AN EVALUATION OF THE CONVERGING CHEVRON PAVEMENT MARKING PATTERN INSTALLATION ON INTERSTATE 94 AT THE MITCHELL INTERCHANGE South-to-West RAMP IN MILWAUKEE COUNTY, WISCONSIN

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FOREWORD

A report on the Chevron Evaluation, funded by the American Automobile Association for Traffic Safety (AAAFTS), is available on-line at: http://www.aaafoundation.org/projects/index.cfm

The attached report is published independently of the AAAFTS-approved evaluation. It presents the authors' work and includes additional topics; **no implicit or explicit AAAFTS or Wisconsin Department of Transportation (WisDOT) approval should be assumed for presented information**. The attached report provides detailed information about the chevron installation, the data (see Appendices) and methods used in evaluating chevron effectiveness, statistical tests, and conclusions based on these tests. It is intended to provide the technical reader with the detailed information needed to form an independent opinion about the effectiveness of this first device installation in the U.S.

Furthermore, it is the intent of this report to help future evaluations i) avoid pitfalls, and ii) shed light on issues that were uncovered but were left without definitive answers in the course of the present evaluation (for example, different effect on autos and semi-trucks, possible reduction in lane-change behavior, possible differences in effectiveness by lane). Conclusions in this report should be applied judiciously at other locations, because **only one chevron installation was evaluated, the only installation present in the U.S. at this time**.

Speed reduction findings are summarized in **table 7**, page 22 (detector **B** speeds). A **discussion about crashes** (test ramp crashes) can be found on page 41. Crash statistics are presented on pages 45 and 46 and are summarized on page 48.

We had to overcome **a few important limitations**: the project was assigned to the investigators approximately 23 months after the chevrons had been installed: location, test and control ramps had already been decided; the speed analysis was necessarily limited to five-minute archived data whose accuracy could not be independently verified in the field; due to hardware problems, data from the critical detector downstream from the end of the chevrons was not available for one year after chevron installation; and, finally, this was the only installation in the U.S, precluding the design of an evaluation based on evaluating a large number of experimental installations.

An extensive effort was made to verify the validity of available information in order to overcome these limitations: a variety of cross-checks was performed on the available information; additional field data was gathered and compared with detector data; and information from a recently completed speed-related study on a nearby freeway curve was contrasted with available historical information.

The good news was that there was an overabundance of archived information, the choice of the test ramp location was, in our opinion, excellent (no nearby merges/diverges, relatively flat terrain, the study location was a curve where a speed reduction was necessary, congestion effects were minimal) and substantial support was provided by the Wisconsin Department of Transportation (WisDOT) and the Milwaukee County Sheriff's Department. Despite the limitations stated above, when all available information was examined, there was strong evidence indicating that the chevron markings were very effective in reducing speeds at this location.

The number of crashes on the test ramp was very small, and perhaps the statistical analysis section is too extensive given this small sample size. There were two motivations behind the extensive coverage of this topic:

- To provide an analysis that paralleled a presentation[i] of chevron installation-related crash experience in Japan (the same statistical tests were performed in our report).
- To provide future chevron evaluators with ideas about the types of crashes that may be affected by a chevron installation. (Perhaps **the** most important criterion in choosing a chevron installation location is the presence of a large number of "correctable" crashes.[ii])

The present report is a revision of a report originally submitted to WisDOT in December of 2001. The report was reorganized in order to improve readability. New information was added from various sources: a recently received 1997 Japanese article on a Chevron Evaluation, authored by Mr. Kazuyuki Terada and other information received from Japan; a U.K. evaluation of a different chevron-based device; and from a recently completed Marquette University evaluation of a traffic-actuated sign intended to reduce speeds at a freeway curve on Interstate 43, near downtown Milwaukee, Wisconsin.[iii] Appendices are identical to those in the original report, with the addition of Appendix 13 that presents information received from a Japanese colleague who works for the Japanese National Institute for Land and Infrastructure Management.

The authors are solely responsible for any errors or omissions. **No part of this report reflects AAAFTS or Wisconsin Department of Transportation policies or opinions**. AAAFTS provided $18,134 toward the device evaluation–the authors dedicated a significant part of additional personal time to expand the scope of the original proposal, prepare this report and gather related literature. The report published by AAAFTS is available on-line, as mentioned above.

The help of numerous organizations and individuals, listed in the Acknowledgments, was indispensable in completing this report.

We hope that you find this report thorough and informative. Please communicate any comments directly to me.

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[i] "A review of Two Innovative Pavement Patterns That Have Been Developed to Reduce Traffic Speeds and Crashes," by Lindsay I. Griffin, III and Robert N. Reinhardt, prepared for the AAA Foundation for Traffic Safety, February 1996.

[ii] We chose to put forth the argument that crashes on snow/ice covered pavement and deer crashes would have occurred whether the chevrons were installed or not. One may agree or disagree with this choice; it is important, however, to decide which crashes are expected to be affected by chevron presence during the site selection process.

[iii] "I-43 Speed Warning Sign Evaluation," by Alex Drakopoulos, Sharad Uprety and Georgia Vergou, Final Report submitted to WisDOT, November 2003.

EXECUTIVE SUMMARY

In February 1999, the Wisconsin Department of Transportation (WisDOT) requested authorization from the Federal Highway Administration (FHWA) to install "an Experimental Converging Chevron Pavement Marking Pattern" to reduce speeds on a freeway interchange ramp.

Previous applications of the device in Japan resulted in reduced speeds, attributed to the illusion created by the chevron pattern, intended "...to convince drivers that they are traveling faster than they really are and to create the impression that the road is narrowing..." No other applications of the converging chevrons had been implemented in the United States.

Authorization to experiment with the device was granted to WisDOT and the converging chevron device was installed in May 1999. Device evaluation was sponsored by the AAA Foundation for Traffic Safety (AAAFTS). Dr. Alexander Drakopoulos of Marquette University, was assigned the evaluation in March 2001. A report on the Chevron Evaluation, funded by AAAFTS, is currently available on-line through http://www.aaafoundation.org/.

The attached report is published independently of the AAAFTS-approved evaluation–it presents the authors' work and includes a few additional topics. It provides detailed information about the chevron installation, the data (see Appendices) and methods used in evaluating chevron effectiveness, statistical tests, and conclusions based on these tests. It is intended to provide the technical reader with the detailed information needed to form an independent opinion about the effectiveness of this first device installation in the U.S. **No implicit or explicit AAAFTS or Wisconsin Department of Transportation (WisDOT) approval should be assumed for presented information**.

Motivation for Device Installation
The motivation for device installation was to reduce speed-related crashes, by inducing drivers to drive at lower speeds at the evaluated site. If the device was effective, lower vehicular speeds and a lower number of speed-related crashes would be observed in the period following device installation. The present evaluation addressed device effectiveness on speeds and crashes.

Research Methods
Device evaluation was based on a before-and-after (device installation) comparison of speed and crash statistics. If the device was effective, speeds would be lower for vehicles exiting the experimental pattern on the ramp, compared to speeds at the same location before device installation. Consequently, the number and/or severity of speed-related crashes would also be expected to be lower. Another ramp on the same interchange was used as a control site, in order to estimate the impact of traffic and environmental effects on observed speed and crash experience changes. Before and after periods of equal durations were used for the speed and the crash analyses; before and after periods included the same months of the year.

Results
Speed information was provided by pavement-embedded detectors installed on the ramp where the device was installed (test ramp) and a nearby control ramp. In the period following chevron installation, the 85th percentile speed on the test ramp was 53 mph, 17 mph lower than before the chevrons were installed. It is estimated that approximately 3 mph of this speed reduction was due to increased traffic volume. Device effectiveness accounted for the remaining 14 mph speed reduction.

There were 14 crashes on the test ramp before the chevrons were installed, and 8 crashes after.

The numbers for the control ramp were 73 and 59, respectively. Thus, approximately 36% of all test ramp crashes occurred in the after period, compared to 45% for the control ramp. Although this indicated that the test ramp outperformed the control ramp, this difference was not statistically significantly different. When crashes that occurred on-snow or ice-covered roadways and collisions with deer were excluded from consideration (as irrelevant to the presence of the chevrons), the reduction in the number of crashes on the test ramp was statistically significant at the 10% level of significance.

Study Limitations
When interpreting the findings of this evaluation, it is important to keep in mind the context within which it was conducted, as well as the limitations that were imposed from the outset. The purpose of this effort was to evaluate the first and only installation of this device in the U.S.; no other installations would be permitted before this site was evaluated. Thus, data was only available from this one site; findings extrapolation to other sites should be judicious. At the time the investigator was assigned to the evaluation, twenty-three months after the device was installed, only historical vehicular speed data were available for analysis. It should be noted that, due to mechanical failure, no data was available from the detector located 30 feet past the end of the chevrons, for the year following device installation.

Available historical information was thoroughly reviewed and cross-checked and additional field data were gathered, for cross-checking. This work was meticulously documented, in order to allow the interested reader to form an independent opinion about the validity of the analyzed information. What was impressive about the findings, is that the speed reduction associated with the device was measured 20 months after device installation, indicating a lasting device effectiveness.

Crash information was limited to two years of before and two years of after information. Given that this was the only site where the device was installed, and the short time that had elapsed since device installation, it was not possible to conduct a multi-site data collection, nor was it possible to perform a trend analysis; the evaluation was limited to a before and after comparison between the test and the control ramp.

Recommendations
The identified speed reduction, leads to a recommendation to install the chevron pattern at carefully selected locations and, in the process, validate the findings of the present evaluation. Ideally (from a device evaluation point of view), selected locations should have a substantial speed-related crash experience; comparable untreated sites with similar crash experience, geometry and traffic volumes should be located within close proximity; accurate historical speed information should be available and the facilities should be provided to continue collecting speed data after device installation.

Very few crashes occurred on the test ramp, especially during the after period. It would be desirable to continue monitoring the safety performance of the study ramps for a few more years, in order to accumulate adequate crash statistics.

A number of additional recommendations for future chevron evaluations, based on information gathered from Wisconsin, Japan and the U.K. are included in the body of the report.

ABSTRACT

Special converging chevron pavement markings, intended to induce drivers to reduce their speed, were used in Japan in the early nineties. Before-after crash comparisons from six sites in Japan, with one-year before and after periods, were reported by Griffin and Reinhardt in a 1997 AAA Foundation for Traffic Safety (AAAFTS) report. The periods following converging chevron installations had lower numbers of crashes, however crash reductions were statistically significant at only three of the installations.

Based on the Japanese experience, the Wisconsin Department of Transportation petitioned the Federal Highway Administration for authorization to install converging chevron pavement markings on an urban high-speed urban freeway interchange directional ramp, where it was desirable to reduce vehicular speeds that had been identified as a contributing factor to a number of crashes. Permission to install the device was granted, and the device was installed on May 15, 1999.

AAAFTS sponsored an evaluation of the converging chevron pattern, undertaken by Alex Drakopoulos,[a] and Georgia Vergou[b] with data provided by the Wisconsin Department of Transportation. The AAA report on this evaluation is available on-line at http://www.aaafoundation.org/projects/index.cfm.

The present report furnishes detailed information about the chevron installation, the data and methods used in evaluating chevron effectiveness, statistical tests, and conclusions based on these tests. It includes extensions of the topics addressed in the work funded by AAAFTS and represents the authors' work; **no implicit or explicit AAAFTS approval should be assumed for information presented herein**. The report is intended to provide the technical reader with the detailed information needed to form an independent opinion about the effectiveness of this first device installation in the U.S. Furthermore, it is the intent of this report to help future evaluations avoid pitfalls and shed light on issues that were uncovered but were left without definitive answers in the course of the present evaluation.

Based on the analysis of four-month before and after periods, it was determined that the converging chevron installation contributed to an 85th percentile speed reduction of approximately 14 mph. The crash analysis based on two-year before and after periods, identified a crash reduction during the after period. This reduction **was not** statistically significant when all crashes were considered; when crashes on snow- or ice-covered pavement and collisions with deer were excluded from consideration as irrelevant to the evaluated device, the reduction **was** statistically significant at the 90% level of significance. Because these findings were based on a small number of crashes on the test ramp, it was recommended to continue monitoring the safety performance of the chevron installation for a few more years.

Both the speed and crash analyses contrasted data with data from a control site on the same interchange during the before and the after periods.

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INTRODUCTION

On February 2, 1999, the Wisconsin Department of Transportation (WisDOT) requested authorization from the Federal Highway Administration (FHWA) to install "an Experimental Converging Chevron Pavement Marking Pattern" to reduce speeds on the South-to-West ramp of the Interstate 94 Mitchell interchange, located in Milwaukee County, Wisconsin.[1] The request cited beneficial use of the pattern in a number of locations in Japan.

The effectiveness of the device was attributed to the illusion created by the chevron pattern, intended "...to convince drivers that they are traveling faster than they really are and to create the impression that the road is narrowing..." Although research was conducted on other patterns of illusory pavement markings, no other applications of the converging chevrons had been conducted in the United States as of that date.

Authorization to experiment with the device was granted to WisDOT and device evaluation was sponsored by the AAA Foundation for Traffic Safety (AAAFTS) and initiated by Dr. Robert Reinhardt of the Texas Transportation Institute, who conducted the literature search on the Japanese experience with the device.[2] Subsequently, Dr. Alexander Drakopoulos of Marquette University, Milwaukee, Wisconsin assumed responsibility for device evaluation, approximately 18 months after chevron installation.

EVALUATION DESCRIPTION

The proposal submitted by Marquette University to the AAAFTS was for a before/after with control evaluation of speed and crash data of this unique installation in the U.S. The chevron pattern was installed on the northbound-to-westbound ramp (test ramp) of the I-94 Mitchell interchange in Milwaukee County on May 15, 1999. The eastbound-to-southbound ramp of the same interchange was identified, ***prior to the initiation of the evaluation by Marquette University***, as a suitable control location, given its close proximity to the test ramp, similar geometry (each ramp had two lanes, radii and superelevations were similar), and similar average daily traffic volumes. An aerial photograph of the interchange and the two ramps under consideration is presented in **figure 1**. In addition, speed detectors were embedded in each ramp at approximately its point of curvature.

Crash experience and speed statistics for the test and control ramps was to be evaluated for similar periods before and after chevron installation; statistics for the two ramps would be

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[1] See Appendix 1 (A1).

