341	0.493282	0.9177	31139	29000	29145	6.773	99
224	1.662	1.206096	0.8447	21636	20500	20603	1.378	VR
220	1.6	0.393024	0.7537	28106	29000	29145	4.071	54
223	1.235	0.268946	0.6453	21029	19900	19999	4.592	VR
306	1.22	10	0.7368	6066	6000	6030	0.122	75
462	0.9387	0.398599	0.5791	28504	31700	32017	2.355	45
312	0.7629	0.152184	0.5589	12637	10900	10954	5.013	54
421	0.7416	0.150334	0.5384	13345	13600	13668	4.933	8
379	0.6654	2.650996	0.5867	30540	33000	33330	0.251	93
356	0.6501	1.805833	0.5698	31049	32500	32825	0.36	4

The rural expressway section with highest estimated frequency of MCCs, about 3.34 over three years, is number 472. The probability that this section has a MCC rate greater than the population mean is about 0.92. The section with the highest estimated density of MCCs is the rather short (0.122 miles) number 306, with about 10 MCCs/mile.

Chapter 4
A Cost Effectiveness Simulation Model

As indicated in Chapter 2, programming safety improvements generally involves two tasks, (1) screening a large number of locations for potentially high-hazard sites, and (2) selecting from a smaller number of promising projects in order to satisfy current resource constraints. Task 4 of this project called for developing a prototype model for evaluating the cost-effectiveness of proposed median barrier projects. Before proceeding to describe our model however, it may be worthwhile to clarify what a crash simulation can, and cannot, provide. Ideally, a simulation model would be able to accurately predict the frequency, severity and other important features of crashes occurring on a specified section of road. This would require identifying the mechanism underlying each relevant crash type, along with the relative frequencies of the initial conditions feeding each mechanism. The state-of-art in crash prediction has not yet reached this level of understanding however, and we must be content with a more modest goal, that of providing a relative ranking of different locations with respect to their response to a standardized set of input conditions.

Perhaps one way to approach this issue is to imagine designing and conducting a standardized test for ranking highway sections with regard to their risk for median crossing crashes. One way to do this might be to first specify a set of standardized encroachment conditions, then launch suitably large samples of encroaching vehicles on each road section of interest, and finally record how many of these standardized encroachments resulted in crashes. The fraction of the encroachments on a section resulting in crashes would then be an objective measure of that section's risk. Obviously, such a test must remain hypothetical, but it may be possible to simulate the outcome of such a test on a computer. This is what a plausible simulation model, such as RSAP, accomplishes, and this is what the model developed for this project is intended to do.

Model Structure

The objective of the cost effectiveness model is to compare the expected number of hypothetical median-crossing crashes prevented by a barrier placement to the cost of placement, in order to identify those locations where barrier placement should have higher priority. The cost of the barrier placement can be estimated by multiplying the length of the highway section in question by a user-provided unit cost, while the predicted number of prevented crashes is computed using a variation of the encroachment model approach used in other roadside safety applications. The fundamental equation is

$$E[C] = E[N]P[U|N]P[X|U]P[C|X] \qquad (4.1)$$

$E[C]$ = expected number of median-crossing crashes/year
$E[N]$ = expected number of median encroachments/year
$P[U|N]$ = probability an encroachment is uncontrolled
$P[X|U]$ = probability an uncontrolled encroachment crosses the median
$P[C|X]$ = probability a crossing encroachment collides with an opposing vehicle

Given the assumption that all potential crossing encroachments would be stopped by the median barrier, E[C] is then an estimate of the number of crashes prevented by the barrier. The cost effectiveness of the proposed barrier project is computed by dividing the project cost by E[C], to give an estimated cost per crash prevented. The components of the basic equation will be addressed next.

Expected encroachments

The expected number of encroachments on a section of highway is given by the following relation

$$E[N] = \eta(\text{MVMT}) \qquad (4.2)$$

MVMT = million vehicle-miles of travel on the section
η = encroachments/MVMT

MVMT is readily determined once we know the length and average daily traffic (ADT) of the section, but determining the encroachment rate η is a bit more difficult. A median encroachment occurs when a vehicle leaves the traveled way and enters the median separating the directional lanes of a divided highway. The encroaching vehicle may come to a stop in the median, may return to its original traveled way without stopping, or it may traverse the median and enter the traveled way of the opposing traffic. Ideally, estimates of the rate of encroachment and the proportion of encroachments of different types would be obtained by direct observation on the road in question over a suitable period of time. Unfortunately, the cost and time needed to collect such data are prohibitive, and the developers of encroachment models have had to rely on a limited number of studies carried out in the past. Hutchinson and Kennedy (1966) conducted a study of median encroachments on a 24.6 mile long section of Interstate 74 in Illinois. In this study, research teams periodically drove both directions of this freeway looking for wheel tracks in the freeway's median. When found, the team then measured the directional angle of the encroaching vehicle's path, the extent of its lateral and longitudinal travel if it appeared to stop in the median or, if it crossed the median, the longitudinal extent of the point where it left the median. No measurements of a vehicle's path were made after it left the median. The observers also classified each track as to whether it was essentially straight-line track, or if there was evidence of steering control. The study ran from October 1960 to April 1964, during which slightly more than 300 median encroachments were recorded.

The other major encroachment study was conducted by Cooper (1980) in the late 1970s, on a sample of highways sections in five Canadian provinces. Both median and rightside encroachments were recorded, and the sample included a range of roadway functional classifications.

Prior to the official start of this project, we obtained a copy of Hutchinson and Kennedy's original report, along with a copy of a follow-up report by Cooper (1981). After reviewing these documents, it was decided to rely on the data collected by Hutchinson and Kennedy. This was primarily because the Hutchinson and Kennedy study focused on median encroachments on a high-speed divided highway, which is also the focus of our study. Hutchinson and Kennedy's report tabulated the data from each of their observed encroachments, and from this table a count of the number of encroachments recorded for each month of the study was prepared, along with estimates of the average daily traffic for each month. A statistical analysis of encroachment rate versus time revealed distinctly higher encroachment rates during the first half of the study, compared to the last half, and also an increase in encroachment rate during the winter months of December, January and February. Since the start of Hutchinson and Kennedy's study coincided with the opening of this freeway section, it was decided that the initial high observed encroachment rate was probably a transient effect, and to rely on the estimates from the last portion of the study. This gave the following estimated encroachment rates:

Time Period	Encroachments/MVMT
March-November	0.77
December-February	1.20

The above estimates were consistent with estimates from other highways, reported in Hutchinson and Kennedy (1966). Documentation of this initial work can be found in Davis and Morris (2006).

Once a vehicle departs from the traveled way it is necessary to describe its path across the median and its ultimate interaction with opposing vehicles. During the Summer and Fall of 2006 the research team investigated a number of vehicle trajectory models, including that used in the accident reconstruction software PC-CRASH (Wach 2001), a simpler trajectory model described in Brach and Brach (2005), and the even simpler "bicycle" model described in Steeds (1960) and Wong (1993). The first two models are known to give reasonably accurate descriptions of vehicle behavior, but essentially require that the make, model and year of the vehicle be known, so that the required vehicle parameters can be obtained from databases. The bicycle model assumes that the vehicle has only one front and one rear wheel, and has been used to capture the steering and stability properties of more complicated vehicles (Wong 1993). The research team coded a version of the bicycle model using the software Mathcad and was able to verify that, at least for travel on level homogeneous surfaces, it gave results consistent with those produced by the Brach and Brach four-wheel model. As to vehicle parameters, the bicycle model requires that the length and weight distribution of the vehicle be given, along with a realistic model relating tire sideslip to longitudinal and lateral forces. It also requires that the vehicle's initial speed and steering angle be given. Finally, for our application, the location of the vehicle on the roadway when the steering input is applied is also required. Attempts to deduce these inputs from a combination of Hutchinson and Kennedy's encroachment data and reasonable assumptions about what may have been typical about the population of vehicles on Hutchinson and Kennedy's freeway were not successful, and it was decided to employ the simple straight-line trajectories used in other encroachment models, such as RSAP.

As indicated above, Hutchinson and Kennedy's report listed data for each of their observed encroachments. One of the features which the observers looked for was whether or not the wheel tracks indicated steering by the driver, as evidenced by curving tracks. Fortunately, the majority of median-crossing encroachments in Hutchinson and Kennedy's data set were those where no steering was evidenced, i.e. where the vehicle path was approximately linear. As long as our focus was on encroachments which could potentially result in collisions with opposing traffic, little was lost by restricting our attention to this subset. An inspection of the encroachment list in Hutchinson and Kennedy's report indicated that 108 out of 308 encroachments were classified as showing no steering control, so our estimate of P[U|N] was

$$P[U|N] = 108/308 = 0.351 \qquad (4.3)$$

Median Traversal Model

Since the encroaching vehicle's trajectory is modeled as a straight line, the only vehicle-specific inputs required are its initial speed (v) , its trajectory angle with respect to the roadway (θ), and its deceleration. Deceleration is modeled by specifying a braking-factor, denoted by b, which is the fraction of the frictional deceleration used. For example, if the friction coefficient for the surface being traversed is 0.4, and the braking factor b=0.5, then the deceleration of the vehicle would be (.5)(.4)g= 6.44 ft/sec^2. The other required input is a description of the median's cross section, consisting of, for each major break in the median's cross-slope, the slope, lateral width, and friction coefficient for the slope's surface. Given such a cross-section description and initial values for v, θ, and b, the median traversal model proceeds as follows:

(1) The deceleration for the cross-section segment is computed from b and the slope's friction factor, and decelerations in the lateral (x) and longitudinal (y) directions are computed using this, the angle θ, and the segment's cross-slope.

(2) The lateral distance needed to bring the vehicle to a stop is computed. If this is less than the lateral extent of the segment the stopping position of the vehicle is computed, and the encroachment is coded as one where the vehicle stops in the median.

(3) If the lateral component of the vehicle's stopping distance exceeds the lateral extent of the segment, the width of the segment (x) is added to the total lateral distance traveled, the corresponding longitudinal distance $y=x/\tan(\theta)$ is computed and added to the total longitudinal distance traveled, and the reduction in the vehicle's kinetic energy is computed and subtracted from the total.