[2] "A review of Two Innovative Pavement Patterns That Have Been Developed to Reduce Traffic Speeds and Crashes," by Lindsay I. Griffin, III and Robert N. Reinhardt, prepared for the AAA Foundation for Traffic Safety, February 1996.

compared between the two periods, in order to assess the effect that the installation of the chevron markings had on crashes and speeds, while accounting for the influence of weather, traffic volume and other factors that would affect both ramps in a similar manner.

REPORT ORGANIZATION

The present report provides detailed information about the chevron installation, the data and methods used in evaluating chevron effectiveness, statistical tests, and conclusions based on these tests. It is intended to provide the technical reader with the detailed information needed to form an independent opinion about the effectiveness of this first device installation in the U.S. Furthermore, it is the intent of this report to help future evaluations avoid pitfalls and shed light on issues that were uncovered but were left without definitive answers in the course of the present evaluation. To this end, extensive Appendices are provided, to allow investigators form independent opinions based on detailed information, and decide on measures that will definitively address any remaining questions regarding chevron effectiveness.

The report is divided in the following parts:

Background: describes test and control ramp geometry through aerial photographs, plan & profile details, digital pictures taken in the field, and tables documenting the placement of sign bridges, other permanent roadway fixtures, pavement detectors and chevron markings in order to provide as comprehensive and accurate information as possible about the analyzed site.

Database Description: describes in detail the three sources of information used in the study--detector data; speed data collected in the field through a laser gun; and crash data provided by WisDOT. It is assumed that the reader is familiar with the operation of pavement-embedded loop detectors and laser gun capabilities; also with typical accuracy and reliability of these devices.

Database Analysis: focuses on the analysis of each of the three sources of information–speeds based on detector data; speeds based on laser gun data gathered in the field; and crash data provided by WisDOT. The section describes how analysis detectors were chosen, and how the before and after analysis periods were established.

Because the speed-reduction effectiveness of the evaluated device was based on loop detector data, a major part of the speed analysis section is devoted in establishing the reliability of speed information obtained from loop detectors. Speed patterns are examined for reasonableness, and then cross-checked with traffic volume patterns. When the reasonableness of speed data is sufficiently established, a statistical analysis of speeds is presented, producing mean speeds, 85th and 95th percentile speeds, confidence intervals for the means and standard errors of the means, for the periods before and after chevron installation; also for weekdays, weekends and all days. Analysis of Variance is performed on speed data for each detector.
The loop detector speed data analysis provides the basis for a comparison with speed data collected in the field through a laser gun in the after period. The goal of this comparison is to

verify loop detector accuracy in the after period. Detector reliability conclusions based on detector information are revisited in light of the additional information provided by laser gun data.
The section concludes with a detailed crash analysis. Very few crashes occurred on the test ramp during the before period and even fewer during the after period. The intent of the crash analysis is mainly to provide a blueprint for future evaluations; an important observation is made about crashes that are not likely to be affected by chevron presence.

Chevron Installation Cost: discusses cost and materials used at the test site.

Conclusions are followed by a section on **Related Information from Recent Publications**. The section describes some of the findings of a Japanese chevron evaluation published in 1997 and draws information from a recently published Marquette University evaluation of a traffic control device, intended to reduce speeds, installed upstream of a freeway curve. Recommendations for future chevron evaluations are drawn from these two efforts.

Recommendations drawn from information presented in this report as well as the presented recent publications, **Acknowledgments** conclude the report.

Appendix 1 contains the Request for Authorization to Experiment with Chevron Pavement Markings, submitted by WisDOT to FHWA. An attachment to the letter provides suggested chevron pattern dimensions.

Appendix 2 presents form MV4000, the Wisconsin Motor Vehicle Accident Report form. The form can be used to develop ideas on crash characteristics that investigators may wish to address.

Appendix 3 contains chevron installation dimensions in relation to roadway features as well as detailed test and control ramp dimensions superimposed on aerial photographs.

Appendices 4 and **5** present mean hourly speed graphs for each day of the before and the after period, respectively. The graphs were used to identify missing information and times during which detectors malfunctioned.

Appendices 6 and **7** present mean hourly volume graphs for each day of the before and the after period, respectively. The graphs were used to identify missing information and times during which detectors malfunctioned.

Appendix 8 presents 95 percent confidence interval graphs for mean hourly speeds for weekdays and weekends, for the before and after periods. The graphs were used to identify speed patterns and compare them with volume patterns; also to determine average speed variability during each hour of the day.

Appendix 9 presents cumulative speed distribution graphs for the before and after periods. The graphs are provided in order to allow investigators choose any speed percentile for analysis.

Appendix 10 presents 95 percent confidence interval graphs for mean hourly volumes for weekdays and weekends, for the before and after periods. The graphs were used to identify volume patterns and compare them with speed patterns; also to determine average volume variability during each hour of the day.

Appendix 11 presents speed and volume hourly statistics for weekdays and weekends, for the before and after periods, in tables. The tables provide basic statistics (mean, standard error of the mean, sample size) of interest to investigators.

Appendix 12 presents detailed listings for each crash on each of the two analyzed ramps, as well as crash summary tables. Crash listings allow investigators construct and test their own hypotheses. Provided tables provide insights to crash characteristics at the analyzed sites.

Appendix 13 presents summaries of three pavement marking evaluation articles published in Japan, and pictures of chevron and transverse anti-skid pavement marking installations on a two-lane road in Japan, provided by Mr. Kazuhiko ANDO of Japan's NILIM.

BACKGROUND

The following paragraphs describe the test and control ramps included in the evaluation. Wisconsin Department Of Transportation (WisDOT) calculations pertaining to device dimensions are summarized in **Appendix 1**.

Description of the Study Location

The Mitchell Interchange is a Y-type urban[3] interchange that provides for all movements through high-speed ramps. Both evaluated ramps have two twelve-foot asphalt traffic lanes and twelve-foot concrete shoulders with rumble strips on either side. The speed limit approaching the study ramps has been 50 mph throughout the evaluation period.

Test ramp

I-94 has four lanes in the northbound direction, approaching the study location. **Figure 2** is a view of I-94 northbound traffic, taken from the Layton Avenue bridge, facing south. Four lanes of traffic are visible; the two lanes closest to the median separate from the northbound direction at the Mitchell Interchange and follow a curve to the left to continue westbound to I-894 (test ramp lanes). Two sign bridges with WisDOT codes S-40-0055 and S-40-0057, respectively, can be seen in **figure 2**. The Layton Avenue off-ramp, starting between the two sign bridges, is identified on **figure 2**.

A description of features associated with the test ramp is provided in **table 1.** Distances are referenced to the end of the last chevron marking, increasing in the direction of travel, and were estimated based on the WisDOT aerial photographs (**Appendix 3 figure 3**), as-built plans (**Appendix 3 figures 1 and 2**), and the State Trunk Log file. The test ramp consists of a series of three consecutive horizontal curves. Detailed plan and profile information is provided in **table 2**.

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[3] Milwaukee County has a population of approximately one million.

Table 1. Description of Freeway Features Related to the Test Ramp.

Interstate Highway	Distance from start of chevrons (feet)[1]	Feature Description
MILW 094W	3075	B-40-0237 BRIDGE OVER W EDGERTON AVE
	2600	SPEED/VOLUME DETECTOR **A**
	2440	OFF RAMP TO LAYTON AVE
	2125	S-40-0055 SIGN BRIDGE OVER FWY
	1015	S-40-0057 SIGN BRIDGE OVER FWY
	640	CHEVRON MARKINGS BEGIN
	540	B-40-0238 W LAYTON AVE EB BRIDGE OVER FWY
	485	B-40-0239 W LAYTON AVE WB BRIDGE OVER FWY
MILW 894W	70	OFF RAMP TO I 894 WB (TEST RAMP BEGINS) & S-40-0058 SIGN BRIDGE OVER FWY
	50	RAMP POINT OF CURVATURE
	0	CHEVRON MARKINGS END
	-30	SPEED/VOLUME DETECTOR **B**
	-620	B-40-0241 BRIDGE OVER IH 43 NB
	-1610	RAMP POINT OF TANGENCY TEST RAMP ENDS

[1] MILW = Milwaukee County, W = Westbound (094W has a northbound orientation at the study location)

Figure 3 is a view of northbound traffic, taken from the Layton Avenue bridge, facing north. The point where the two median lanes separate from the two I-94 northbound lanes, the last few chevron patterns, and sign bridge S-40-0058, mentioned in **table 1** are visible. An advisory speed limit of 50 mph is posted on the sign bridge, and the exit sign at the ramp gore. Three chevron alignment signs (W1-8) and a large arrow sign (W1-6) are also visible behind the right-side concrete barrier, along the ramp.

In addition, two warning signs are posted in advance of the sign bridge (**figure 4**): a curve sign W1-2L, with an additional advisory speed plate of 50 mph, and a warning "tippy truck" sign.[4]

Data collected from two detectors, placed in the left (median) lane were used in the test ramp analysis: Detector **A** was located approximately 475 feet north of the bridge over W. Edgerton Avenue (see **figure 5**), and 1960 feet south of the first chevron pattern, and provided information upstream of the chevrons. Detector **B**, was located approximately 670 feet north of the start of the first chevron pattern (30 feet past the end of the last chevron pattern) and provided information immediately past the chevrons. The ramp curve started approximately 80 feet before the point where speed measurements were taken.

The curved part of the ramp has a total length of 1660 feet (**table 2**) and comprises of a compound curve: motorists enter a curve with a radius of 859 feet on which they travel 261 feet, then enter a curve with a radius of 881 feet to travel the next 1050 feet and continue on the final curve with a radius of 764 feet for 348 feet. The total curved length and deflection angle correspond to an "equivalent" fixed radius curve with a radius of 850 feet.

Test ramp Average Daily Traffic (ADT) for 1999 was 39,010 vehicles per day (vpd), and 42,800 vpd for the year 2000,[5] an increase of 9.7%. Traffic continuing northbound was 34,920 vpd in 1999 and 35,100 vpd in 2000.

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[4] "Tippy Truck" sign W7-51R Wisconsin Sign Plate book.

[5] 1999 and 2000 Wisconsin Highway Traffic Volume Data, published March 2000, and March 2001, respectively.

Figure 1.Mitchell Interchange Test and Control Ramps.

Figure 2. View of I-94 Northbound from Layton Avenue Bridge (Facing South).

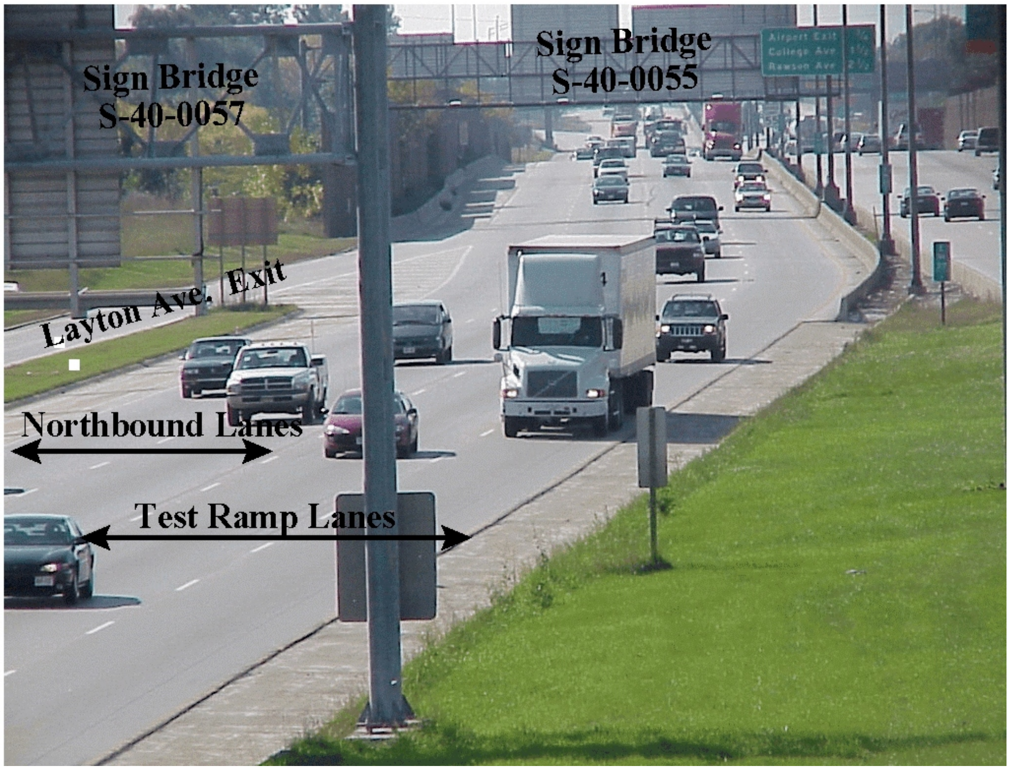

Figure 3 View of I-94 Northbound from Layton Avenue Bridge (Facing North).

Figure 4. Warning Signs Near Test Ramp Point of Curvature.

Figure 5. Detector Locations.

Table 2. Test Ramp Geometric Characteristics.

Lane width 12 feet				
Shoulder width (both sides) 12 feet				
Longitudinal gradient				
	From Layton Ave. through chevrons +3.011%			
	Entering horizontal curve +2.170%			
	Past bridge B-40-241 -3.000%			
	Horizontal curve #1	Horizontal curve #2	Horizontal curve #3	Total
Radius (feet)	859.44	881.47	763.94	≈850.58*
Deflection angle	17º25'00"	68º16'02"	26º06'59"	111º48'01"
Length (feet)	261.25	1050.26	348.22	1659.73
Superelevation	6%	6%	6%	

* An "equivalent radius" value calculated based on total deflection angle and total length.

Control ramp

A description of features associated with the control ramp is provided in **table 3.** Distances are referenced to the location of detectors **C** and **D** (median lane and shoulder lane respectively), and were estimated based on WisDOT aerial photographs (**Appendix 3 figure 4**), as-built plans and the State Trunk Log. Curve geometry is described in **table 4**.

I-894 has three lanes in the eastbound direction, approaching the control ramp. The three lanes separate into four lanes through a fork located approximately 50 feet after the curve point of curvature. Two lanes curve to the left to continue northbound and two lanes curve to the right to continue southbound. Detectors **C** and **D** are located approximately 150 feet after the fork.