(4) The above computations are then repeated for the next cross-section segment.

(5) If the vehicle reaches the far side of the median without stopping, θ, b, and its speed upon exiting the median become inputs into the collision simulation routine.

Collision Model

When an encroaching vehicle reaches the far side of the median, its trajectory is modeled by numerically solving a system of ordinary differential equations, one each for its lateral (x) and longitudinal (y) position, one each for its speeds in the x and y directions, and one each for its x and y decelerations. The total deceleration at the start of first opposing lane is computed as in the median traversal routine and decomposed into x and y direction components using θ, and these are treated as constant throughout the vehicle's trajectory across the opposing lanes. The initial speed is also decomposed into x and y components, and then for each small time step, the position and speed of the vehicle are updated using a simple Euler's method.

In addition, when an encroaching vehicle reaches the far side of the median, two opposing vehicles are generated for each lane on the opposing side of the highway. For each of these opposing vehicles an initial location and speed are assigned to it, along with a reaction time for the opposing driver and an emergency braking deceleration. In each lane, the initial location of the first opposing vehicle is generated as a random outcome from an exponential random variable with mean equal to the reciprocal of the user-defined traffic density, while the initial location of the second vehicle in a lane is the sum of the first vehicle's location and an additional exponential random outcome. These then define initial conditions for a set of coupled equations similar to those describing the encroaching vehicle's trajectory, with each opposing vehicle's longitudinal deceleration being zero until that driver's reaction time is exceeded, after which the longitudinal deceleration is set to the emergency value. For each time step, the location and speed of the opposing vehicles are updated using the simple Euler's method, and the distance between each opposing vehicle and the encroaching vehicle is computed. If this distance is less than a user-specified collision threshold then a collision is recorded. Otherwise, if the encroaching vehicle comes to a stop or crosses all opposing lanes without colliding, a non-collision is recorded.

Computing Expected Crash Frequencies

Following the basic equation (4.1), computing the expected number of median-crossing crashes on a highway section requires computing the probability an encroaching vehicle crosses the median P[X|N] and the probability a crossing vehicle collides with an opposing vehicle P[C|X]. The above-described trajectory model is deterministic, in that once the appropriate initial conditions are assigned to the encroaching and opposing vehicles a collision either occurs or it does not. The random element comes from placing a probability distribution over the set of possible initial conditions. That is, each combination of initial conditions is assigned a probability, and the probability of a collision is then the probability assigned to all combinations of initial conditions that result in a collision. In principle, the desired probabilities can be computed by integrating this probability distribution over the appropriate subset, but the complexity of the model relating the initial conditions to the outcome means that closed form solutions to this integration problem are not to be expected. Numerical integration via quadrature would be a possibility but, for example for two opposing lanes, a total of 19 values (three for the encroaching vehicle and four for each opposing vehicle) need to be specified, and so the relative high dimensionality of this problem makes the application of quadrature-based methods problematic. The remaining option is Monte Carlo integration, where a computer is used to generate a large pseudo-random sample of initial conditions, the deterministic model is applied to each of these, and the relative frequency of simulated collisions is recorded. As the size of the sample gets arbitrarily large, the Law of Large Numbers implies that this relative frequency will converge to the true (but unknown) probability. This is the tactic adopted here.

For each opposing vehicle, the initial speed is sampled from a normal distribution with mean and standard deviation specified by the user. The initial locations of the opposing vehicles are sampled from an exponential distribution governed by a user-specified traffic density. The reaction times and braking decelerations of the opposing drivers are sampled from normal distributions with means and standard deviations derived from the emergency braking study conducted by Fambro et al (1997).

The main challenge was determining an appropriate distribution for the initial speed, direction and braking factor for the encroaching vehicle. Our decision was to generate these as random outcomes consistent with the data collected by Hutchinson and Kennedy. To this end, 97 encroachments were identified where no evidence of steering was observed, where the vehicle was not stopped by a collision with a fixed object, and where the encroaching angle and the lateral and longitudinal distances were recorded. The sampling algorithm then proceeds as follows. One of the 97 observed encroachments is sampled at random from the list, and the encroaching angle θ is set to that observed value. A random speed is then generated from a uniform distribution with bounds 10 mph and 70 mph, and random braking factor is generated from a uniform distribution with bounds 0.1 and 1.0. These then serve as inputs to the median-crossing routine, with a cross-section description corresponding to the typical cross-section listed by Hutchinson and Kennedy. If the output of the routine is consistent with the lateral and longitudinal measurements from the sampled encroachment, the combination of θ, v, and b is retained. Otherwise, new values for v and b are sampled and the process repeated until a combination of values for θ, b, and v that reproduce the observed encroachment are obtained.

Model Implementation

The simulation model was implemented as an Excel spreadsheet, with the Monte Carlo simulation being carried out by a specially-written macro. A listing of this macro is given in Appendix B. Table 4.1 shows the spreadsheet, with its input and output

This spreadsheet computes estimates of median-crossing crashes for one direction of travel. The median cross-section for this example consists of a 10-foot paved shoulder with a slope of 24:1, followed by an 18-foot ditch foreslope with slope of 6:1, and then a four-foot flat ditch bottom. Similar segments define the median's backslope, and the opposing direction traveled way consists of two 12-foot lanes (nlane op=2), with 1.5% slopes. This gives a total of seven (nsec=7) segments defining the cross-section, with the edge of the opposite direction traveled way at the edge of the fifth segment (edge=5). The friction coefficient for the paved surfaces is 0.75, and that for the median non-paved surfaces is 0.4. The ADT for the direction of interest 40000 vehicles/day, the highway section is 1.0 miles long, and the design life of the barrier project is 10 years (horizon=10). The spreadsheet computed the exposure for the direction of interest as 14.6 MVMT and, applying the encroachment rate estimates given above, computed an expected encroachment frequency of 4.492 encroachments/year. The opposing traffic has a mean speed of 65 mph, with a standard deviation of 5 mph. The mean reaction time for opposing drivers is 1.1 seconds, with a standard deviation of 0.25 seconds, while the mean emergency braking deceleration is 0.65g, with a standard deviation of 0.1g. The density of the opposing traffic is 12.82 vehicles/lane/mile. The unit cost of the barrier placement is $100,000/mile.

Table 4.1. Example of Cost-Effectiveness Worksheet.

Cost Effectiveness of Median Barrier Treatments						**version:**	**1.4**					
Gary A. Davis		University of Minnesota			2 opposing vehicles/lane							
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0417	10.0000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.1667	18.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	4.0000	0.4000								veh/l/mi=	12.82	12.82051
0.1667	18.0000	0.4000					ybar=	411.856			enter	compute
0.0417	10.0000	0.7500					vybar=	95.333				
0.0150	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	60		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	6571	pmid=	0.438067	Exmid=	1.967946
				nsteps=	500		mccrash=	571	pcrash=	0.038067	Excrash=	0.171009
				close2=	4.50		mccross=	1707	pcross=	0.1138	Excross=	0.511229
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	29238.3

The spreadsheet computed the project cost as $100,000. Invoking the Monte Carlo routine then gave estimates of the probability an encroachment reaches the middle of the median (pmid=0.438), the probability an encroachment crosses the median (pcross=0.1138) and the probability an encroachment results in a crash (pcrash=0.038) This leads to an expected crash frequency (Excrash) of about 0.171 crashes/year for this direction, and a cost effectiveness, over the 10-year time horizon, of $29238/crash prevented. This last estimate assumes that the barrier would block crashes from both directions equally.

Calibration

The simulation model contains a number of user-inputs, all of which influence the model's predictions. Many of the inputs (e.g. cross-section specification, ADT, mean and standard deviation of opposing traffic speeds) describe road and traffic conditions which the user can adjust to reflect the situation on the road section of interest. The inputs describing the behavior of the opposing drivers, means and standard deviations for the reaction time and braking deceleration, are taken from the statistics reported by Fambro et al. (1997), and it is recommended that they be kept as defaults unless the user has good local data with which to replace them. One input that needs more explanation however is the crash closeness threshold (close2), which in the above table is set to 4.5 feet. The simulation model uses this input to determine when an encounter between an encroaching vehicle and an opposing vehicle results in a crash, in this case if their centers of mass pass within 4.5 feet of each other. The model's results are sensitive to this parameter, and it is desirable to make sure that the value recommended above is reasonable. To this end, the value of the crash threshold was adjusted to approximate the output of an updated version of the Pennsylvania model for Interstate highways (Donnell 2008). This model has the form

$$N_{MCC} = e^{-21.628}(L)(ADT)^{2.044}e^{-.026W} \qquad (4.4)$$

where

N_{MCC} = predicted number of median-crossing crashes/direction/year
L = section length (miles)
ADT = directional average daily traffic (vehicles/day)
W = median width (feet)

For calibration purposes we selected a freeway section one mile long, with a median width of 60 feet. This median width was chosen because the majority of the sites in the Pennsylvania data set had median widths greater than 50 feet, and it was felt that the Pennsylvania model more accurately reflects crash tendencies on sections with wider medians. The updated Pennsylvania model was then used to compute expected MCC frequencies for ADTs ranging from 5000 to 40000, and these are displayed in Table 4.2. The simulation model was then used to compute similar predicted crash frequencies, with the crash threshold being varied between 3.0 and 6.0 feet, to determine which crash threshold gives predictions most closely matching those of the Pennsylvania model. The results for crash thresholds of 4.0, 4.5, and 5.0 feet are also shown in Table 4.2, along with the percent differences between the Pennsylvania model and the simulation model. For a crash threshold of 4.5 feet, the percent difference for these Monte Carlo runs did not exceed 22%, while for shorter or longer crash thresholds the percent difference could exceed 30%.

Table 4.2. Calibration of Simulation Model to Updated Pennsylvania Model. Median width = 60 feet, and Approximate Percent Differences between Simulation Model and Pennsylvania Model are Given in Parentheses.

	Predicted Median Crossing Crashes/direction/year			
Directional ADT	Pennsylvania	Simulation 4.0 feet	Simulation 4.5 feet	Simulation 5.0 feet
5000	.0031	.0032 (4)	**.0038 (22)**	**.0040 (30)**
10000	.0128	.0118 (8)	.0149 (17)	**.0157 (23)**
15000	.0292	.0250 (14)	.0306 (5)	**.0363 (24)**
20000	.0526	.0464 (12)	.0497 (5)	.0614 (17)
25000	.083	.0672 (19)	.0772 (7)	.0883 (6)
30000	.1205	**.0831 (31)**	.0996 (17)	.1233 (2)
35000	.1651	**.1184 (28)**	.1431 (13)	.1670 (1)
40000	.2169	**.1551 (28)**	**.1703 (22)**	.1962 (10)

Model Validation.

One application of the statistical models described in Chapter 2 is to compute predicted frequencies of MCCs, as a function of median width and ADT. If we accept that the statistical models are reasonable summaries of the associations between MCC frequency, ADT, and median width, then our simulation model should generate predictions that are roughly consistent with the statistical models. A set of representative cross sections, with median widths ranging from 30 to 70 feet, was prepared and the simulation model, with inputs as listed in Table 4.2, was used to compute predicted MCC frequencies. The results of this exercise are summarized in Table 4.3, while images of the actual spreadsheets, with details of model input values, are given in Appendix C.

Table 4.3. Simulation Model's Predicted Median Crashes/Direction/Mile/Year.

Median Width (ft)	Directional ADT (vehicles/day)							
	5000	10000	15000	20000	25000	30000	35000	40000
30	.018	.070	.147	.249	.364	.512	.652	.828
40	.012	.045	.098	.155	.245	.319	.409	.505
50	.009	.036	.081	.121	.184	.248	.340	.427
60	.003	.014	.033	.051	.074	.115	.132	.175
70	.003	.012	.025	.042	.053	.092	.127	.142

The predictions listed in Table 4.3 were then compared to similar predictions made by the updated Pennsylvania model and the Texas model. The comparison measure was the following T-statistic

$$T = \frac{\ln(m_{stat}) - \ln(m_{sim})}{s_{stat}} \tag{4.5}$$

where

m_{stat} = predicted MCC frequency from statistical model,
m_{sim} = predicted MCC frequency from simulation model,
s_{stat} = standard deviation for $\ln(m_{stat})$, due to uncertainty in model parameters,
$\ln(x)$ = natural logarithm of x.

A T-statistic with absolute value greater than 1.6 could be regarded as indicating a significant difference between the predictions generated by two models. The logarithms of the predicted frequencies were used primarily because, as Table 4.3 shows, the predicted MCC frequencies can vary by two orders of magnitude over the ranges of median width and ADT. Since both the Pennsylvania and Texas models are examples of log-linear models, with the form

$$m_{stat} = \exp(\sum_i \beta_i x_i) \tag{4.6}$$

x_i = value of independent variable i
β_i = coefficient for independent variable i

the standard deviation s_{stat} is given by the expression

$$s_{stat} = \sqrt{\sum_i (x_i s_i)^2} \tag{4.7}$$

where s_i is the standard error of estimate for coefficient β_i.

Table 4.4 shows the comparison between the simulation model and the Pennsylvania model. Within the uncertainty produced by the Pennsylvania model's parameter estimates, the two models give similar results.

Table 4.4. T-stat Differences between Simulation Model and Pennsylvania Model.

Median Width (ft)	Directional ADT (vehicles/day)							
	5000	10000	15000	20000	25000	30000	35000	40000
30	-0.40	-0.37	-0.33	-0.30	-0.27	-0.25	-0.22	-0.21
40	-0.33	-0.29	-0.27	-0.21	-0.21	-0.17	-0.14	-0.12
50	-0.34	-0.31	-0.30	-0.22	-0.20	-0.17	-0.17	-0.15
60	-0.04	-0.04	-0.05	0.01	0.04	0.02	0.08	0.08
70	-0.04	-0.09	-0.04	-0.01	0.07	0.00	0.00	0.07

Table 4.5 shows a similar comparison between the predictions generated by the simulation model and those produced by the Texas model. In this case, for a 30-foot median and directional ADTs of 30000 or more, the simulation model predicts more MCCs than does the Texas model, while for an ADT of 5000 and median widths of 60 or 70 feet, the simulation model predicts fewer MCCs than does the Texas model. For all other median width/ADT combinations the two models are roughly equivalent.

Table 4.5. T-stat Differences between Simulation Model and Texas Model.

Median Width (ft)	Directional ADT (vehicles/day)							
	5000	10000	15000	20000	25000	30000	35000	40000
30	0.66	-0.38	-0.92	-1.30	-1.55	**-1.80**	**-1.94**	**-2.11**
40	1.18	0.15	-0.45	-0.71	-1.08	-1.21	-1.36	-1.49
50	1.37	0.32	-0.32	-0.50	-0.80	-0.98	-1.24	-1.38
60	**2.70**	1.58	0.89	0.66	0.43	0.04	-.07	-0.16
70	**2.90**	1.59	1.14	0.78	0.76	0.21	-0.04	-0.01

Graphical displays of some of the results from Tables 4.4 and 4.5 are shown in Figures 4.1 and 4.2. Figure 4.1 compares the predictions from the simulation model and the Pennsylvania model, for a 40-foot median. Figure 4.2 shows a similar comparison between the simulation model and the Texas model, again for a 40-foot median.

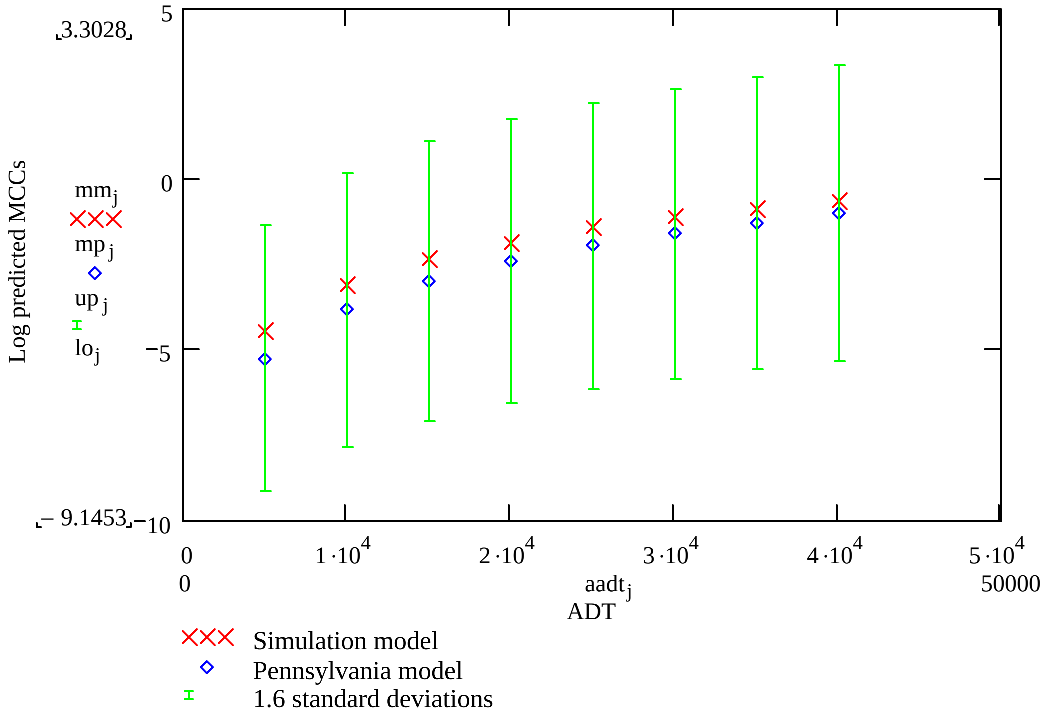

Figure 4.1. Log-predicted median crossing crash frequencies produced by the simulation model and Pennsylvania model, for a 40-foot median. Error bars indicate ± 1.6 standard deviation range for Pennsylvania model.

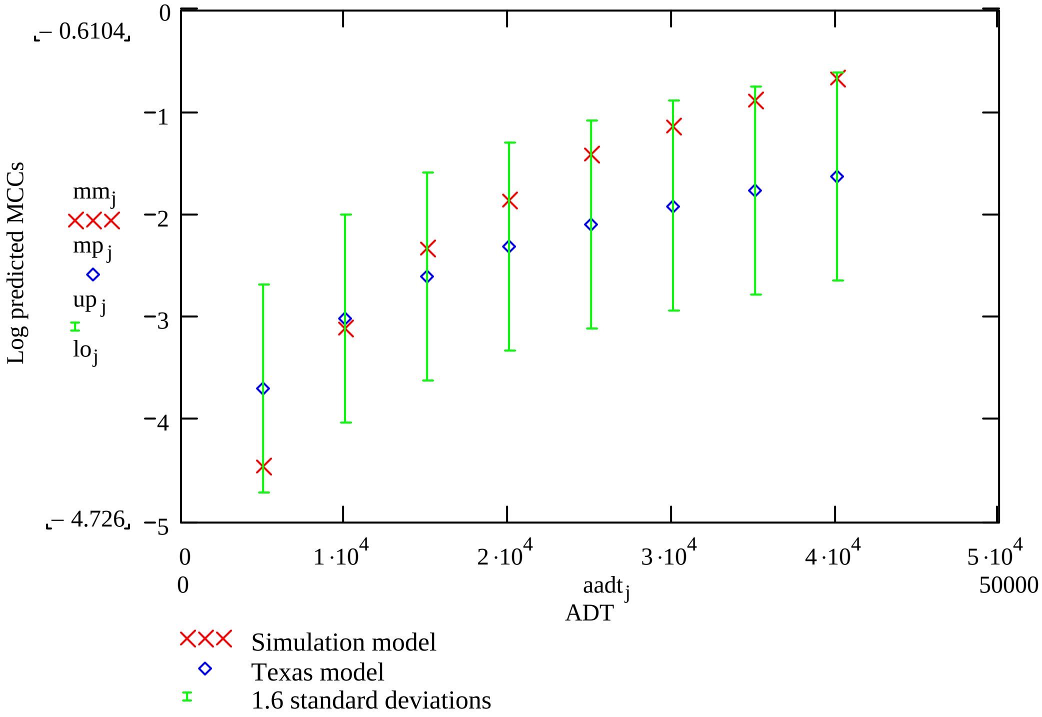

Figure 4.2. Log-predicted median crossing crash frequencies produced by the simulation model and Texas model, for a 40-foot median. Error bars indicate ± 1.6 standard deviation range for Texas model.