The ramp consists of a set of reverse curves. Motorists enter the ramp following a 1456-foot-long curve to the right, with a radius of 818 feet, and, after traversing a 175-foot tangent, enter a gentle curve to the left with a radius of 2149 feet to travel 517 feet, before joining southbound I-94 traffic.

Control ramp Average Daily Traffic (ADT) for 1999 was 39,230 vehicles per day (vpd), and 42,200 vpd for the year 2000,[6] an increase of 7%. Traffic continuing northbound was 23,580 vpd in 1999 and 24,600 vpd in 2000.

[6] 1999 and 2000 Wisconsin Highway Traffic Volume Data, published March 2000, and March 2001, respectively.

Table 3. Description of Freeway Features Related to the Control Ramp.

Interstate Highway	Distance detectors C_1 & D (feet)	Feature Description
MILW 894E	-550	B-40-0243 BRIDGE S 20TH ST OVER FWY
	-200	CONTROL RAMP POINT OF CURVATURE
	-150	I 43 NB
	0	DETECTORS **C** & **D**
	560	B-40-0240 BRIDGE OVER IH 94 EB-MITCHELL
	1405	B-40-0239 BRIDGE W LAYTON AVE WB OVER FWY
	1460	B-40-0238 BRIDGE W LAYTON AVE EB OVER FWY
MILW 094E	1950	RAMP POINT OF TANGENCY CONTROL RAMP ENDS

[1] MILW = Milwaukee County, E = Eastbound (094E has a southbound orientation at the study location)

Table 4. Control Ramp Geometric Characteristics.

Lane width 12 feet				
Shoulder width (both sides) 12 feet				
Longitudinal gradient				
	Through chevrons +3.011%			
	Entering horizontal curve +2.170%			
	Past bridge B-40-241 -3.000%			
	Horizontal curve #1	Tangent	Horizontal curve #2	Total
Radius (feet)	818.51		2148.59	
Deflection angle	101°55'30"		13°47'41"	
Length (feet)	1456.07	175.00	517.31	2148.38
Superelevation	6%		3.9%	

DATABASE DESCRIPTION

Speed and volume information collected from inductive loop detectors embedded in the pavement near the study ramps was acquired from WisDOT. A small field data collection effort was also conducted in order to assess the reasonableness of loop detector speed data. Crash data was provided by WisDOT District 2 personnel.

Detector data

Five-minute inductive loop detector data summaries are stored by WisDOT in electronic form. **Table 5** presents a sample of available information. This sample represents information collected through detector with ID 4215 (detector **A**), on the first day of July 1998 from midnight (12:00 am) corresponding to time 00:00 to forty minutes past midnight (00:40). Each row represents information collected during one five-minute interval. During the five-minute interval from 00:00 to 00:05, a total of 22 vehicles were detected, the equivalent of a traffic volume of 264 vehicles per hour (vph). The corresponding lane occupancy was 2%, and the average speed of these vehicles was 62 mph.

Table 5. Sample Loop Detector Data.

Detector ID	Date	Time	Volume (vph)	Occupancy (%)	Speed (mph)
4215	19980701	00:00	264	2	62
4215	19980701	00:05	240	2	63
4215	19980701	00:10	252	2	62
4215	19980701	00:15	216	2	61
4215	19980701	00:20	180	1	62
4215	19980701	00:25	144	2	61
4215	19980701	00:30	144	1	61
4215	19980701	00:35	168	1	58
4215	19980701	00:40	168	1	62

WisDOT furnished five-minute information for twelve detectors (three detectors for each lane of traffic on each of the test and control ramps), from May 1998 to December of 1999, and from February 2000 to March of 2001. Each detector would have provided 105,120 observations per year (365 days/year x 24 hours/day x 12 observations/hr), if it was continuously on-line. The analyzed database contained 34 months (approximately 2.8 years) of data for twelve detectors, for a total of approximately 3.57 million lines of data.

Data Collected in the Field

The investigative team collected a limited sample of speed data, using a laser gun, with the help of a Milwaukee County Sheriff's Department Deputy, who was a Radar and Laser Instructor. The purpose of this limited-scope effort was to provide a degree of verification for test ramp detector data during the "after" period. This effort was not included in the original scope of work, but was useful in addressing some questions that arose after data from pavement-embedded detectors had been analyzed. A laser gun[7] was used to collect 187 speed observations on the test ramp, between 10:37 am and 11:42 am, on Wednesday, October 3, 2001, a clear, sunny, windy day. Data was collected from locations A, B and C shown in **figure 6**: Layton Avenue bridge facing south (location A), Layton Avenue bridge facing north (location C), and behind the "Exit 316" sign (location B–**figure 3**). Data collectors were adequately concealed from traffic, thus no effect due to their presence was expected on measured speeds.

Location A provided data at an average distance of 1570 feet before the end of the chevrons, location B provided data at an average distance of 245 feet from the end of the chevrons (**the curve PC**), and the average distance for location C was 45 feet from the end of the chevrons. For the remainder of this report, these distances will be referred to on figures as "before chevrons," "begin chevrons" and "end chevrons," respectively, keeping in mind that the latter two descriptors do not represent the beginning and the end of the chevron pattern, but locations past the beginning and before the end of the chevron pattern.

Vehicles were targeted for data collection as often as possible, when a clear line of sight was available between observer and vehicle. Thus the ratio of auto and truck observations does not represent the vehicle mix at the study location during the data collection period. Only free-flowing vehicle speeds were recorded. Information was collected on: distance from laser gun, vehicle speed, vehicle type (truck or auto), and lane vehicle was in (median or right lane), however, given the limited amount of time available for data collection, not enough information was available for a statistical analysis of all variables.

Field information, collected through the laser gun for vehicles traveling toward the test ramp, was manually recorded in the field and later entered in a spreadsheet for analysis. A sample of the collected information appears in **table 6.** The column "Location" refers to locations A, B and C, from which the data was recorded, shown in **figure 6**. Vehicle type was classified as "A" (automobile), or "T" (truck–only semi-trucks were targeted). Individual vehicle speed (in miles per hour), and vehicle distance from the laser gun (in feet) was recorded, as well as the lane the vehicle was in (lane 1 = median lane, lane 2 = right lane). Time was recorded periodically.

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[7] Custom Signals Pro Laser II PL 4741.

Figure 6. Field Data Collection Locations.

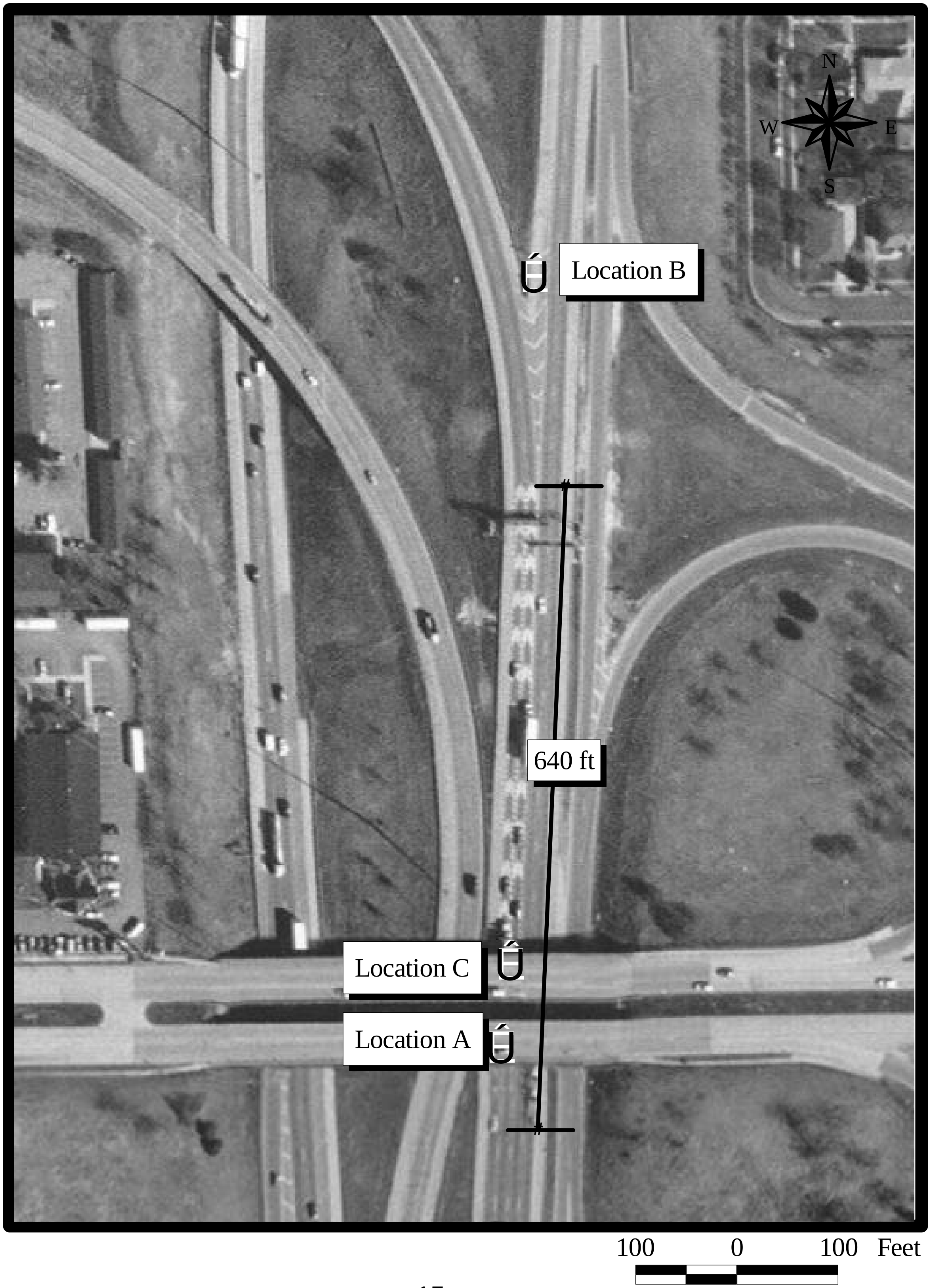


Table 6. Sample Field Data.

Obs	Location	Veh_type	Speed (mph)	Distance (feet)	Lane	Time
1	A	A	63	1001	1	1037
2	A	T	63	1269	1	
3	A	A	67	869	1	
4	A	T	67	1010	2	
5	A	T	71	743	2	
6	A	A	59	664	1	
7	A	T	60	1101	2	
8	A	A	62	1068	1	
9	A	T	64	1462	1	
10	A	T	70	948	2	

Crash data

The Milwaukee County Sheriff's Department is the primary police agency responding to freeway crashes and incidents in Milwaukee County–very few freeway crashes are reported by other agencies. All police agencies in the state use the "Wisconsin Motor Vehicle Accident Report" form MV4000.[8] Crash report hard copies are used to manually assign location markers corresponding to the Wisconsin State Trunk Log referencing system and the data is entered in an electronic database maintained by WisDOT. Enforcement officers record the name of the highway on which a crash occurred, the name of the closest cross-street, the distance and direction from the cross-street, vehicle direction of travel, and provide a crash site sketch. For urban crashes (including urban freeway crashes), the light post label of the light post closest to the crash scene is also recorded. This recorded information provides a good degree of location accuracy for freeway crashes.

WisDOT personnel queried the electronic crash record database for all crashes that occurred between May 15, 1997 and June 15, 2001 on the test and the control ramps. Hard copies of all crashes were reviewed in order to verify that their location was reported appropriately, before the data was furnished to Marquette University for analysis. Marquette University verified that lamp post locations for the furnished crashes corresponded with the evaluation ramps.

DATABASE ANALYSIS

The following sections describe the speed, volume and crash data analyses. Detector information was primarily used to analyze the effect of the converging chevron patterns on vehicular speeds; volume information was used to cross-check speed information. A presentation of the types of summaries and logical checks used for a general detector data quality evaluation is followed by a

[8] Sample form included in Appendix 2.

statistical analysis of speed data. Subsequently, a brief field data analysis provides additional information that is used in further assessing detector information reliability, before final test ramp conclusions are stated. General crash patterns, crash statistics and conclusions about chevron pattern effects on crashes conclude this part of the report.

Speeds: Detector Data

Findings about chevron pattern effects on vehicular speeds are based on loop detector data; the criteria used in selecting appropriate analysis detectors and analysis periods, general patterns observed at the selected detector locations, data consistency checks, and a summary table of findings are described in what follows. The reasonableness of daily speed and volume patterns and the consistency between the two is examined in the volume and speed pattern section. A separate detector information reliability discussion further examines data validity in light of the speed data analysis. Detector reliability conclusions are presented at the end of the speed analysis sections.

Speed data were collected from permanent pavement-embedded loop detectors that had been in place for many years, and were part of the freeway monitoring system. The detectors reported five-minute traffic volume and average speed; they did not provide individual vehicle speed or vehicle classification information. *At the time the investigative team was assigned to the evaluation, twenty-three months after chevron installation, historical five-minute information, archived by WisDOT was the only available traffic information for the evaluation site.*

Analysis goals

An extensive review of the archived data provided by WisDOT was performed in order to assess data quality. The goals of this review were to:

1. Document times during which information was available.
2. Document data reasonableness.
3. Cross-check detector information for consistency.
4. Use as much reliable information as possible.
5. Analyze speed variations and conditions under which these variations occurred.

Choice of analysis detectors and analysis periods

Experimental device effectiveness was evaluated based on before and after speed changes on the South-to-West ramp (test ramp), using a control site (the West-to-South ramp of the same interchange) to provide information about traffic and environmental influences on speeds during the evaluation periods.

Critical speed information was obtained from a detector location on the test ramp, mentioned in the WisDOT request to FHWA for authorization to install the device (see **Appendix 1**):

> *"...Given that the last set [of chevrons] needs to be completed prior to the detector loop, that loop will act as the reference point. At the anticipated speeds involved, the maximum distance between the end of the pattern and the loop detector should be 40 feet..."*

The detector location is indicated in **Figure 5** (see line identified as Detector **B**). The actual distance between the end of the chevrons, as installed, and detector B was estimated to be 30 feet. Information from this detector location was critical for the evaluation, since it provided the opportunity to compare vehicular speeds for vehicles exiting the experimental pattern in the after period, with speeds at the same location during the before period. Control ramp data was provided from a detector location downstream from the control ramp PC (see Detectors **C** and **D** identified on **Figure 5**).