Conclusion

In this Chapter we described a simple, but physically meaningful, model for simulating median crossing crashes on section of divided highway. The model allows for reasonably detailed specification of the highway's cross-section, along with characteristics of traffic flow in opposing lanes. The model can be used to estimate the cost-effectiveness of installing median barriers on the highway section. *Although the model produces predicted MCC frequencies that are roughly consistent with two published statistical models, we caution against treating the model as giving absolute estimates of MCC frequencies. Rather, the model should be used to compare the relative effectiveness of median treatments on different candidate highway sections.*

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APPENDIX A

Freeway and Rural Expressway Sections with Non-Zero Estimated MCC Frequencies

Appendix A
Freeway and Rural Expressway Sections with Non-Zero Estimated MCC Frequencies

Freeway Sections with Estimated 2003-2005 MCC Frequencies > 0

ID#	E[mu]	E[mu]/length	P[lambda>1]	2003 aadt	2004 aadt	2005 aadt	length	medwidth
626	2.919	0.62532134	0.6833	71260	71500	72215	4.668	VR
415	2.796	0.38353909	0.6848	34071	39000	39195	7.29	60
445	2.318	0.42917978	0.5043	95834	96792	94940	5.401	VR
757	1.889	0.48041709	0.5441	85767	84500	85345	3.932	30
125	1.795	0.31624383	0.6634	17895	22100	22210	5.676	54
653	1.759	1.19254237	0.6631	72278	72000	72720	1.475	40
569	1.686	0.63550697	0.5938	75332	76000	76760	2.653	VR
725	1.63	0.43259023	0.5918	44635	46250	46481	3.768	34
194	1.626	3.23904382	0.7025	55990	55000	55550	0.502	VR
365	1.367	0.25124058	0.6171	15266	15000	15075	5.441	54
32	1.365	0.58258643	0.6337	28708	25300	25553	2.343	VR
152	1.344	0.29506037	0.5958	22242	25000	25125	4.555	29
171	1.331	0.36849391	0.5699	40720	46000	46460	3.612	60
97	1.329	0.23348559	0.5655	29218	30000	30150	5.692	54
301	1.222	0.4071976	0.4311	117070	114750	115898	3.001	28
756	1.188	10.0677966	0.6488	91620	88000	88880	0.118	12
625	1.187	5.16086957	0.6475	63116	67000	67670	0.23	VR
871	1.184	3.90759076	0.6371	67188	70000	70700	0.303	57
142	1.183	1.55657895	0.6417	29218	31000	31155	0.76	45
146	1.182	1.16798419	0.6315	29016	31000	31155	1.012	45
440	1.17	1.04371097	0.5899	80422	89000	89890	1.121	VR
356	1.168	9.57377049	0.6166	55403	62000	62310	0.122	VR
268	1.164	1.00692042	0.5619	105872	106000	107060	1.156	26
588	1.161	0.69272076	0.5503	84494	87000	87870	1.676	46
426	1.158	0.36266834	0.5292	52269	57000	57285	3.193	52
420	1.019	0.11974148	0.362	48528	47000	47235	8.51	54
174	0.9612	0.24665127	0.4461	61589	63000	63630	3.897	54
655	0.9603	0.35792024	0.4482	91620	93000	93930	2.683	40
545	0.9042	0.20138085	0.5554	13244	15700	15778	4.49	54
417	0.8696	0.31336937	0.5122	39429	41000	41205	2.775	54
206	0.7803	0.20615588	0.398	71260	72500	73225	3.785	40
797	0.7508	5.25034965	0.5647	81949	82500	83325	0.143	VR
909	0.7508	0.24852698	0.4786	49373	49000	49490	3.021	58
383	0.7213	0.26577008	0.5263	21029	21500	21607	2.714	VR
512	0.6991	0.08353447	0.4834	11222	13400	13467	8.369	54
564	0.6889	0.43739683	0.4644	87548	86500	87365	1.575	VR
305	0.6851	0.05207114	0.4637	10730	10713	10766	13.157	50
272	0.5984	0.67922815	0.4722	115034	114000	115140	0.881	26
373	0.5688	1.70810811	0.535	18198	18300	18391	0.333	54

384	0.567	0.756	0.5325	21029	21500	21607	0.75	54
220	0.5662	4.10289855	0.5279	101800	103000	104030	0.138	28
715	0.5644	2.31311475	0.5302	61080	61000	61610	0.244	32
207	0.5623	1.40575	0.5207	75332	77000	77770	0.4	46
25	0.5613	0.3200114	0.5211	19310	20800	20904	1.754	54
274	0.5606	2.74803922	0.5225	114016	118000	119180	0.204	26
402	0.5566	0.45511038	0.5112	31240	34000	34170	1.223	45
177	0.5559	0.88238095	0.504	80422	87000	87870	0.63	VR
540	0.5557	0.1675309	0.5056	13750	15200	15276	3.317	54
581	0.5554	0.83644578	0.5017	68206	71000	71710	0.664	54
562	0.5504	1.14666667	0.4954	102818	109000	110090	0.48	34
89	0.5503	0.15804136	0.4935	18703	16400	16482	3.482	VR
732	0.5502	0.49345291	0.4909	64134	55000	56055	1.115	30
435	0.5491	0.51462043	0.4856	61671	64000	64320	1.067	52
167	0.5196	0.10731103	0.4018	36901	39000	39195	4.842	60
560	0.4997	0.15441904	0.3392	92638	94000	94940	3.236	34
679	0.4904	5.16210526	0.5226	16176	14500	14572	0.095	50
218	0.486	7.47692308	0.5162	48864	50000	50500	0.065	34
13	0.4848	4.70679612	0.5138	47846	50000	50500	0.103	34
337	0.4775	0.23213418	0.5079	10514	11300	11356	2.057	54
459	0.4758	0.87785978	0.5063	53954	53000	53530	0.542	16
629	0.4702	1.14126214	0.4983	74314	73000	73730	0.412	VR
242	0.443	0.87722772	0.4611	142520	141000	142410	0.505	06
232	0.4305	0.74224138	0.4463	180186	173000	174730	0.58	10
1	0.4289	0.07490395	0.4376	17389	18325	18416	5.726	VR
692	0.3097	12.388	0.4852	16075	13300	13366	0.025	50
763	0.3085	15.425	0.4862	62098	58000	58580	0.02	VR
674	0.306	1.67213115	0.4839	26589	30000	30150	0.183	50
762	0.3059	1.61	0.4873	62098	58000	58580	0.19	VR
91	0.3046	0.36522782	0.4788	21534	20800	20904	0.834	VR
609	0.3036	2.53	0.4798	111980	117000	118170	0.12	VR
713	0.3029	1.18320313	0.482	59044	58500	59085	0.256	32
240	0.3021	1.91202532	0.4755	120124	121000	122210	0.158	06
750	0.3003	1.21578947	0.4754	90602	88000	88880	0.247	30
759	0.2986	0.76368286	0.4723	79404	78000	78780	0.391	30
287	0.2982	0.52966252	0.4707	53954	60000	60600	0.563	38
393	0.2978	0.19866578	0.4691	14154	15800	15879	1.499	54
462	0.2921	1.02491228	0.4516	165934	165000	166650	0.285	VR
328	0.2916	0.09566929	0.4541	15974	15500	15577	3.048	32
277	0.2887	0.60145833	0.4513	123178	130000	131300	0.48	26
615	0.2887	0.46489533	0.4468	88566	89000	89890	0.621	VR
761	0.2867	0.31784922	0.4451	62098	58000	58580	0.902	30
758	0.2851	0.356375	0.441	79404	78000	78780	0.8	30
432	0.28	0.19957234	0.4318	50601	59500	59798	1.403	52
292	0.2786	0.1379891	0.4239	36139	41500	41915	2.019	54
248	0.2778	0.29743041	0.4233	96710	97000	97970	0.934	04
442	0.2756	0.2544783	0.4204	80422	89000	89890	1.083	VR
410	0.2713	0.05932648	0.4034	24871	25000	25125	4.573	60

201	0.2706	0.11514894	0.4068	46319	47500	47975	2.35	52
452	0.2705	0.24216652	0.4072	103836	105000	106050	1.117	VR
449	0.269	0.2074017	0.4016	96710	98000	98980	1.297	VR
484	0.269	0.17155612	0.3987	82967	85000	85850	1.568	56
447	0.2682	0.19749632	0.3992	94674	94000	96960	1.358	VR
314	0.268	0.02583631	0.3947	12637	11700	11758	10.373	54
620	0.2674	0.15447718	0.3922	75332	76000	76760	1.731	VR
851	0.2626	0.17624161	0.3861	92299	95000	95950	1.49	34
322	0.1481	0.80928962	0.461	17996	17000	17085	0.183	30
281	0.1479	5.68846154	0.4662	97728	99000	99990	0.026	04
94	0.1473	2.53965517	0.4564	28611	30000	30150	0.058	VR
570	0.1472	2.53793103	0.4632	75332	76000	76760	0.058	34
721	0.1472	1.84	0.4623	17794	17000	17085	0.08	VR
578	0.147	3.86842105	0.4603	75332	76000	76760	0.038	VR
824	0.147	73.5	0.4561	9200	9900	9949	0.002	VR
439	0.1466	1.37009346	0.4577	62098	73000	73730	0.107	VR
319	0.1465	0.54259259	0.4601	11829	12000	12060	0.27	VR
541	0.1464	0.1757503	0.4527	13750	15200	15276	0.833	54
215	0.1463	1.82875	0.4552	105872	107000	108070	0.08	42
84	0.1462	0.56447876	0.4598	17389	15400	15477	0.259	VR
859	0.1462	0.53553114	0.4542	55990	56000	56560	0.273	34
41	0.1461	0.38447368	0.4562	19512	21900	22009	0.38	VR
685	0.146	0.24052718	0.4563	15064	13000	13065	0.607	50
159	0.1457	1.08731343	0.4576	26488	29000	29145	0.134	VR
740	0.1454	1.25344828	0.4533	60062	58000	58580	0.116	30
43	0.145	0.32438479	0.4522	19512	21900	22009	0.447	VR
158	0.1449	0.29692623	0.4516	26893	28000	28140	0.488	VR
482	0.1448	1.05693431	0.4516	111980	105000	106050	0.137	56
7	0.1447	0.24360269	0.44	19310	20800	20904	0.594	54
114	0.1446	0.25060659	0.4496	41249	43000	43215	0.577	6
523	0.1446	0.12202532	0.4494	15873	16500	16582	1.185	54
771	0.1446	0.95761589	0.449	73296	67000	67670	0.151	36
886	0.1445	1.1468254	0.4485	46828	45000	45450	0.126	VR
451	0.1444	0.86987952	0.4456	96710	98000	98980	0.166	VR
124	0.1439	0.2640367	0.4436	38115	39000	39195	0.545	10
468	0.1439	0.90503145	0.4429	130304	132000	133320	0.159	VR
121	0.1437	0.5748	0.4476	56212	61000	61305	0.25	VR
105	0.1435	0.3231982	0.4476	32049	29000	29145	0.444	VR
602	0.1435	0.14627931	0.4429	28409	28000	28140	0.981	04
840	0.1435	0.17542787	0.443	37666	37000	37370	0.818	32
584	0.1434	0.49448276	0.4456	58026	64000	64640	0.29	12
234	0.1433	0.86325301	0.4396	104854	105000	106050	0.166	06
498	0.1431	0.07480397	0.4391	12536	13700	13768	1.913	54
748	0.143	0.48474576	0.4441	88566	86000	86860	0.295	30
154	0.1429	0.14106614	0.4395	22242	25000	25125	1.013	VR
424	0.1429	0.28074656	0.4431	45899	51000	51255	0.509	54
316	0.1428	0.07445255	0.4395	12739	11300	11356	1.918	54
241	0.1421	0.57530364	0.4409	120124	121000	122210	0.247	06

204	0.142	0.32272727	0.4351	64643	65500	66155	0.44	52
260	0.1418	0.45448718	0.4356	120124	112000	113120	0.312	06
847	0.1415	0.43538462	0.436	94674	98000	98980	0.325	VR
257	0.1414	0.34403893	0.434	96710	97000	97970	0.411	06
369	0.141	0.0790802	0.432	17794	20900	21004	1.783	54
658	0.1407	0.34067797	0.4296	72278	78000	78780	0.413	VR
210	0.1403	0.32252874	0.4295	76350	79000	79790	0.435	42
796	0.1403	0.29229167	0.4314	81440	82000	82820	0.48	VR
610	0.1401	0.30859031	0.4247	95692	101000	102010	0.454	VR
151	0.14	0.06164685	0.4294	20220	20700	20803	2.271	VR
190	0.1395	0.32746479	0.4271	122160	120000	121200	0.426	VR
568	0.1395	0.29555085	0.4242	80422	79000	79790	0.472	VR
907	0.1385	0.09739803	0.4208	35121	36250	36613	1.422	58
67	0.1383	0.04002894	0.4185	15266	16700	16783	3.455	VR
390	0.1383	0.06939288	0.4143	23961	27000	27135	1.993	VR
507	0.1382	0.03828255	0.4176	12132	13000	13065	3.61	54
126	0.1381	0.04466365	0.4141	18299	23000	23115	3.092	54
367	0.1378	0.03674667	0.4158	16075	18100	18190	3.75	54
752	0.1377	0.21381988	0.4164	95692	93333	94267	0.644	30
310	0.1374	0.02116125	0.4223	10818	9100	9145	6.493	50
27	0.1368	0.04947559	0.4098	27690	24900	25149	2.765	32
178	0.1368	0.17338403	0.4126	80422	87000	87870	0.789	VR
526	0.1367	0.03298745	0.4104	16681	18500	18592	4.144	54
887	0.1363	0.10549536	0.4107	47083	45000	45450	1.292	VR
481	0.136	0.17237009	0.4038	111980	105000	106050	0.789	36
585	0.136	0.11083945	0.4072	58026	64000	64640	1.227	54
219	0.1357	0.16078199	0.4084	78386	78000	78780	0.844	40
423	0.1352	0.08941799	0.4053	45899	51000	51255	1.512	54
208	0.135	0.15606936	0.4022	76350	79000	79790	0.865	46
454	0.1347	0.19215407	0.397	103836	105000	106050	0.701	35
363	0.1346	0.02589457	0.3956	15266	15000	15075	5.198	54
128	0.1343	0.0338202	0.3958	18299	23000	23115	3.971	54
283	0.134	0.15857988	0.3972	97728	99000	99990	0.845	04
278	0.1336	0.19851412	0.3951	128268	136000	137360	0.673	26
31	0.1331	0.03597297	0.3951	28708	25300	25553	3.7	32
444	0.133	0.12429907	0.3872	80422	89000	89890	1.07	VR
289	0.1314	0.0504221	0.3853	39702	44500	44945	2.606	54
486	0.1313	0.09682891	0.3852	72278	77000	77770	1.356	56
419	0.1305	0.05348361	0.3795	48528	47000	47235	2.44	54
596	0.1303	0.12109665	0.379	107569	101000		1.076	54
443	0.1296	0.08919477	0.3704	80422	89000	89890	1.453	VR
229	0.1284	0.1605	0.3626	179168	177000	178770	0.8	VR
8	0.1282	0.07367816	0.3675	76350	83000	83830	1.74	VR
883	0.1282	0.0914408	0.3676	91620	94000	94940	1.402	56
611	0.1221	0.05833731	0.3292	98237	98500	99485	2.093	50
487	0.1134	0.02789668	0.2737	72278	77000	77770	4.065	56

Rural Expressway Sections with Estimated 2003-2005 MCC Frequencies > 0

ID#	E[mu]	E[mu]/length	P(lambda>1)	2003_ADT	2004_ADT	2005_ADT	length	Width
472	3.341	0.493282	0.9177	31139	29000	29145	6.773	99
224	1.662	1.206096	0.8447	21636	20500	20603	1.378	VR
220	1.6	0.393024	0.7537	28106	29000	29145	4.071	54
223	1.235	0.268946	0.6453	21029	19900	19999	4.592	VR
306	1.22	10	0.7368	6066	6000	6030	0.122	75
462	0.9387	0.398599	0.5791	28504	31700	32017	2.355	45
312	0.7629	0.152184	0.5589	12637	10900	10954	5.013	54
421	0.7416	0.150334	0.5384	13345	13600	13668	4.933	8
379	0.6654	2.650996	0.5867	30540	33000	33330	0.251	93
356	0.6501	1.805833	0.5698	31049	32500	32825	0.36	4
497	0.6344	0.32285	0.5537	13547	15200	15276	1.965	49
291	0.6092	0.588599	0.5364	35630	34000	34340	1.035	51
473	0.5933	0.084395	0.4137	21029	21300	21406	7.03	99
370	0.5914	0.273543	0.5192	22849	24400	24522	2.162	68
505	0.4955	0.314005	0.5497	6066	7300	7336	1.578	92
122	0.4917	1.50367	0.5446	9807	10900	10954	0.327	VR
438	0.4908	0.913966	0.5399	13244	13400	13467	0.537	4
526	0.4864	0.451625	0.5375	9467	8400	8484	1.077	50
129	0.4846	0.421758	0.5391	8088	8100	8140	1.149	99
258	0.4608	0.133953	0.4942	10413	9800	9849	3.44	54
319	0.45	0.062884	0.4796	6976	7700	7738	7.156	VR
257	0.4469	0.098069	0.4813	9301	9400	9447	4.557	54
188	0.4192	0.091829	0.4228	20321	19200	19296	4.565	54
52	0.4042	2.994074	0.5031	7987	8200	8241	0.135	54
80	0.3513	0.367469	0.4556	14053	18900	18994	0.956	VR
404	0.2237	2.728049	0.4348	11707	12200	12322	0.082	VR
415	0.1889	0.154963	0.3802	18501	14800	14874	1.219	VR
247	0.154	0.078252	0.3338	40720	39500	39895	1.968	45
241	0.1146	0.015675	0.236	25959	26400	26664	7.311	45
143	0.0929	0.355939	0.3906	22950	22400	22512	0.261	30
146	0.0924	0.378689	0.3807	22849	24400	24522	0.244	VR
436	0.0915	1.076471	0.3906	13952	15000	15075	0.085	VR
161	0.0902	0.236745	0.3774	12840	20100	20200	0.381	VR
321	0.0902	0.113745	0.3799	6976	7700	7738	0.793	VR
48	0.09	0.118265	0.3732	7987	8200	8241	0.761	54
239	0.09	0.230769	0.3761	20869	20000	20200	0.39	16
157	0.0899	0.289068	0.3783	16884	19600	19698	0.311	52
523	0.0896	0.149833	0.3735	20827	21500	21607	0.598	VR
396	0.0894	0.040915	0.3707	6571	6800	6834	2.185	60
315	0.0887	0.074916	0.3718	11424	11500	11557	1.184	99
492	0.0883	0.043974	0.3741	11222	11600	11658	2.008	VR
528	0.088	0.09628	0.3767	8653	8450	8534	0.914	66
423	0.0878	0.078323	0.3767	17895	18000	18090	1.121	VR
211	0.0874	0.085185	0.3658	11121	14400	14472	1.026	36
246	0.0872	0.153792	0.3627	40720	39500	39895	0.567	VR
282	0.0871	0.845631	0.3632	59044	59000	59590	0.103	51