Two detectors, placed side-by-side were present at each of the two detector locations described above, one in the median lane and one in the shoulder lane, for a total of four detectors. These detectors were identified as the "core" detectors, providing the most essential information for the evaluation.

Extensive tabulations and graphs were used to identify periods during which all core detectors provided good quality information. One problem that was identified early-on, was that both test ramp detectors stopped providing data around the chevron installation period (May of 1999), and did not provide any data for the following year (until May of 2000). Short-term communications outages occurred during other times, thus there were periods that some core detectors were not functional. It was desirable to identify the longest possible continuous periods during which all core detectors provided information; furthermore, before and after periods including the same days of the year were desirable, in order to avoid seasonal speed biases. Two such periods were identified: December 1998 through March 1999 and December 2000 through March of 2001.

Although information was available from the test ramp shoulder lane detector, this information was not reasonable, and was dropped from further consideration. Thus, only the median lane test ramp detector (Detector **B**) provided useable information for that ramp.

Once the before and after periods were identified, as described above, an effort was made to locate other detectors in the vicinity of the study ramps that provided good quality information (infrequent outages during the analysis periods, and reasonable speed information). A detector located in the median lane 1960 feet upstream from the beginning of the chevron pattern was the only additional detector identified through this process. This detector was used to identify speed changes in that lane, due to traffic and environmental factors, in the period following chevron installation (speeds would not be influenced by chevron presence, since drivers could not see the chevrons from this location).

Thus, the analysis proceeded with information from four detectors:

- Detector **A**: Median lane, 1,960 feet before the chevrons.
- Detector **B**: Median lane, 30 feet after the end of the chevrons (80 feet after the ramp point of curvature).
- Detector **C**: Control ramp median lane, 200 feet after the point of curvature.
- Detector **D**: Control ramp shoulder lane, 200 feet after the point of curvature (next to detector **C**).

Data quality control

Test ramp volumes did not exceed 1800 vehicles per hour per lane (vphpl) during peak hours, with speeds not dropping below 43 mph during these hours. It was reasonable to expect that exceptionally low speeds would be associated with unusual events, such as maintenance operations, harsh weather conditions and incidents. Thus, it was decided to include only speeds exceeding a threshold of 25 mph in order exclude unusual situations from the analysis. Similarly, speeds higher than 85 mph were not included in the analysis. Hourly profiles for each day were used to observe unusual speed (see **Appendices 4** and **5**) and volume patterns (**Appendices 6** and **7**) , and missing hours and days. When a detector reported the same information continuously, data for that day were excluded from the analysis. Very few data points were excluded through this process.

Volume and speed data presentation

The hourly speed profile graphs for each analysis day, indicated characteristically different hourly speed distributions for weekdays and weekends: Weekday speeds dropped during the morning and afternoon peak traffic hours, a pattern absent during weekends, when traffic volumes remained below weekday peak hour volumes, throughout the day. Graphs were developed to provide a visual presentation of the average hourly distributions of speeds and traffic volumes, and their 95 percent confidence intervals, separately for weekdays and weekends, for each detector in the before and the after period (see **Appendices 8 and 10**). Cumulative speed distributions are presented in **Appendix 9**. Similar information was generated in tabular form (see **Appendix 11**), that provided the mean value, standard error of the mean and number of observations for each hour represented in each speed and volume figure.

Volume and speed patterns

This section describes volume and speed data general characteristics and provides a first review of data reasonableness, a topic that will be revisited in more detail in the discussion following the speed data analysis presentation, when more specific information is available for data evaluation. The emphasis in this subsection is on speed information; volume information is presented in order to provide a background against which speed reasonableness can be cross-checked.

Weekday Volumes: peaked between 7:00 am and 8:00 am, and between 4:00 pm and 6:00 pm. Volumes reached 1700 vphpl to 1850 vphpl during these periods. One notable exception were much lower volumes recorded at detector **C**. The detector is located 150 feet from where northbound and southbound I-894 median lane traffic separate in a fork (detector **C** records the southbound traffic). The observed pattern was present in both analysis periods.

Weekend volumes: were at their lowest levels from midnight to 5:00 am, rose steadily until 12:00 pm and remained relatively constant until 5:00 pm. Peak traffic volumes varied by location: 1200 vphpl for detectors **A** and **B**, 750 vphpl for detector **C** and 1600 vphpl for detector **D**. Volumes dropped continuously after this time. These patterns were also present in both analysis periods.

Weekday speeds: dropped during peak volume hours, but the impact congestion had on speed varied between locations. The highest speeds were recorded between 5:00 am and 6:00 am, but they were not much higher than speeds during other non-congested hours. These patterns were present both in the before and the after period.

Speed patterns for detector **B** were rather unique, in that they exhibited a very small increase after the morning peak and remained almost constant with a very small fluctuation during the afternoon peak. Speeds started rising only after 7:00 pm. These speed patterns were similar in the before and the after periods.

Weekend speeds: were higher than weekday speeds. They were typically at their highest levels some time between 7:00 am and 9:00 am, and did not drop appreciably, until 1:00 pm or later. This pattern was present in both the before and the after periods. Excluding the hours corresponding to weekday peak hours, weekend speeds were typically very close to weekday speeds during the same hours. The notable exception is detector **B** which exhibited speed differences of up to 5 mph during mid-day hours.

Summary: Volume and speed patterns appeared intuitively correct and consistent. Volumes and speeds were within reasonable ranges both in the before and the after periods. A statistical examination of speed data is undertaken in the next section.

Speed data-general statistics

It should be noted here, that each analyzed datum represented one five-minute period, thus there were always twelve data points in each hour, regardless of how many vehicles were recorded during this hour. Thus, five-minute speed averages were weighted by the traffic volumes observed during the corresponding five-minute periods, in order to derive more representative average speeds.

It was desired to investigate whether device effectiveness was different during different hours of the day, depending on congestion level. Because hourly speed and volume patterns were different for weekdays and weekends, as shown in **Appendices 8, 10 and 11**, separate speed statistics for weekdays and weekends are presented in **table 7,** in addition to the overall speed statistics. Reasons for this were:

- Separate summaries for weekdays and weekends precluded lower speeds during weekday peak hours to be averaged with higher speeds during the same hours on weekends.
- If, hypothetically, device effectiveness was higher during weekends (due to, say, lower volumes), this effect would be diluted in a presentation of total statistics, since weekdays dominate statistics with their higher traffic volumes.

- If, for any reason (e.g., special events) either weekday or weekend traffic volumes changed in the after period, the corresponding effect on speeds would be mistakenly assumed to be due to the evaluated device.

Table 7 statistics indicate that: Device effectiveness was very similar on weekdays and weekends; speeds were higher during weekends; also, the weekday-weekend speed differential remained at the same levels in the after period.

Summary: A dramatic change in speeds was observed for detector **B**, where average speeds dropped by 15 mph, and 85th percentile speeds dropped by 17 mph during the after period. Detectors **A** and **C** also experienced average speed reductions, but of much smaller magnitude: 3 and 1 mph respectively. Detector **D** had an average speed increase of 2 mph. Average and 85th percentile weekend speeds were universally higher than weekday speeds. Speed changes between the ‘before’ and the ‘after’ period were such that speeds at all hours of the day shifted in the same direction and by the same amount (parallel translation upward for detector **D**, downward for detectors **A**, **B** and **C**) as evidenced in **Appendices 8, and 11**.

Speed data-analysis of variance

Detector speeds were weighted by the corresponding five-minute volumes and analyzed using Analysis of Variance (ANOVA) for the effects of analysis period (before or after chevron installation), weekday versus weekend, day of the week, analysis month, and hour of the day. Analysis period and weekday versus weekend explained 67.3% of the speed variation for detector **B**. The same variables explained 10.0% of the speed variation for detector **A**, 7.5% for detector **C**, and 17.9% for detector **D**. The remaining variables were not found to explain the observed speed variation to any significant extent and were dropped from further consideration.

Given the large number of observations included in the analysis, standard errors of the means and 95 percent confidence intervals for each calculated mean were very narrow (see **Table 7**), and even small differences in speeds were statistically significant. Narrow confidence intervals necessitated the use of decimal miles per hour in the following discussion, however such small magnitudes have no practical importance from a practitioner’s point of view.

The following paragraphs describe findings for detectors **A**, **B**, **C** and **D**.

Table 7. Speed Statistics Before and After Chevron Installation (mph).

All Days of the Week

Detector	Before				After				Mean After - Before	85th Ptile After - Before	95th Ptile After - Before
	Mean	85th Ptile	95th Ptile	S.E. of Mean	Mean	85th Ptile	95th Ptile	S.E. of Mean			
A	60	63	64	.0009	57	60	61	.0008	-3	-3	-3
B	64	70	73	.0013	49	53	56	.0010	-15	-17	-17
C	50	53	54	.0009	49	51	53	.0009	-1	-2	-2
D	46	48	49	.0005	48	51	52	.0007	+2	+3	+3

Weekdays

Detector	Before				After				Mean After - Before	85th Ptile After - Before	95th Ptile After - Before
	Mean	85th Ptile	95th Ptile	S.E. of Mean	Mean	85th Ptile	95th Ptile	S.E. of Mean			
A	60	62	63	.0011	57	60	61	.0009	-3	-2	-2
B	63	69	72	.0014	48	52	55	.0010	-15	-17	-17
C	50	53	54	.0010	49	51	52	.0010	-1	-2	-2
D	45	47	48	.0005	48	51	52	.0007	+3	+4	+4

Weekends

Detector	Before				After				Mean After - Before	85th Ptile After - Before	95th Ptile After - Before
	Mean	85th Ptile	95th Ptile	S.E. of Mean	Mean	85th Ptile	95th Ptile	S.E. of Mean			
A	61	63	64	.0012	59	61	62	.0017	-2	-2	-2
B	66	71	75	.0025	52	56	58	.0021	-14	-15	-17
C	51	54	55	.0017	49	52	53	.0022	-2	-2	-2
D	47	49	49	.0009	49	52	53	.0013	+2	+3	+4

S.E. of Mean = Standard Error of the Mean; Ptile = Percentile.
All data weighted by 5-minute Volumes.
S.E. of the Mean for unweighted observations: All Days of the Week, Weekdays, Weekends.
Speeds rounded to closest integer.

Figure 7. Detector **B** Speed Distribution December 2000.
(Complete series in **Appendices 4** and **5**).

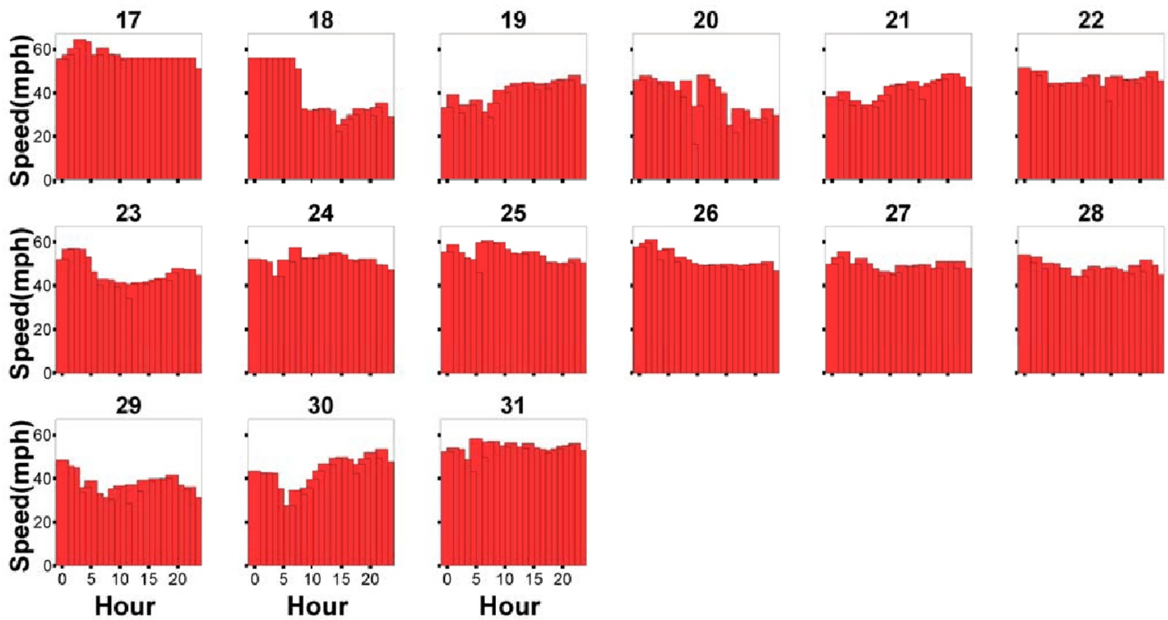


Figure 8. Detector **B** Volume Distribution December 2000.
(Complete series in **Appendices 6** and **7**).