202	0.087	0.127941	0.371	25174	24500	24622	0.68	28
37	0.0857	0.023056	0.3653	6571	6200	6231	3.717	99
114	0.0857	0.041989	0.3657	7279	7400	7437	2.041	65
338	0.0856	0.163048	0.3676	21029	20600	20703	0.525	VR
387	0.0848	0.168588	0.3572	18629	21800	22018	0.503	VR
264	0.0846	0.089146	0.3646	16479	16900	16984	0.949	34
93	0.0834	0.032263	0.3679	7077	7500	7537	2.585	99
355	0.0833	0.130975	0.3468	31049	32500	32825	0.636	VR
178	0.0832	0.162818	0.3559	35630	36500	36865	0.511	73
280	0.0828	0.15082	0.35	45810	46000	46460	0.549	45
416	0.0828	0.199038	0.3522	20725	19000	19095	0.416	VR
219	0.0825	0.080175	0.3556	30633	32000	32160	1.029	54
498	0.0823	0.038404	0.3491	14659	14400	14472	2.143	VR
172	0.0821	0.133931	0.3405	30431	34000	34170	0.613	45
524	0.0808	0.03533	0.3426	13234	12500	12625	2.287	50
490	0.0805	0.014432	0.3472	7380	7200	7236	5.578	VR
304	0.0799	0.011588	0.3424	6066	6000	6030	6.895	94
181	0.0796	0.076538	0.3399	48864	48000	48480	1.04	73
318	0.079	0.017223	0.3421	6976	7700	7738	4.587	99
417	0.0789	0.027358	0.3474	13345	13600	13668	2.884	8
13	0.0782	0.010245	0.3369	4802	5500	5527	7.633	94
128	0.0781	0.026305	0.3371	6167	6500	6532	2.969	99
380	0.0778	0.061164	0.3347	30540	33000	33330	1.272	VR
465	0.0778	0.165532	0.3367	47517	52000	52520	0.47	VR
155	0.0776	0.020799	0.3381	12435	12500	12562	3.731	52
352	0.0758	0.032132	0.3261	14558	16900	16984	2.359	30
476	0.0735	0.025808	0.3212	16075	18500	18592	2.848	99
248	0.0732	0.052814	0.3069	44792	44500	44945	1.386	45
121	0.0699	0.011629	0.3034	9807	10900	10954	6.011	51
228	0.0666	0.01367	0.2828	16681	16500	16582	4.872	62
481	0.063	0.007123	0.2749	9706	12100	12160	8.845	84
390	0.0588	0.007978	0.2453	17895	19900	19999	7.37	54
216	0.0567	0.013561	0.2416	38175	44000	44440	4.181	70
256	0.0475	0.001793	0.1838	9301	9400	9447	26.499	VR

APPENDIX B

Model Code Developed in this Project

Appendix B
Model Code Developed in this Project

Example WinBUGS Code Used in Chapter 3

```
model
# high hazard identification for median crossing crashes 2
# includes random effects for median crossing crashes only
# lognormal random effects
{
for (k in 1:N) {
mu11[k] <- lambda1*lamrand1[k]*p1*x[k]
mu10[k] <- lambda1*lamrand1[k]*(1-p1)*x[k]
mu01[k] <- lambda0*p0*x[k]
mu00[k] <- lambda0*(1-p0)*x[k]
y11[k] ~ dpois(mu11[k])
y10[k] ~ dpois(mu10[k])
y01[k] ~ dpois(mu01[k])
y00[k] ~ dpois(mu00[k])

lamrand1[k] ~ dlnorm(0,tau)

mus1[k] <- (lambda1*lamrand1[k]*p1+lambda0*p0)*xs[k]
mus0[k] <- (lambda1*lamrand1[k]*(1-p1)+lambda0*(1-p0))*xs[k]
y1s[k] ~ dpois(mus1[k])
y0s[k] ~ dpois(mus0[k])

p11sim[k] <- lambda1*lamrand1[k]*p1/(lambda1*lamrand1[k]*p1+lambda0*p0)
p10sim[k] <- lambda1*lamrand1[k]*(1-p1)/(lambda1*lamrand1[k]*(1-
p1)+lambda0*(1-p0))
mu1all[k] <- y1s[k]*p11sim[k]+y0s[k]*p10sim[k]+y11[k]+y10[k]

hizard[k] <- step(lamrand1[k]-1)
}

p1~ dunif(0,1)
p0~dunif(0,1)
lambda1 ~ dunif(0,1)
lambda0~ dunif(0,1)
tau ~ dgamma(.001,.001)

# rx1~dpar(1,1)
# r1 <- rx1-1

}

Data    click on one of the arrows to open the data

Inits  list(lambda1=0.032, lambda0=0.123, p1=0.44, p0=0.081,tau=1.0)
```