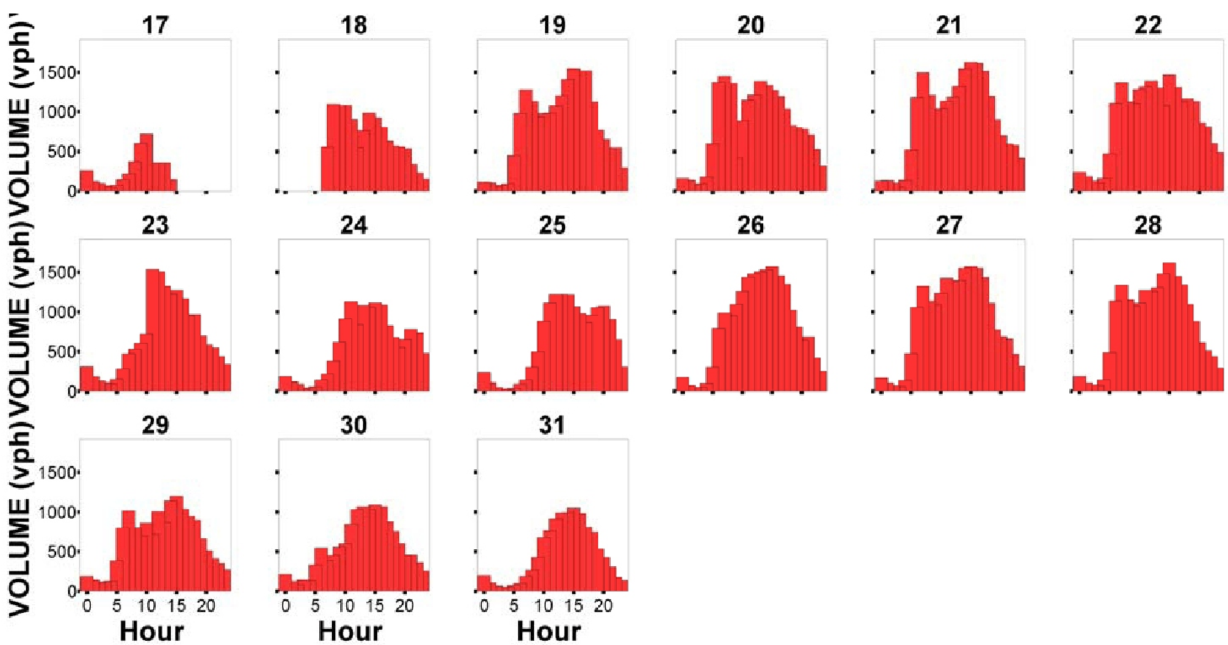


Figure 9. Detector B 95% CI for Mean Hourly Weekday and Weekend Speeds

(Complete series in Appendix 8)

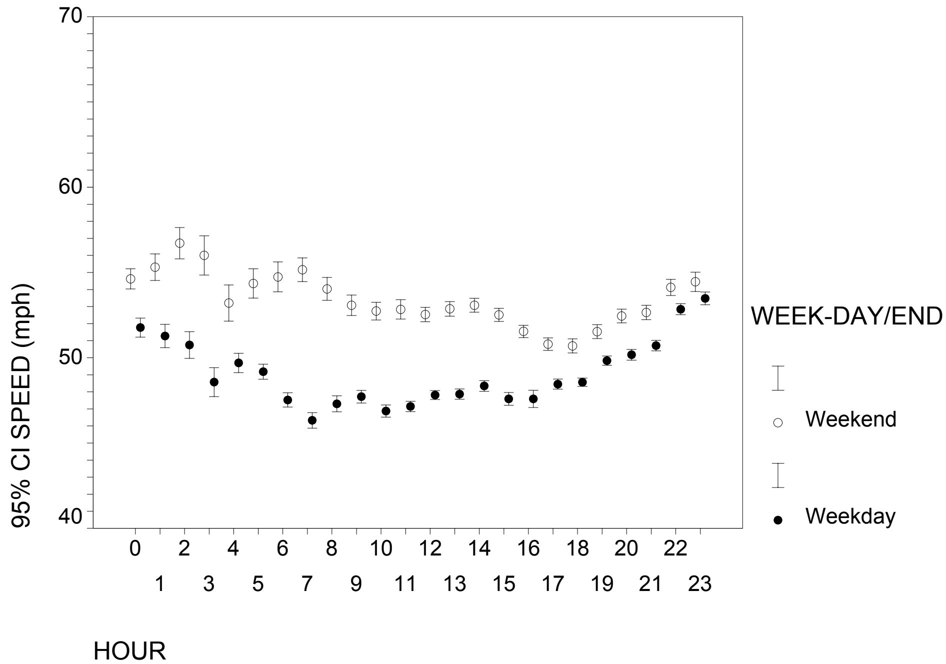


Figure 10. Detector B 95% CI for Mean Hourly Weekday and Weekend Volumes

(Complete Series in Appendix 9)

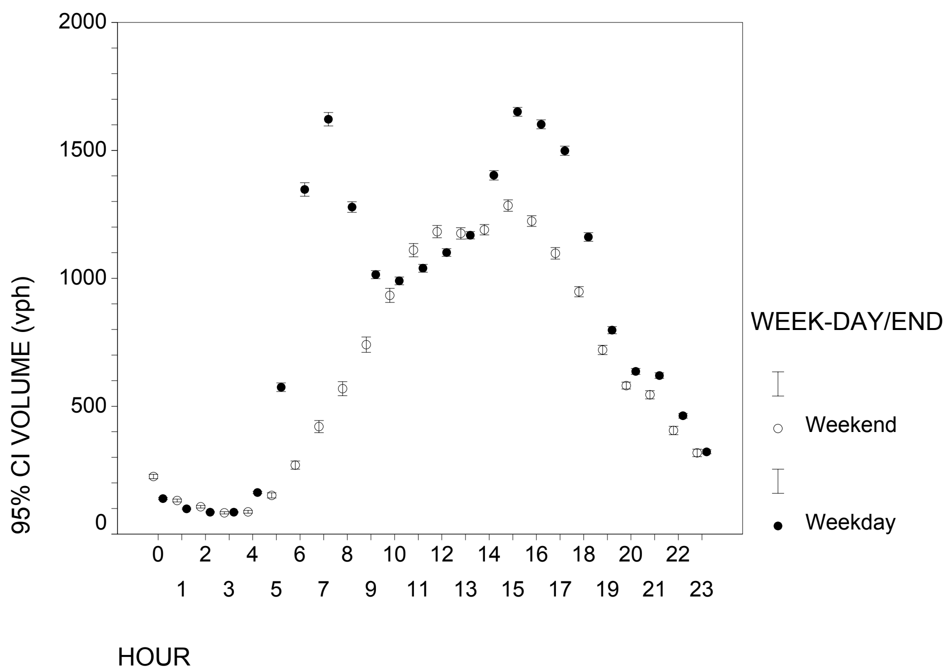


Table 8. Detector B Hourly Statistics for the After Period. (Complete series in Appendix 11)

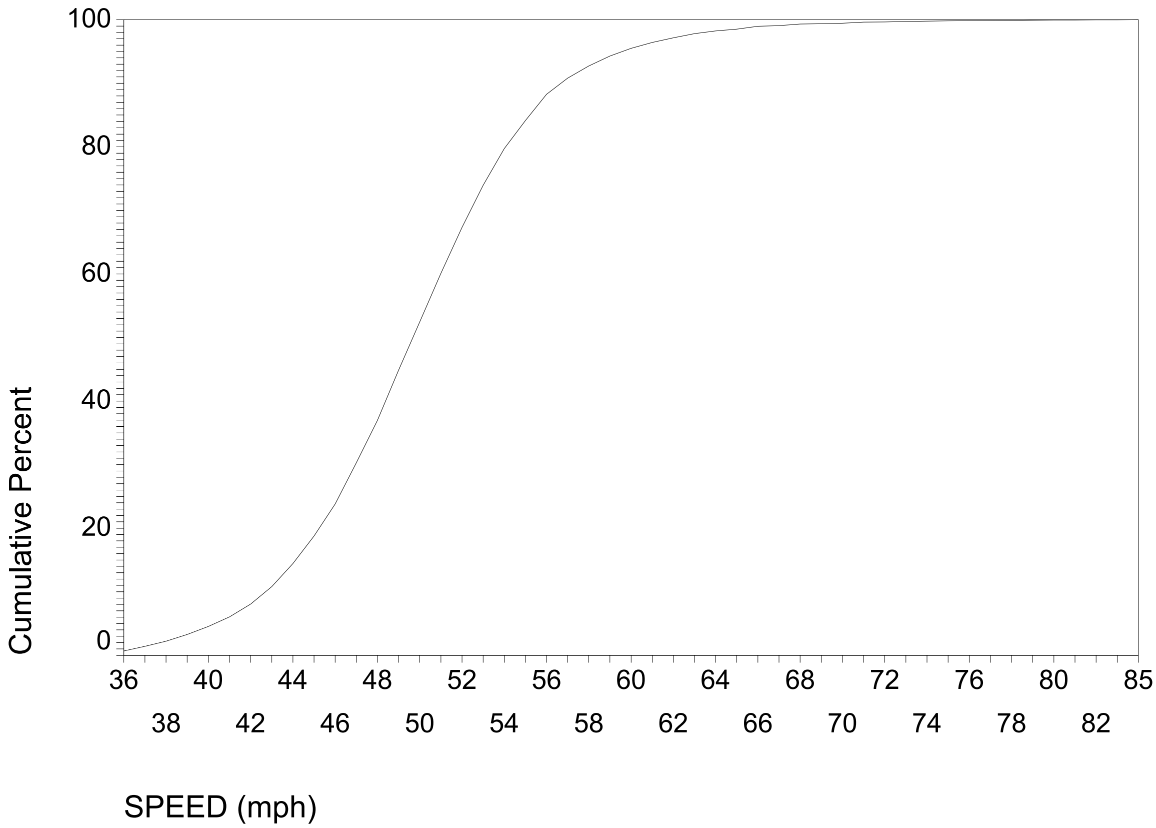
DETECTOR ID Detector B

			WEEK-DAY/END					
			Weekday			Weekend		
			Mean	Standard Error of Mean	Valid N	Mean	Standard Error of Mean	Valid N
HOUR	0	SPEED (mph)	52	0	N=845	54	0	N=287
		VOLUME (vph)	138	2	N=845	222	4	N=287
	1	SPEED (mph)	52	0	N=807	55	0	N=285
		VOLUME (vph)	100	2	N=807	132	3	N=285
	2	SPEED (mph)	52	0	N=738	56	0	N=281
		VOLUME (vph)	88	1	N=738	109	3	N=281
	3	SPEED (mph)	51	0	N=693	56	1	N=249
		VOLUME (vph)	86	1	N=693	86	2	N=249
	4	SPEED (mph)	50	0	N=793	54	1	N=239
		VOLUME (vph)	159	2	N=793	88	3	N=239
	5	SPEED (mph)	49	0	N=822	54	0	N=261
		VOLUME (vph)	571	8	N=822	152	5	N=261
	6	SPEED (mph)	48	0	N=824	55	0	N=260
		VOLUME (vph)	1344	12	N=824	277	8	N=260
	7	SPEED (mph)	47	0	N=848	55	0	N=269
		VOLUME (vph)	1632	12	N=848	423	12	N=269
	8	SPEED (mph)	48	0	N=851	54	0	N=250
		VOLUME (vph)	1279	9	N=851	559	14	N=250
	9	SPEED (mph)	48	0	N=882	53	0	N=257
		VOLUME (vph)	1007	7	N=882	725	16	N=257
	...[a]	SPEED (mph)	...	...	...	...	...	...
		VOLUME (vph)	...	...	...	...	...	...
Table Total		SPEED (mph)	49	0	N=20346	53	0	N=6413
		VOLUME (vph)	889	4	N=20346	644	6	N=6413

a. Hours 10 through 23 not listed here, but included in listed totals--see Appendix 11 for complete listing.

Figure 11. Detector B Cumulative Speed Distribution After Period

(Complete series in Appendix 9)



Detector A Test Ramp 1960 feet before the chevron start (2550 feet before point of curvature).

Analysis period (Before-After chevron installation) and weekday-weekend explain 10.0% of the variation in speed (R^2 = 0.100-**table 9**). A summary of mean speeds and their 95 percent confidence intervals is presented in **table 10**. Confidence intervals do not overlap, indicating statistically significant speed differences between all four means. 'After' speeds are 2.4 mph lower than 'Before' speeds. The 95% confidence interval for the mean difference is between 2.3 and 2.5 mph (**table 11**). Weekday speeds were lower by 1.3 mph than weekend speeds (confidence interval between 1.26 and 1.42 mph), both in the before and the after period.

Table 9. Detector **A** Speed Analysis of Variance by Before/After and Weekday/Weekend.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6309063	2	3154531	3072.478	.000
Intercept	7738703774	1	7738703774	7537408	.000
BEF_AFT	5202973	1	5202973	5067	.000
WEEK_END	997818	1	997818	971	.000
Error	56557136	55086	1026		
Total	12432081254	55089			
Corrected Total	62866200	55088			

R Squared = .100 (Adjusted R Squared = .100)
Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 10. Detector **A** Speed 95 % Confidence Intervals for Means.

Before/After	WEEK-DAY/END	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Before	Weekend	60.957	.042	60.875	61.039
	Weekday	59.615	.025	59.565	59.665
After	Weekend	58.550	.043	58.466	58.633
	Weekday	57.208	.025	57.158	57.257

Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 11. Detector **A** Pairwise Comparisons Before-After and Weekday-Weekend.

(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Before	After	2.407*	.034	.000	2.341	2.473
Weekend	Weekday	1.342*	.043	.000	1.258	1.426

Based on estimated marginal means. Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME
* The mean difference is significant at the .05 level.
a Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Detector B Test Ramp 670 feet after the chevron start (80 feet after point of curvature).

Analysis period (Before-After chevron installation) and weekday-weekend explain 67.3% of the variation in speed (R^2 = 0.673-**table 12**). Mean speeds and their 95 percent confidence intervals are presented in **table 13**. Confidence intervals do not overlap, indicating statistically significant speed differences between all four means. 'After' speeds are 14.9 mph lower than 'Before' speeds. The 95% confidence interval for the difference of means is between 14.8 and 15.0 mph (**table 14**). Weekday speeds were 3.5 mph lower than weekend speeds (confidence interval 3.4 to 3.6 mph); this was true for both the before and the after period.

Table 12. Detector **B** Speed Analysis of Variance by Before/After and Weekday/Weekend.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	219603890	2	109801945	56061	.000
Intercept	7810557432	1	7810557432	3987807	.000
BEF_AFT	210643695	1	210643695	107547	.000
WEEK_END	7283828	1	7283828	3718	.000
Error	106683509	54469	1958		
Total	12427410423	54472			
Corrected Total	326287400	54471			

R Squared = .673 (Adjusted R Squared = .673)
Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 13. Detector **B** Speed 95 % Confidence Intervals for Means.

Before/After	WEEK-DAY/END	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Before	Weekend	66.685	.056	66.576	66.795
	Weekday	63.176	.034	63.110	63.243
After	Weekend	51.757	.057	51.645	51.869
	Weekday	48.248	.034	48.181	48.315

Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 14. Detector **B** Pairwise Comparisons Before-After and Weekday-Weekend.

(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Before	After	14.928*	.046	.000	14.839	15.018
Weekday	Weekend	3.509*	.058	.000	3.396	3.622

Based on estimated marginal means. Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

* The mean difference is significant at the .05 level.

a Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Detector C Control Ramp 200 feet after the point of curvature.

Analysis period (Before-After chevron installation) and weekday-weekend explain 7.5% of the variation in speed (R^2 = 0.075-**table 15**). Mean speeds and their 95 percent confidence intervals are presented in **table 16**. Confidence intervals do not overlap, indicating statistically significant speed differences between all four means. 'After' speeds are 1.7 mph lower than 'Before' speeds. The 95% confidence interval for the difference of means is between 1.6 and 1.7 mph (**table 17**). Weekday speeds were 0.9 mph lower than weekend speeds (confidence interval 0.9 to 1.0 mph); this was true for both the before and the after period.