EXCEL Macro Implementing MCC Collision Model

```
Function rnorm1(mu, sigma)
' normal random number generator
Dim u(1 To 12) As Double

Sum = 0
For i = 1 To 12
    u(i) = Rnd
    Sum = Sum + u(i)
Next i
z = Sum - 6
rnorm1 = mu + z * sigma
End Function

Function xout1(vin, thetain, bin)

'input:
' vin = encroaching vehicle's initial speed
' thetain = encroacing vehicle's encroachment angle
' bin = encroaching vehicle's braking factor
' output:
' lateral distance traveled on Hutchinson and Kennedy's
' cross-section

Dim G1(1 To 7) As Double
Dim d1(1 To 7) As Double
Dim mu1(1 To 7) As Double
' Dim vin, bin, thetain As Double
Dim xout, yout, vout As Double
Dim a, G, dhat, dstop, dt, thetarad As Double
Dim i, nsec As Integer

' Read Hutchinson and Kennedy's cross-section from Sheet1

For i = 1 To 7
    G1(i) = Worksheets("Sheet1").Cells(1 + i, 8).Value
    d1(i) = Worksheets("Sheet1").Cells(1 + i, 8 + 1).Value
    mu1(i) = Worksheets("Sheet1").Cells(1 + i, 8 + 2).Value
Next i

' input check
' vin = Range("H13:H13").Value
' thetain = Range("H14:H14").Value
' bin = Range("H15:H15").Value

nsec = 7
x = 0
y = 0
G = 32.2
v2 = vin * vin
thetarad = thetain * (3.141592 / 180)

i = 1
Do While v2 > 0 And i <= nsec
    a = G * (bin * mu1(i) + G1(i) * Sin(thetarad))
```

```
    dhat = d1(i) / Sin(thetarad)
    dstop = v2 / (2 * a)
    If dstop > 0 Then
        If dhat > dstop Then
            dt = dstop
        Else
            dt = dhat
        End If
    Else
        dt = dstop
    End If
    x = x + dt * Sin(thetarad)
    y = y + dt * Cos(thetarad)
    v2 = v2 - 2 * dt * a
    i = i + 1
Loop
If v2 >= 0 Then
    v0 = v2 ^ (0.5)
Else
    v0 = 0
End If
xout1 = x
' yout = y
' vout = v0

' output check
' Range("K13:K13").Value = xout
' Range("K14:K14").Value = yout
' Range("K15:K15").Value = vout

End Function


Sub Vbtheta(vout, bout, thetaout)

' output:
' vout = encroaching vehicle's initial speed
' bout = encroaching vehicle's braking factor
' thetaout = encroaching vehicle's encroachment angle

Dim thetahk(1 To 97) As Double
Dim xhk(1 To 97) As Double
Dim yhk(1 To 97) As Double
Dim crosshk(1 To 97) As Integer
Dim d1, d2, v1, v2, b1, b2 As Double
Dim v, f, xx As Double
' Dim vout, thetaout, bout As Double

Dim i, ipick, kout, kount As Integer

' lower and upper bounds for speed
v1 = 10 * (88 / 60)
v2 = 70 * (88 / 60)
' lower and upper bounds for braking factor
b1 = 0.1
b2 = 1
```

```
'read angle, x-distance, y-distance and crossing code
' for 97 of H&K's observed encroachments from Sheet 1

For i = 1 To 97
    thetahk(i) = Worksheets("Sheet1").Cells(1 + i, 2).Value
    xhk(i) = Worksheets("Sheet1").Cells(1 + i, 3).Value
    yhk(i) = Worksheets("Sheet1").Cells(1 + i, 4).Value
    crosshk(i) = Worksheets("Sheet1").Cells(1 + i, 5).Value
Next i
kount = 0

Do While kount <= 550

' randomly select an observed encroachment

ipick = Int(Round(1 + Rnd * (97 - 1), 0))
' ipick = Int(Cells(2, 13).Value)

' measurement uncertainty for vehicles stopping in median
' + or - 2 feet

    If crosshk(ipick) = 0 Then
        d1 = xhk(ipick) - 2
        d2 = xhk(ipick) + 2
    End If
'measurement uncertainty for vehicle's crossing median
' but not crossing traveled way=width of traveled way

    If crosshk(ipick) = 1 Then
        d1 = 40
        d2 = 62
    End If

'measurement uncertainty for vehicle's crossing traveled way
' = edge of far lane to 100 feet

    If crosshk(ipick) >= 2 Then
        d1 = 62
        d2 = 100
    End If

' set encroachment angle
    theta = thetahk(ipick)

' output check
'     Worksheets("Sheet1").Range("N12:N12").Value = ipick
'     Worksheets("Sheet1").Range("N13:N13").Value = d1
'     Worksheets("Sheet1").Range("N14:N14").Value = d2
'     Worksheets("Sheet1").Range("N15:N15").Value = theta


' sample speed and braking factor until acceptable combination found
' or 500 itertions tried

    kout = 0
    kount = 0
    Do While kout < 1 And kount <= 500
```

```
        v = v1 + Rnd * (v2 - v1)
        f = b1 + Rnd * (b2 - b1)
        xx = xout1(v, theta, f)
        kount = kount + 1
        Worksheets("Sheet1").Range("N11:N11").Value = kount
        If xx >= d1 And xx <= d2 Then
            kout = 1
            vout = v
            thetaout = theta
            bout = f
            kount = 600
        End If
    Loop
Loop

' output check
' Worksheets("Sheet2").Cells(1, 9).Value = vout
' Worksheets("Sheet2").Cells(2, 9).Value = thetaout
' Worksheets("Sheet2").Cells(3, 9).Value = bout

End Sub

Sub mccsim()
' Simulates trajectory of encroaching vehicle and when the encroaching
vehicle
' crosses the median, the trajectories of opposing vehicles in lanes 1
and 2

' Maximum sizes
' number of segments in cross section = 10
' number of time steps in collision simulation = 500
' number of opposing lanes = 4


Dim Gin(1 To 10) As Double
Dim din(1 To 10) As Double
Dim muin(1 To 10) As Double
Dim vin, b, theta As Double
Dim XY(1 To 10, 1 To 5) As Double
Dim x0(1 To 500) As Double
Dim y0(1 To 500) As Double
Dim vx0(1 To 500) As Double
Dim vy0(1 To 500) As Double
Dim ax0(1 To 500) As Double
Dim ay0(1 To 500) As Double
Dim x(1 To 500, 1 To 4, 1 To 2) As Double
Dim y(1 To 500, 1 To 4, 1 To 2) As Double
Dim vx(1 To 500, 1 To 4, 1 To 2) As Double
Dim vy(1 To 500, 1 To 4, 1 To 2) As Double
Dim ax(1 To 500, 1 To 4, 1 To 2) As Double
Dim ay(1 To 500, 1 To 4, 1 To 2) As Double
Dim d(1 To 500, 1 To 4, 1 To 2) As Double
Dim tp(1 To 4, 1 To 2) As Double
Dim aygo(1 To 4, 1 To 2) As Double
Dim dmin(1 To 4, 1 To 2) As Double

Dim xout, yout, vout As Double
```

```
Dim a, G, dhat, dstop, dt, thetarad, close2  As Double
Dim i, j, k, n, nsec, niter, ncrash, ncross As Integer
Dim nlane, nmid, nsteps, shift, check, nveh As Integer

' cross section specificiation from Sheet 2

shift = 5

nsec = Worksheets("Sheet2").Cells(1 + shift, 6).Value
edge = Worksheets("Sheet2").Cells(2 + shift, 6).Value
nlane = Worksheets("Sheet2").Cells(3 + shift, 6).Value
delta = Worksheets("Sheet2").Cells(11 + shift, 6).Value
niter = Worksheets("Sheet2").Cells(12 + shift, 6).Value
nstep = Worksheets("Sheet2").Cells(13 + shift, 6).Value
close2 = Worksheets("Sheet2").Cells(14 + shift, 6).Value
nveh = Worksheets("Sheet2").Cells(15 + shift, 6).Value


For i = 1 To nsec
    Gin(i) = Worksheets("Sheet2").Cells(shift + 1 + i, 1).Value
    din(i) = Worksheets("Sheet2").Cells(shift + 1 + i, 2).Value
    muin(i) = Worksheets("Sheet2").Cells(shift + 1 + i, 3).Value
Next i

opwidth = 0
For i = edge + 1 To nsec
    opwidth = opwidth + din(i)
Next i

' opposing vehicle specifications

vbar = Worksheets("Sheet2").Cells(shift + 1, 12).Value
vsig = Worksheets("Sheet2").Cells(shift + 1, 13).Value
tpbar = Worksheets("Sheet2").Cells(shift + 2, 12).Value
tpsig = Worksheets("Sheet2").Cells(shift + 2, 13).Value
abar = Worksheets("Sheet2").Cells(shift + 3, 12).Value
asig = Worksheets("Sheet2").Cells(shift + 3, 13).Value
density = Worksheets("Sheet2").Cells(shift + 4, 12).Value

vbarfps = vbar * (88 / 60)
vsigfps = vsig * (88 / 60)
abarfps2 = abar * 32.2
asigfps2 = asig * 32.2

ybar = 5280 / density

Worksheets("Sheet2").Cells(shift + 5, 9).Value = ybar
Worksheets("Sheet2").Cells(shift + 6, 9).Value = vbarfps
Worksheets("Sheet2").Cells(shift + 7, 9).Value = tpbar
Worksheets("Sheet2").Cells(shift + 8, 9).Value = abarfps2

xmedian = 0
For i = 1 To edge
    xmedian = xmedian + din(i)
Next i

Worksheets("Sheet2").Cells(shift + 8, 11).Value = xmedian
```

```
ncrash = 0
nmid = 0
ncross = 0

For n = 1 To niter

' encroaching vehicle specifications

Call Vbtheta(vin, b, theta)


' check for median cross by encroaching vehicle

xx = 0
yy = 0
G = 32.2
v2 = vin * vin
thetarad = theta * (3.141592 / 180)


For i = 1 To nsec
    a = G * (b * muin(i) + Gin(i) * Sin(thetarad))
    dhat = din(i) / Sin(thetarad)
    dstop = v2 / (2 * a)
    If dstop > 0 Then
        If dhat > dstop Then
            dt = dstop
        Else
            dt = dhat
        End If
    Else
        dt = dstop
    End If
    xx = xx + dt * Sin(thetarad)
    yy = yy + dt * Cos(thetarad)
    v2 = v2 - 2 * dt * a
    XY(i, 1) = xx
    XY(i, 2) = yy
    XY(i, 3) = 0
    If v2 > 0 Then
        XY(i, 3) = v2 ^ (0.5)
    End If
    XY(i, 4) = a
Next i

If XY(edge + 1, 1) <= xmedian Then
    stop1 = 0
    Else
    stop1 = 1
End If

If XY(edge, 1) >= xmedian / 2 Then
    nmid = nmid + 1
End If
```

```
' If encroaching vehicle crosses the median, simulate its trajectory
and that of
' opposing vehicles in lanes 1 and 2

If stop1 > 0 Then
    ncross = ncross + 1
' initialize encroaching vehicles
    x0(1) = 0
    y0(1) = 0
    a0 = -G * (b * muin(edge + 1) + Gin(edge + 1) * Sin(thetarad))
    vx0(1) = XY(edge, 3) * Sin(thetarad)
    vy0(1) = XY(edge, 3) * Cos(thetarad)
    ay0(1) = a0 * Cos(thetarad)
    ax0(1) = a0 * Sin(thetarad)

' initialize opposing vehicles in each lane

xsofar = 0
For j = 1 To nlane
    x(1, j, 1) = xsofar + din(edge + j) / 2
    p1 = Rnd
    y(1, j, 1) = -Log(1 - p1) * ybar + (XY(edge + (j - 1), 2) -
XY(edge, 2))
'    y(1, j) = ybar
    If nveh > 1 Then
        x(1, j, 2) = xsofar + din(edge + 2) / 2
        p2 = Rnd
        y(1, j, 2) = -Log(1 - p2) * ybar + y(1, j, 1)
    End If

    For k = 1 To nveh
    vx(1, j, k) = 0
'    vy(1, j) = -vbar
    vtemp = rnorm1(vbarfps, vsigfps)
    If vtemp > 0 Then
        vy(1, j, k) = -vtemp
        Else
        vy(1, j, k) = -vbarfps
    End If
    ax(1, j, k) = 0
    ay(1, j, k) = 0
    d(1, j, k) = (x(1, j, k) ^ 2 + y(1, j, k) ^ 2) ^ (0.5)
    tptemp = rnorm1(tpbar, tpsig)
    If tptemp > 0 Then
        tp(j, k) = tptemp
        Else
        tp(j, k) = tpbar
    End If
 '   tp(j)=tpbar
 '   aygo(j) = abarfps2
    aytemp = rnorm1(abarfps2, asigfps2)
    If aytemp > 0 Then
        aygo(j, k) = aytemp
        Else
        aygo(j, k) = abarfps2
    End If
```

```
    dmin(j, k) = 100000
    Next k
xsofar = xsofar + din(edge + j)
 '  aygo(j)=rnorm1(abarfps2,asigfps2)

Next j

 ' trajectory simulation
    i = 1
    Do While x0(i) < opwidth And i < nstep
        i = i + 1
' encoaching vehicle
        x0(i) = x0(i - 1) + vx0(i - 1) * delta
        y0(i) = y0(i - 1) + vy0(i - 1) * delta
        vxtemp = vx0(i - 1) + ax0(i - 1) * delta
        If vxtemp > 0 Then
            vx0(i) = vxtemp
            Else
            vx0(i) = 0
        End If
        vytemp = vy0(i - 1) + ay0(i - 1) * delta
        If vytemp > 0 Then
            vy0(i) = vytemp
            Else
            vy0(i) = 0
        End If
        ax0(i) = ax0(i - 1)
        ay0(i) = ay0(i - 1)

        For j = 1 To nlane

        x(i, j, 1) = x(i - 1, j, 1) + vx(i - 1, j, 1) * delta
        y(i, j, 1) = y(i - 1, j, 1) + vy(i - 1, j, 1) * delta

        If nveh > 1 Then
            x(i, j, 2) = x(i - 1, j, 2) + vx(i - 1, j, 2) * delta
            ytemp = y(i - 1, j, 2) + vy(i - 1, j, 2) * delta
            If ytemp > y(i, j, 1) Then
                y(i, j, 2) = ytemp
                Else
                y(i, j, 2) = y(i, j, 1)
            End If
        End If

        For k = 1 To nveh
        vxtemp = vx(i - 1, j, k) + ax(i - 1, j, k) * delta
        If vxtemp > 0 Then
            vx(i, j, k) = vxtemp
            Else
            vx(i, j, k) = 0
        End If
        vytemp = vy(i - 1, j, k) + ay(i - 1, j, k) * delta
        If vytemp < 0 Then
            vy(i, j, k) = vytemp
            Else
            vy(i, j, k) = 0
        End If
```

```
        ax(i, j, k) = 0
        If i * delta >= tp(j, k) Then
            ay(i, j, k) = aygo(j, k)
            Else
            ay(i, j, k) = 0
        End If

' separation of encroaching and opposing vehicles
    d(i, j, k) = ((x0(i) - x(i, j, k)) ^ 2 + (y0(i) - y(i, j, k)) ^ 2)
^ (0.5)


    If d(i, j, k) < dmin(j, k) Then
        dmin(j, k) = d(i, j, k)
    End If
    Next k
    Next j
  Loop

 check = 0
 For j = 1 To nlane
    For k = 1 To nveh
        If dmin(j, k) <= close2 Then
            check = check + 1
        End If
    Next k
 Next j

If check > 0 Then
    ncrash = ncrash + 1
End If

End If

Worksheets("Sheet2").Cells(12 + shift, 9).Value = nmid
Worksheets("Sheet2").Cells(13 + shift, 9).Value = ncrash
Worksheets("Sheet2").Cells(14 + shift, 9).Value = ncross

Next n


' output simulated trajectories of tlist > 0

tlist = 0
If tlist > 0 Then

    jout = 1
'    kout = 1
    For i = 1 To nstep
        Worksheets("Sheet2").Cells(i, 15).Value = x0(i)
        Worksheets("Sheet2").Cells(i, 16).Value = y0(i)
        Worksheets("Sheet2").Cells(i, 17).Value = vx0(i)
        Worksheets("Sheet2").Cells(i, 18).Value = vy0(i)

        Worksheets("Sheet2").Cells(i, 19).Value = x(i, jout, 1)
        Worksheets("Sheet2").Cells(i, 20).Value = y(i, jout, 1)
        Worksheets("Sheet2").Cells(i, 21).Value = vx(i, jout, 1)
```

```
        Worksheets("Sheet2").Cells(i, 22).Value = vy(i, jout, 1)
        Worksheets("Sheet2").Cells(i, 23).Value = ax(i, jout, 1)
        Worksheets("Sheet2").Cells(i, 24).Value = ay(i, jout, 1)
        Worksheets("Sheet2").Cells(i, 25).Value = d(i, jout, 1)
        If nveh > 1 Then
        Worksheets("Sheet2").Cells(i, 26).Value = x(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 27).Value = y(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 28).Value = vx(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 29).Value = vy(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 30).Value = ax(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 31).Value = ay(i, jout, 2)
        Worksheets("Sheet2").Cells(i, 32).Value = d(i, jout, 2)
        End If
    Next i
End If


End Sub
```