Table 15. Detector **C** Speed Analysis of Variance by Before/After and Weekday/Weekend.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1872847	2	936423	2029	.000
Intercept	3186408562	1	3186408562	6905893	.000
BEF_AFT	1541743	1	1541743	3341	.000
WEEK_END	288938	1	288938	626	.000
Error	23168953	50214	461		
Total	5357871701	50217			
Corrected Total	25041801	50216			

R Squared = .075 (Adjusted R Squared = .075)
Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 16. Detector **C** Speed 95 % Confidence Intervals for Means.

Before/After	WEEK-DAY/END	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Before	Weekend	51.147	.037	51.075	51.220
	Weekday	50.198	.022	50.155	50.241
After	Weekend	49.462	.038	49.389	49.536
	Weekday	48.513	.021	48.471	48.555

Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 17. Detector **C** Pairwise Comparisons Before-After and Weekday-Weekend.

(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Before	After	1.685*	0.029	.000	1.628	1.742
Weekend	Weekday	0.949*	0.038	.000	0.875	1.024

Based on estimated marginal means. Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME
* The mean difference is significant at the .05 level.
a Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Detector **D** Control Ramp 200 feet after the point of curvature.

Analysis period (Before-After chevron installation) and weekday-weekend explain 17.9% of the variation in speed (R^2 = 0.179-**table 18**). Mean speeds and their 95 percent confidence intervals are presented in **table 19**. Confidence intervals do not overlap, indicating statistically significant speed differences between all four means. 'After' speeds are 2.6 mph ***higher*** than 'Before' speeds. The 95% confidence interval for the difference of means is between -2.6 and -2.5 mph (**table 20**). Weekday speeds were 1.4 mph lower than weekend speeds (confidence interval 1.4 to 1.5 mph); this was true for both the before and the after period.

Table 18. Detector **D** Speed Analysis of Variance by Before/After and Weekday/Weekend.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9301423	2	4650711	5913	.000
Intercept	6890800580	1	6890800580	8761373	.000
BEF_AFT	7891223	1	7891223	10033	.000
WEEK_END	1620606	1	1620606	2060	.000
Error	42583346	54143	786		
Total	10331689639	54146			
Corrected Total	51884769	54145			

R Squared = .179 (Adjusted R Squared = .179)
Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 19. Detector **D** Speed 95 % Confidence Intervals for Means.

Before/After	WEEK-DAY/END	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Before	Weekend	46.634	.031	46.573	46.694
	Weekday	45.185	.020	45.147	45.224
After	Weekend	49.227	.032	49.165	49.288
	Weekday	47.778	.019	47.740	47.817

Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME

Table 20. Detector **D** Pairwise Comparisons Before-After and Weekday-Weekend.

(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Before	After	-2.593*	.026	.000	-2.644	-2.542
Weekend	Weekday	1.448*	0.032	0.000	1.386	1.511

Weighted Least Squares Regression - Weighted by 5-MINUTE VOLUME
* The mean difference is significant at the .05 level.
a Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Summary: A dramatic change in speeds was observed for detector **B**, where average speeds dropped by almost 15 mph. Detectors **A** and **C** also experienced speed reductions, but of much smaller magnitude: 2.4 and 1.6 mph respectively. Detector **D** had a speed increase of 2.6 mph. Average weekend speeds were universally higher than weekday speeds. The highest speed differential (3.5 mph) was observed for detector **B**; the range was 0.9 to 1.4 mph for the other three detectors. All observed speed changes were statistically significant at the 0.001 level. Speed changes between the 'before' and the 'after' period were such that speeds at all hours of the day shifted in the same direction and by the same amount (parallel translation upward for detector **D**, downward for detectors **A**, **B** and **C**). One manifestation of this trend is that speed differentials between weekdays and weekends remained unchanged.

Speeds: Field Data

Loop detector data analysis pointed to an inconsistency between speeds at detector **A** and detector **B** (during the before period vehicles appeared to accelerate from 60 mph at detector **A** to 64 mph at detector **B**). Data was collected in the field, at a time following the after period, in an attempt to resolve this inconsistency: laser gun data, known to be accurate, would be compared to loop detector data. This effort was not included in the original data analysis plan. The data was collected on Wednesday, October 3, 2001, between 10:37 am and 11:42 am, seven months past the end of the "after" period, in the vicinity of detectors **A** and **B**. Given the extremely stable speeds for each hour of the day during the analysis periods, the assumption was made that speeds would have remained stable in the months following the after period. Sample sizes were adequate for truck observations; also when all observations were pooled; analyses based on the smaller data set collected for passenger cars are presented only for the sake of discussion completeness.

Analysis goals

The collected information was analyzed in order to assess whether loop detector **A** and **B** speed information in the after period was realistic. In addition, it was desired to measure speed reduction between a location upstream of the chevron markings, the beginning and the end of the chevron markings, making use of the laser gun capability to accurately measure distances between the gun and the sampled vehicles.

Data sampling

Distances measured between the laser gun and sampled vehicles were adjusted using the known coordinates of **points A**, **B** and **C** in **figure 6** to reflect distances from the end of the chevrons. **Figure 12** summarizes the distances at which observations were recorded. Separate statistics are presented for automobiles and trucks. Only free-flowing vehicles were selected, whenever a clear line of sight was available between the laser gun and a free-flowing vehicle. Thus the proportion of auto and truck observations does not represent the vehicle mix at the study location during the data collection period; average speeds collected in the field were very likely higher that average speeds (the statistic captured by pavement-embedded detectors). Unfortunately, due to time limitations, ***automobile samples did not have enough observations for valid statistical conclusions***.

Measurement distance
The average measurement distance (weighted average for truck and auto samples) before the end of the chevron patterns, recorded from location **A** was 1,569 feet (929 feet before the start of the chevron patterns). Although the intent of the field data collection effort from locations **B** and **C** was to capture speeds at the beginning and the end of the chevron patterns, respectively, when results were analyzed, it was realized that speeds recorded from location **B** were captured approximately 245 feet before the end of the chevrons instead of 640 feet (see label 'Begin chevrons,' **figure 12**). This location coincided with the curve PC. Speeds recorded from location **C** were captured 45 feet before the end of the chevrons instead of 0 feet (see label 'End chevrons').

Speed data-general statistics
Summary speed statistics are presented in **figure 13** separately for autos and trucks. The inadequate sample sizes for autos (at least 30 observations were desirable at each location) did not allow statistically defensible conclusions for this category, however a speed reduction of 8 mph, on average, was apparent between the first and the second data collection point. A speed reduction of 1 mph was evident between the second and third point. Truck speed reduction between the first and second point was 9 mph, on average, and an additional reduction by 4 mph was present observed between the second and third data collection points. Sample sizes for truck speeds are adequate for valid conclusions.

Speed at a given distance-general statistics
Figure 14 presents **all** collected speed data at the three data collection points (pooled data). Vertical reference lines are provided to indicate the ***85^{th} percentile speeds***:

- 67 mph at 1,569 feet,
- 60 mph at 245 feet, and
- 56 mph at 45 feet before the end of the chevrons, respectively.

Average speeds were:

- 64 mph at 1,569 feet
- 55 mph at 245 feet, and
- 52 mph at 45 feet before the end of the chevrons, respectively.

Speed-distance regression equations
Regression lines superimposed on the scatter plots in **figures 15** and **16** present the speed-distance relationship for autos and trucks respectively. *(The reader is reminded that the samples for autos are too small (n < 30) for statistical inferences–auto speeds are only included for the sake of discussion completeness.)* Simple linear regression lines were fitted to the auto and the truck data sets:

$$Speed_{\mathbf{auto}} = 55.658 + 0.0063 \text{ x (Distance to End of Chevrons in feet)}$$
[calibrated for data shown in **figure 15**]

$$Speed_{\mathbf{truck}} = 50.548 + 0.0077 \text{ x (Distance to End of Chevrons in feet)}$$
[calibrated for data shown in **figure 16**]

The regression lines using distance from the end of the chevrons as an independent variable, explain 39% of the variation in speeds for autos and 59% of the variation in speeds for trucks, respectively.

The regression equations above provide an average speed reduction rate, calibrated on all distances over which speed data were collected. This average speed reduction rate is, for example, 0.0077 mph per foot distance to the end of the chevron pattern for trucks.

Speed change based on field data

Vehicle deceleration, however, is not uniform as vehicles approach the curve. Information in **figures 12** and **13** indicates that **trucks reduced speeds by 9 mph between 1,594 feet and 248 feet** before the end of the chevrons (**1 mph per 150 feet of travel**) and **4 mph between 248 feet and 53 feet** before the end of the chevrons **(1 mph per 49 feet)**. Thus speed reduction rate over the chevrons was three times the rate approaching the chevrons. If this steeper speed reduction rate was extrapolated over the remaining 53 feet to the end of the chevrons, plus the distance of 30 feet between the end of the chevrons and detector **B** (a distance of 83 feet), truck speeds would have dropped by another 1.7 mph, thus truck average speed over detector **B** would have been 50 - 1.7 = 48.3 mph. Overall truck speed reduction was 14.7 mph (from 63 mph to 48.3 mph). Similar calculations for autos indicate a ***tentative*** (due to inadequate sample sizes) speed reduction of 9.4 mph.

Speed change using detector data

Speed statistics were extracted from detector data, for Wednesdays between 10:30 am and 11:40 am (in order to match field data collection time as closely as possible), in the after period, for comparison purposes. Detector data represented 5-minute average speeds for all vehicles that crossed a detector. Thus, detector speeds were likely to be lower than laser-gun-measured speeds that were based on a sample of free-flowing vehicles.

Recorded speeds at detector **A**:

- mean speed was 57.4 mph,
- 85^{th} percentile speed was 60.0 mph, and the
- 95% confidence interval for the mean was between 57.0 and 57.8 mph.

Recorded speeds at detector **B**:

- mean speed was 47 mph,
- 85^{th} percentile was 51 mph, and the
- 95% confidence interval for the mean was between 46.5 and 48.1 mph.

Thus, average speed reduction between the two detectors was 10.4 mph (with a 95% confidence interval between 8.9 and 11.3 mph) during the hours that field data was collected. (Detector data was collected more than seven months prior to the field data collection effort. The assumption was made that speeds would have remained stable during these months, given the very narrow 95% confidence intervals for hourly mean speeds shown for weekdays at detector **B**.) Detector and laser gun speed findings are summarized in **table 21** below.

Table 21. Speeds After Chevron Installation.

Pt #	Location	Distance from end of chevrons (feet)	Speed (mph)❖	
			Laser gun (semi-trucks)	Detector (all traffic)
1	Detector **A**	2600		57.4
2★	"Before Chevrons"	1594	63	
3★	"Begin Chevrons" (Curve PC)	248	54	
4★	"End Chevrons"	53	50	
5	Chevron pattern end	0		
6	Detector **B**	-30	48.3✪	47.0

❖ Laser gun data gathered 7 months after detector data.
★ Mentioned in **figures 12 through 16**
✪ Extrapolated, based on speeds at points #3 and #4.

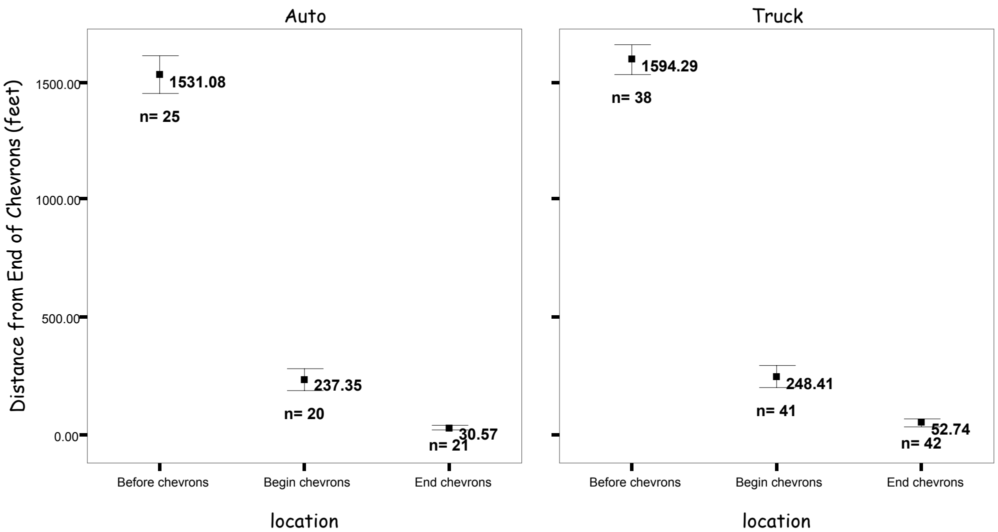
Detector Data Discussion

Given the dependence of the present effort on detector data, the topic of detector information reliability is revisited here, in light of the detector **and** field database analysis findings. Findings supporting reliance on the analyzed loop detector information, but also questions remaining unanswered are presented below.

Detector information reliability

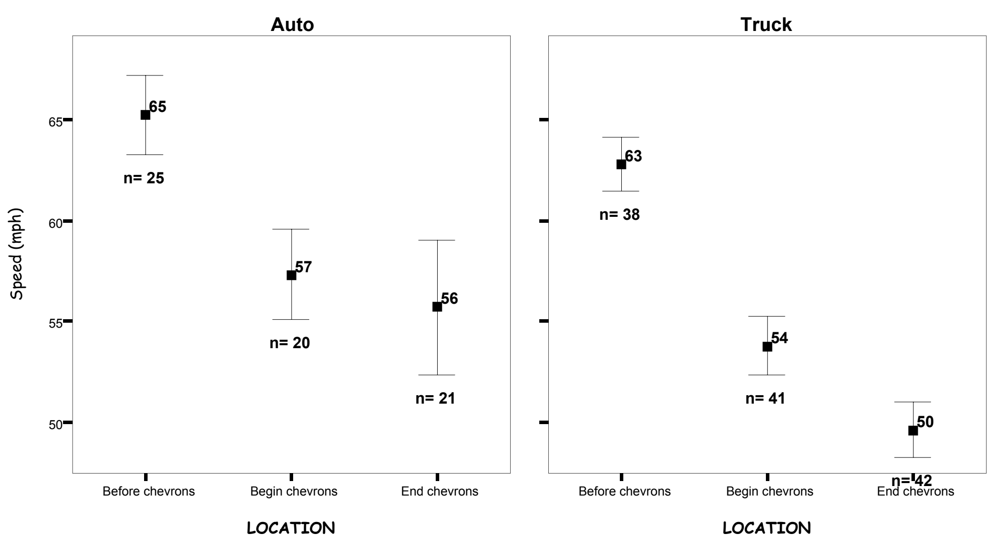
The 15 mph speed reduction observed at detector **B** in the after period is impressive; what is even more impressive, is that speeds were measured 19 months after chevron installation, when it may be expected that device effectiveness would have been reduced as drivers became used to its presence. However, it is very important to find assurances that loop detector data was accurate both in the before and the after periods. Ideally, detectors in the study area would have been under constant monitoring and data collection would have been supplemented with occasional field measurements, in order to verify detector accuracy. These options, were not available to the evaluation team due to the time that had already elapsed since device installation, when the team assumed the project. However, every effort was made to verify finding reasonableness by comparing all available sources of information. Three types of cross-checking were performed: i) loop detector-based traffic volume information consistency; ii) loop detector-based speed information consistency and agreement with volume information; and, iii) field-collected speed data cross-checking with loop detector information (applicable only in the after period).