APPENDIX C

Spreadsheets Generated in Chapter 4

Appendix C
Spreadsheets Generated in Chapter 4

Median width = 30 feet

Gary A. Davis		University of Minnesota			2 vehicles/lane		adt range					
Uses Eric Donnell's later model												
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0400	5.5000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.3333	9.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	1.0000	0.4000								veh/l/mi=	12.82	12.82051
0.3333	9.0000	0.4000					ybar=				enter	compute
0.0400	5.5000	0.7500					vybar=	95.333				
0.1500	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	30		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	12026	pmid=	0.801733	Exmid=	3.601662
				nsteps=	500		mccrash=	2743	pcrash=	0.182867	Excrash=	0.8215
				close2=	4.50		mccross=	6258	pcross=	0.4172	Excross=	1.874206
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	6086.427
								1				
				ADT	Density	ncrash	MVMT	enc/yr	pcrash	Excrash	pennmod	ratio
				5000	1.6025641	511	1.825	0.561543019	0.034067	0.01913	0.0067	2.855209
				10000	3.2051282	895	3.65	1.123086039	0.059667	0.067011	0.0278	2.41046
				15000	4.8076923	1309	5.475	1.684629058	0.087267	0.147012	0.0637	2.30788
				20000	6.4102564	1700	7.3	2.246172078	0.113333	0.254566	0.1147	2.219409
				25000	8.0128205	1958	9.125	2.807715097	0.130533	0.3665	0.181	2.024864
				30000	9.6153846	2250	10.95	3.369258117	0.15	0.505389	0.2628	1.923093
				35000	11.217949	2529	12.775	3.930801136	0.1686	0.662733	0.3601	1.840414
				40000	12.820513	2743	14.6	4.492344156	0.182867	0.8215	0.4731	1.736419

Median width = 40 feet

Gary A. Davis		University of Minnesota			2 vehicles/lane		adt range					
Uses Eric Donnell's later model												
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0417	8.0000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.2732	11.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	2.0000	0.4000								veh/l/mi=	12.82	12.82051
0.2732	11.0000	0.4000					ybar=				enter	compute
0.0417	8.0000	0.7500					vybar=	95.333				
0.0150	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	40		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	9062	pmid=	0.604133	Exmid=	2.713975
				nsteps=	500		mccrash=	1686	pcrash=	0.1124	Excrash=	0.504939
				close2=	4.50		mccross=	4219	pcross=	0.281267	Excross=	1.263547
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	9902.177
								1				
				ADT	Density	ncrash	MVMT	enc/yr	pcrash	Excrash	pennmod	ratio
				5000	1.6025641	311	1.825	0.561543019	0.020733	0.011643	0.0052	2.238973
				10000	3.2051282	596	3.65	1.123086039	0.039733	0.044624	0.0214	2.085231
				15000	4.8076923	871	5.475	1.684629058	0.058067	0.097821	0.0491	1.992277
				20000	6.4102564	1032	7.3	2.246172078	0.0688	0.154537	0.0885	1.746177
				25000	8.0128205	1306	9.125	2.807715097	0.087067	0.244458	0.1396	1.751135
				30000	9.6153846	1419	10.95	3.369258117	0.0946	0.318732	0.2026	1.573207
				35000	11.217949	1560	12.775	3.930801136	0.104	0.408803	0.2776	1.472634
				40000	12.820513	1686	14.6	4.492344156	0.1124	0.504939	0.3646	1.384914

Median width = 50 feet

Cost Effectiveness of Median Barrier Treatments						**version:**	**1.4.2**					
Gary A. Davis		University of Minnesota			2 vehicles/lane		adt range					
Uses Eric Donnell's later model												
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0400	6.0000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.1667	18.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	2.0000	0.4000								veh/l/mi=	12.82	12.82051
0.1667	18.0000	0.4000					ybar=				enter	compute
0.0400	6.0000	0.7500					vybar=	95.333				
0.0150	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	50		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	8196	pmid=	0.5464	Exmid=	2.454617
				nsteps=	500		mccrash=	1426	pcrash=	0.095067	Excrash=	0.427072
				close2=	4.50		mccross=	3533	pcross=	0.235533	Excross=	1.058097
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	11707.62
								1				
				ADT	Density	ncrash	MVMT	enc/yr	pcrash	Excrash	pennmod	ratio
				5000	1.6025641	244	1.825	0.561543019	0.016267	0.009134	0.004	2.283608
				10000	3.2051282	477	3.65	1.123086039	0.0318	0.035714	0.0165	2.164493
				15000	4.8076923	722	5.475	1.684629058	0.048133	0.081087	0.0379	2.139494
				20000	6.4102564	811	7.3	2.246172078	0.054067	0.121443	0.0682	1.78069
				25000	8.0128205	982	9.125	2.807715097	0.065467	0.183812	0.1076	1.708288
				30000	9.6153846	1102	10.95	3.369258117	0.073467	0.247528	0.1562	1.584687
				35000	11.217949	1299	12.775	3.930801136	0.0866	0.340407	0.2141	1.589946
				40000	12.820513	1426	14.6	4.492344156	0.095067	0.427072	0.2813	1.518209

Median width = 60 feet

Cost Effectiveness of Median Barrier Treatments						**version:**	**1.4.2**					
Gary A. Davis		University of Minnesota			2 vehicles/lane		adt range					
Uses Eric Donnell's later model												
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0400	10.0000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.1667	18.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	4.0000	0.4000								veh/l/mi=	12.82	12.82051
0.1667	18.0000	0.4000					ybar=				enter	compute
0.0400	10.0000	0.7500					vybar=	95.333				
0.0150	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	60		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	6760	pmid=	0.450667	Exmid=	2.02455
				nsteps=	500		mccrash=	583	pcrash=	0.038867	Excrash=	0.174602
				close2=	4.50		mccross=	1774	pcross=	0.118267	Excross=	0.531295
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	28636.48
								1				
				ADT	Density	ncrash	MVMT	enc/yr	pcrash	Excrash	pennmod	ratio
				5000	1.6025641	92	1.825	0.561543019	0.006133	0.003444	0.0031	1.11101
				10000	3.2051282	188	3.65	1.123086039	0.012533	0.014076	0.0128	1.099688
				15000	4.8076923	295	5.475	1.684629058	0.019667	0.033131	0.0292	1.134625
				20000	6.4102564	342	7.3	2.246172078	0.0228	0.051213	0.0526	0.973626
				25000	8.0128205	397	9.125	2.807715097	0.026467	0.074311	0.083	0.895312
				30000	9.6153846	511	10.95	3.369258117	0.034067	0.114779	0.1205	0.952526
				35000	11.217949	503	12.775	3.930801136	0.033533	0.131813	0.1651	0.798382
				40000	12.820513	583	14.6	4.492344156	0.038867	0.174602	0.2169	0.804991

Median width = 70 feet

Cost Effectiveness of Median Barrier Treatments						**version:**	**1.4.2**					
Gary A. Davis		University of Minnesota			2 vehicles/lane		adt range					
Uses Eric Donnell's later model												
											opposing traffic	
Cross Section Data:											mean	st.dev
G	d	mu		nsec=	7		ADT=	40000		v	65	5
-0.0400	10.0000	0.7500		edge=	5		Length=	1		tp	1.1	0.25
-0.1667	18.0000	0.4000		nlane_op=	2		Horizon=	10		a	0.65	0.1
0.0000	14.0000	0.4000								veh/l/mi=	12.82	12.82051
0.1667	18.0000	0.4000					ybar=				enter	compute
0.0400	10.0000	0.7500					vybar=	95.333				
0.0150	12.0000	0.7500					tpbar=	1.100				
-0.0150	12.0000	0.7500					aybar=	20.930	medwid=	70		
				Simulation Specs			MVMT=	14.600				
				delta=	0.02		enc/yr=	4.492				
				niter=	15000		mcmid=	6303	pmid=	0.4202	Exmid=	1.887683
				nsteps=	500		mccrash=	473	pcrash=	0.031533	Excrash=	0.141659
				close2=	4.50		mccross=	1320	pcross=	0.088	Excross=	0.395326
				nveh=	2							
							$/mile=	100000				
							cost=	100000			**$/crash=**	35296.13
								1				
				ADT	Density	ncrash	MVMT	enc/yr	pcrash	Excrash	pennmod	ratio
				5000	1.6025641	69	1.825	0.561543019	0.0046	0.002583	0.0024	1.076291
				10000	3.2051282	165	3.65	1.123086039	0.011	0.012354	0.0098	1.260607
				15000	4.8076923	223	5.475	1.684629058	0.014867	0.025045	0.0225	1.113103
				20000	6.4102564	281	7.3	2.246172078	0.018733	0.042078	0.0405	1.03897
				25000	8.0128205	285	9.125	2.807715097	0.019	0.053347	0.064	0.83354
				30000	9.6153846	410	10.95	3.369258117	0.027333	0.092093	0.0929	0.991314
				35000	11.217949	484	12.775	3.930801136	0.032267	0.126834	0.1273	0.996338
				40000	12.820513	473	14.6	4.492344156	0.031533	0.141659	0.1672	0.84724