Figure 12. Distances at Which Observations Were Recorded.



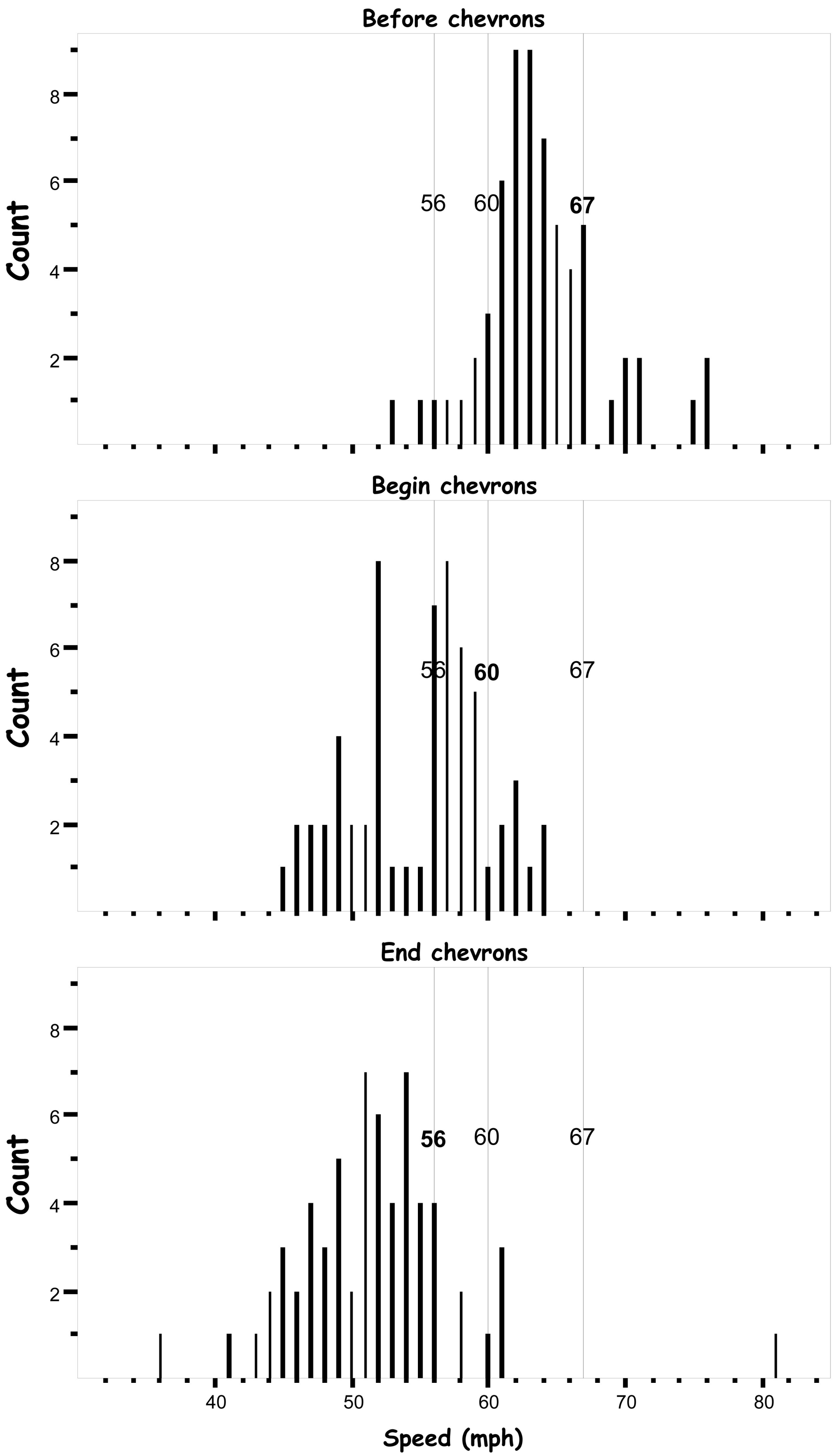
95% Confidence Interval for the Mean

Figure 13. 95% Confidence Intervals for Mean Speed.



95% Confidence Interval for the Mean

Figure 14. Speed Distributions at the three Data Collection Distances



Speed (mph)

N	Valid	63
	Missing	0
Mean		63.78
Median		63.00
Minimum		53
Maximum		76
Percentiles	85	67.00

Speed (mph)

N	Valid	61
	Missing	0
Mean		54.97
Median		56.00
Minimum		45
Maximum		64
Percentiles	85	59.70

Speed (mph)

N	Valid	63
	Missing	0
Mean		51.67
Median		52.00
Minimum		36
Maximum		81
Percentiles	85	56.00

Vertical reference lines indicate 85th percentile speeds

Figure 15. Speed-Distance Regression Line for Autos

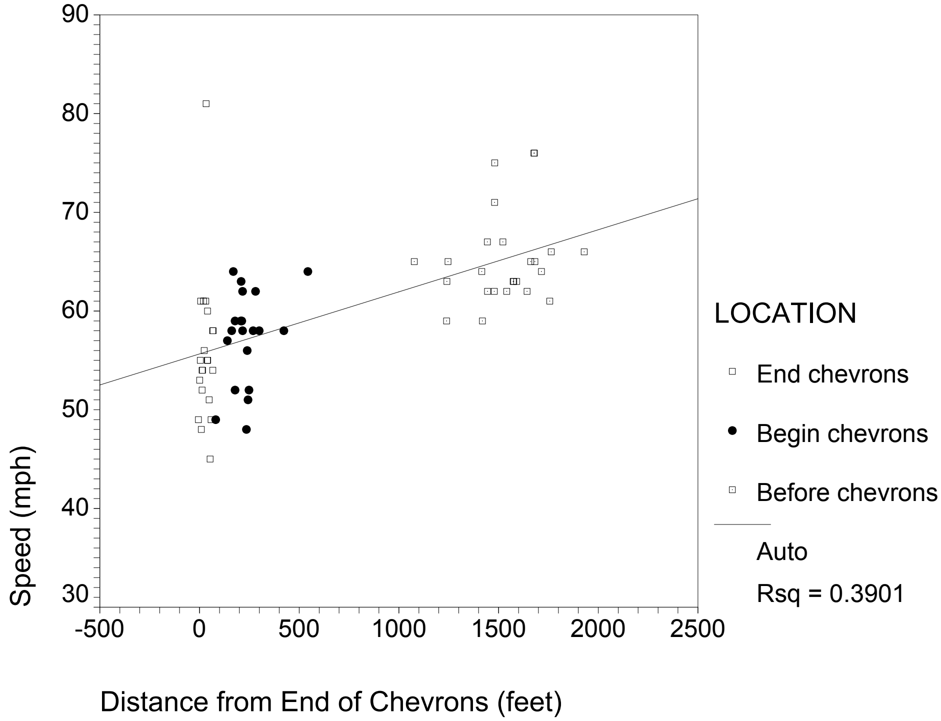
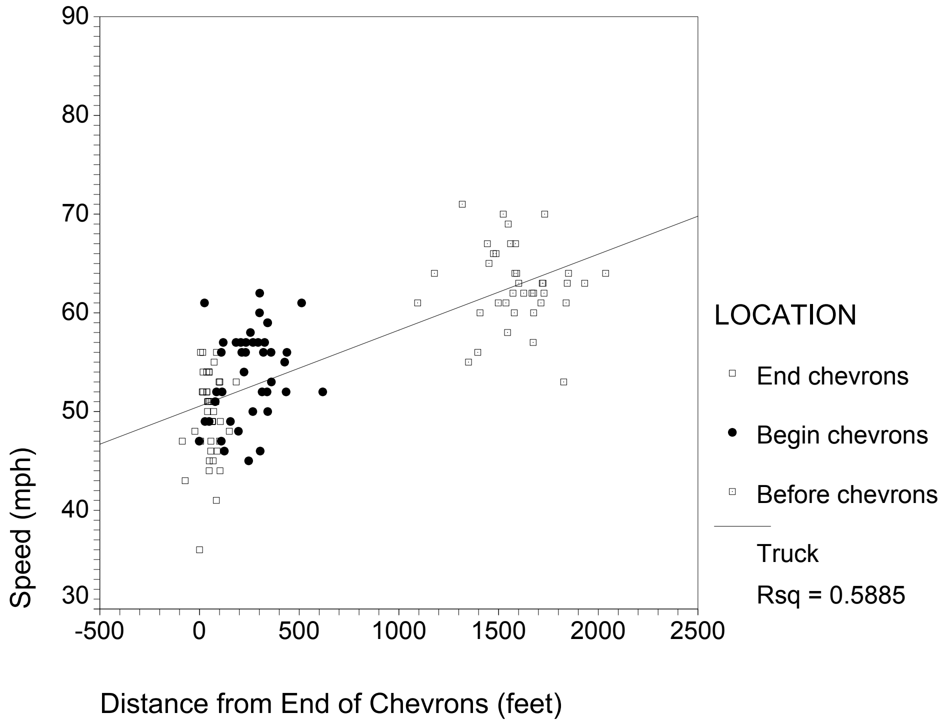


Figure 16. Speed-Distance Regression Line for Trucks



General observations
Day-to-day and hour-to-hour speed profiles presented in **Appendices 4 - 11** for the eight analysis months indicate consistently reasonable speeds for all analyzed detectors. Very few detector outages, and few instances that detectors reported a constant speed for many contiguous hours were present. Speed profiles provided a degree of comfort about data quality and stability. In addition, weekday and weekend traffic volume and speed patterns, provided in Appendices A8-A11, were consistent across all analyzed detectors: lower speeds coincided with peak traffic volume periods during weekdays, and a pattern of higher weekend speeds as traffic volumes rose in the morning to reach the weekend peak volume hours was consistently present across detectors.

Individual detectors
Field-recorded speeds measured after chevron installation approximately 1,030 feet downstream from detector **A** on straight and level alignment, averaged 64 mph, a speed 6.6 mph higher than the speed of 57.4 mph typically present during the same hours[9] at detector **A**. Given the reliability of the field-collected data, it is very likely that detector **A** was simply under-reporting speeds. Assuming small speed changes during the 1,030 feet mentioned above, speeds were under-reported by detector **A** by approximately 6.6 mph in the after period (some allowance for higher laser-gun-reported speeds should be made, because they represented speeds of free-flowing traffic, not the average speeds reported by detector **A**).

A similar phenomenon was observed for detector **A** speeds during the before period, namely a speed increase of 4 mph between detector **A** (60 mph) and detector **B** (64 mph) located 2,630 feet further downstream. There was no readily available explanation for this behavior, given that traffic was heading into a horizontal curve (test ramp) right after traveling on a 3% grade, thus drivers had good reason (the curve) and opportunity (the grade) to slow down. It is very likely, once again, that detector **A** under-reported speeds.

A mean speed reduction of 3 mph was documented for detector **A** in the after period, which is consistent with the observed 9.7% traffic volume increase for the test ramp during the same period. (Volumes between 9:00 am and 3:00 pm were slightly higher and volumes between 4:00 pm and 6:00 pm were slightly lower.) Thus, it is very likely that detector **A** consistently under-reported speeds during the before and the after periods. If this, indeed, was the case, actual average speeds at detector **A** during the before period would have been approximately 66.6 mph and the calculated average detector **B** speeds of 64 mph would have indicated a deceleration of 2.6 mph for traffic entering the test ramp.

Detector **B** speed information reliability in the after period was established. A speed of 48.3 mph was estimated for free-flowing trucks, based on the collected laser gun data; loop detector speeds averaged 47 mph during the same period for all vehicles. A lower than free-flowing speed **was** expected--however, average speeds reported by detector **B** would be influenced by autos that constituted the majority of the traffic and drove faster than trucks. A truck speed reduction of 14.7 mph was estimated during the last 1,624 feet before detector **B,** based on field

[9] (but seven months earlier)

data and an assumption of a constant speed reduction rate over the chevrons. Based on similar data and assumptions, a ***tentative*** (due to lack of adequate sample sizes) speed reduction of 9.4 mph was estimated for autos.

Average speed for detector **D** (46 mph) was about 4 mph lower than detector **C** (50 mph) in the before period. It is reasonable to expect detector **D** to have somewhat lower speeds than detector **C**, given the higher traffic volumes in that lane. Detector **C** was 150 feet from the point where northbound traffic separated from southbound traffic; more gaps were created in the lane where the detector was located.

Average speeds at the two detectors differed by 1 mph in the after period (49 mph and 48 mph). Speeds increased by 2 mph for detector **D** and decreased by 1 mph for detector **C**. A decrease in peak traffic volumes by approximately 100 vph could be seen for detector **D** in the after period, which may have contributed to the observed increase in peak hour speeds (+ 3 mph for the afternoon peak). Detector **C** experienced a 100 vph increase in the after period from 2:00 pm to 6:00 pm which may explain the reduced peak hour speeds (- 2 mph for the afternoon peak). Peak period volume changes were important, because average speeds were calculated using volume-weighted data; peak hour speeds disproportionately affected overall daily average speeds. However, there was a parallel translation of the entire 24-hour speed pattern for both detectors (up for detector **D**, down for detector **C**), even during hours when volumes were similar in the before and the after period.

Detector Reliability Conclusions

Overall speed and volume data quality appears satisfactory: very few days or parts of days had to be excluded from the analysis due to problems with the data. Volume information is consistent with speed information, across detectors and across analysis periods.

Two noted inconsistencies were present between detectors **A** and **B** that did not reflect expected traffic behavior:

- i) A speed increase by 4 mph measured from detector **A** (60 mph) to detector **B** (64 mph) in the before period; and,
- ii) A speed increase from detector **A** (57.4 mph) located 2,600 feet from the end of the chevrons, to a point 1,569 feet from the end of the chevrons (64 mph[10]), and subsequent speed decrease measured 30 feet past the end of the chevrons, at detector **B** (47 mph), during Wednesdays between 10:30 am and 11:40 am in the after period.

Detector **A** was very likely under-reporting speeds in the after period, based on laser gun speed data. Detector **A**-reported speeds appear to be consistent in both study periods; if detector **A** under-reported speeds in both study periods, both above-described inconsistencies are explained.

Detector **B**-reported speeds were consistent with laser gun-measured speeds in the after period. The detector's accuracy during the before period could not be verified.

[10]Measured by laser gun during field data collection (pooled auto and truck data).

Conclusions About Speeds

Average daily traffic increased by 9.7% for the test ramp and 7.0% for the control ramp in the after period. These increases may have had a small impact on the measured speeds. The availability of more than 25,000 observations for each detector in each analysis period provided enough information to allow for very narrow 95 percent confidence intervals for mean speeds in the analysis of variance presented above. Mean speeds for the four analysis categories–before or after period by weekday or weekend–were statistically significantly different from each-other for any one of the analysis detectors. However, some of the detected differences were too small to be of practical importance from a traffic engineering point of view. For example, weekend and weekday speeds differ by 0.949 mph for detector **C**, by 1.342 mph for detector **A** and by 1.448 mph for detector **D**.

Speed changes for detectors **A**, **C** and **D**, between the before and after periods range between +2.59 mph (**D**) and -2.41 mph (**A**), and are consistent with changes in traffic volumes (lower speeds associated with higher volumes and vice versa).

Hourly volume patterns were very similar between detector **A** and detector **B** when comparing the before and the after periods. Higher hourly volumes between 9:00 am and 3:00 pm, and lower volumes from 4:00 pm to 6:00 pm in the after period were present at both detectors. There is sufficient evidence that detector **A** under-reported speeds during the after period and that detector **B** reported speeds accurately; whether or not detector **A** under-reported speeds, there is no reason not to accept the recorded **change** in speeds of -2.4 mph between the before and the after periods for this detector. Given the similarity of hourly volume pattern changes between detectors **A** and **B** in the before and the after periods, it would be reasonable to accept that speeds at detector **B** experienced a similar reduction of 2.4 mph, regardless of chevron presence. Thus, of the measured speed reduction of 14.9 mph at detector **B**, 12.5 mph could be attributed to the chevron installation, and 2.4 mph to increased traffic volume on the test ramp.

Crash Characteristics

The following paragraphs present a discussion of crash characteristics for the test and the control ramp, separately for the before and the after chevron installation periods. The before period was from May 15, 1997 to May 14, 1999, and the after period was from May 15, 1999 to June 15, 2001. Given the small numbers of crashes on the test ramp, the identified crash patterns are only presented in order to develop a general sense of conditions under which crashes occurred. Crash frequency tables for selected variables are presented in **Appendix 12** (**A12**); **tables 1 through 9** summarize test ramp statistics and **tables 10 through 18** summarize control ramp statistics. Tables for the same variables are presented in order to allow comparisons between the two ramps. The presentation of test ramp crash experience parallels that for the control ramp; the larger number of crashes on the control ramp makes percentages of particular crash sub-categories for that ramp more meaningful. A summary of percentages presented in these paragraphs can be found in **table 22**.

Test ramp crashes
A total of 22 crashes occurred on the test ramp during the before and the after periods.

Before period: Of the 14 crashes that occurred in the before period, five (36%) involved semi-trucks, and two involved utility trucks[11] **(A12 table 1**), thus heavier vehicles were involved in 50% of the crashes. Six of the seven crashes involving heavier vehicles occurred between 8 pm and 6 am. Three crashes (21%) occurred during the peak traffic hours (6:00 am to 9:00 am and 2:00 pm to 5:00 pm)-**A12 table 2**. Nine crashes (64%) occurred under non-daylight conditions-**A12 table 3**. Half of the crashes occurred on wet or icy pavement-**A12 table 4**. There were six single-vehicle crashes (42% of the total**)-A12 table 5**. All, occurred during off-peak hours. Five out of the six (83%) occurred on wet pavement-**A12 table 4**, and four (67%) occurred during non-daylight hours.

Of the five injury crashes, representing 36% of all crashes-**A12 table 6**, three were single-vehicle, of which two involved semi-trucks-**A12 table 1**. Each of the two multi-vehicle injury crashes involved a car and a utility truck. Thus, four of the five injury crashes (80%) involved a heavier vehicle.

Crashes were evenly spread between weekdays and weekends-no crashes were reported on a Friday-**A12 table 7**. Nine crashes involved objects -**A12 table 8**. The most commonly hit objects were concrete barriers, that were hit in four crashes.

After period: Of the eight crashes in the after period, one involved a semi truck. All crashes occurred during off peak hours-**A12 table 9**, seven (88%) occurred under non daylight conditions. Six crashes (75%) occurred when pavements were not dry: half occurred on wet, and half on snow- or ice-covered pavement. Of the five single-vehicle crashes (63% of the total), four occurred under dark-lighted conditions (80% of such crashes); three occurred on wet or icy pavement (60% of single vehicle crashes).

What is striking about the after period is the concentration of crashes on two days of the week: seven of the eight crashes occurred on either a Thursday or a Saturday**. *All three Thursday crashes occurred the same day when the pavement was either covered with snow or ice, under dark lighted conditions, within the span of two hours.*** However, the four Saturday crashes occurred on separate dates.

Five crashes involved objects. One of these crashes involved a deer, a very uncommon occurrence in this densely populated urban area. This crash occurred on Saturday, May 20, 2000, during the hour after midnight. Concrete barriers were hit twice.

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[11] These vehicles were reported either as "vehicle 1" or "vehicle 2" in the crash report. The "Law Enforcement Officer's Instruction Manual For Completing the Wisconsin Motor Vehicle Accident Report Form (MV4000)" does not specify whether driver 1 is the driver at fault in the reporting officer's opinion.

Control ramp crashes
There were a total of 132 crashes on the control ramp during the before and the after periods.

Before period: Of the 73 crashes in the before period, 6 involved a semi-truck, an equal number involved a straight truck, and 20 involved utility trucks, either as vehicle 1 or vehicle 2-**A12 table 10**. Thus 44% of all crashes involved a heavy vehicle. Twenty-seven crashes (38%) occurred during peak traffic hours (6:00 am to 9:00 am and 2:00 pm to 5:00 pm)-**A12 table 11**. Twenty-nine crashes (40%) occurred under non-daylight conditions-**A12 table 12**. A large percentage of crashes occurred on wet pavement (77%)-**A12 table 13**. Single-vehicle crashes constitute a large percentage (68%) of all crashes-**A12 table 14**. It is important to note that 41 of the 50 single vehicle crashes (82% of such crashes) occurred on wet pavements-**A12 table 13**. Almost equal numbers of single-vehicle crashes occurred during daylight (28 crashes) and nighttime or dawn (22 crashes). Out of a total of 54 crashes with objects, 49 (91%) were associated with a single-vehicle crash-**A12 table 17**. The most commonly struck objects in these crashes were median barriers (28 crashes), "other" fixed objects (5 crashes) and bridge rails (4 crashes).

Approximately one-quarter of all crashes (26%) resulted in an injury **A12 table 15**. Heavier vehicles were involved in 16% of injury crashes. Single-vehicle and two-vehicle crashes had approximately equal chances to result in an injury (24% and 30% respectively)-**A12 table 15**. Wednesdays and Thursdays had the lowest numbers of crashes, with five and six crashes respectively-**A12 table 16**. The other days of the week ranged between 10 and 15 crashes each. Monday had the highest number of crashes. Most multi-vehicle crashes occurred during weekdays. Single-vehicle crashes peaked Saturday-Monday.

After period: A total of 59 crashes occurred on the control ramp during the after period. Eighteen crashes (31%) involved heavier vehicles either as vehicle 1 or vehicle 2: seven involved a semi-truck, one involved a straight truck, and 10 involved utility trucks. Fourteen crashes (24%) occurred during peak traffic hours (6:00 am to 9:00 am and 2:00 pm to 5:00 pm)--**A12 table 18**. Twenty-nine crashes (49%) occurred under non-daylight conditions. Wet pavement crashes represented 71% of all crashes. Single-vehicle crashes with 35 occurrences, constituted a large percentage (59%) of all crashes. It is important to note that 30 of these crashes (86%) occurred on wet pavements. Almost equal numbers of these crashes occurred during daylight (18 crashes) and non-daylight hours (17 crashes). Out of a total of 45 crashes with fixed objects, 35 (78%) were associated with a single-vehicle crash. The most commonly struck objects in these crashes were median barriers (21 crashes), and guardrail ends (5 crashes).

Approximately 31% of all crashes resulted in injury. Heavier vehicles were involved in 17% of injury crashes. Single-vehicle and two-vehicle crashes had approximately equal chances to result in an injury (32% and 29% respectively). The one fatality that occurred on this ramp involved a single vehicle (semi-truck) and took place between 1:00 am and 2:00 am on Friday, February 25, 2000. Crash frequency was the lowest on Fridays with five crashes, and the highest on Saturdays with 12 crashes. Single- and multi-vehicle crashes were evenly distributed across days of the week.

Summary
Table 22 presents a summary of the above narrative. It should be emphasized that percentages are presented only in order to develop a sense of the nature of crashes occurring on the analysis ramps. These percentages become less meaningful as the numbers of crashes on which they are based become smaller. Thus, percentages for the test ramp in the after period should not be used as indicators of crash pattern changes.

Crash data discussion
From the information presented above, it becomes apparent that a large share of test ramp crashes during the before period occurred during non-daylight conditions, and an unusually high percentage–half–of the crashes involved semi- or utility trucks, occurring predominantly between 8 pm and 6 am. Single-vehicle crashes were quite common and occurred overwhelmingly when the pavement was not dry and most frequently not in the daytime. Among injury crashes, heavier vehicle involvement was very prominent; single-vehicle crashes resulted in injuries half the time–only a quarter of multi-vehicle crashes resulted in injuries. Thus, crash experience on the test ramp was consistent with hours during which average speeds were higher. During these hours, heavy vehicle and single-vehicle crashes were prominent and often resulted in injuries.

Percentages shown in **table 22** for the test ramp in the after period are not useful for comparisons with the before period, given that crashes were almost half of those in the before period, thus overall number of crashes was very small. For example, although the percentage of non-daylight crashes increased from 66% in the before period to 88% in the after period, crashes decreased from nine to seven. Still, the percentages are useful in demonstrating tentative crash pattern similarities between the before and the after period: with the exception of heavier vehicle involvement, a preponderance of non-daylight, single-vehicle and wet or ice crashes is also present in the after period.

It should be kept in mind that very few crashes occurred on the test ramp during either the before or the after period to allow a definitive statement about crash patterns in either period; only the most prominent patterns were addressed here, and even these patterns may not remain as prominent as more crash experience accumulates on the test ramp.

For the control ramp, the most prominent features were a preponderance of wet pavement crashes and a very prominent number of single-vehicle crashes. Heavier vehicle involvement was also quite noticeable, however involvement of these vehicles in injury crashes was not dominant. Absent was the non-daylight pattern observed on the test ramp, for all crashes, but especially single-vehicle crashes. It is interesting to note that detectors **C** and **D** indicated much smaller speed fluctuations between hours of the day and between weekdays and weekends than detector **B**, providing a partial explanation for the more even temporal distribution of speed-related crashes on the control ramp.

Table 22. Crash Percentages for Test and Control Ramps in the Before and the After Periods.

		Test		Control	
		Before n = 14	After n = 8	Before n = 73	After n = 59
Heavy Vehicles		50	*a*	44	31
Peak Hours		21	*0*	38	24
Non-daylight		64	88	40	47
Wet		43	38	77	71
Snow or Ice		7	38	0	0
Single-vehicle		42	63	68	59
	Snow/Wet/Ice	83	*a*	82	86
	Non-daylight	67	*a*	44	49
Injury		36	*a*	26	31
	% involving HV[b]	80	*a*	17	17
	% of Single-veh.	50	*a*	24	32
	% of Mutli-veh.	25	*a*	30	29

a Very small numbers of crashes in this category.
b HV = Heavier Vehicle.

As observed above, three of the eight test ramp crashes in the after period occurred on the same day, Thursday, December 23, 1999, on snow- or ice-covered pavement. Two of the crashes occurred during the same hour and one two hours later. In the context of the present evaluation, it is reasonable to consider that crashes on snow- or ice-covered pavements would not be affected by the presence or not of the chevron markings (markings will not be visible when covered with snow; crashes on ice-covered pavement would not have been avoided even if the chevron markings were effective in reducing speeds). Similarly, the presence of the chevron markings would not have affected the occurrence of the deer collision that took place in the hour following midnight, on May 20, 2000 . If crashes on snow- and ice-covered pavement and deer collisions were excluded from consideration, only four crashes would have remained on the test ramp in the after period, too few to observe any crash patterns.

Given these considerations, two separate statistics were calculated to assess the safety effectiveness of the chevron markings, one including all crashes and one excluding the types of crashes described above, from both analysis periods and both ramps. These statistics are presented in the following section.

It should be noted here, that a pavement resurfacing project was completed on the test ramp (and the approach to that ramp) at the same time the chevrons were installed, thus part of the crash reduction observed for that ramp should be attributed to the new pavement surface. No resurfacing was performed on the control ramp during the study periods.

Crash Statistics

Two types of statistics were used in the crash analysis: the chi-square statistic was used to test for statistically significant differences between test and control ramp crash frequencies in the before and the after period; the z-test for independent proportions was used to compare the statistical significance of the difference between the proportions of before/total crashes between the test and the control ramp. Two sets of crashes were tested with each statistic: i) all crashes; and ii) ***all crashes, except crashes occurring on snow- or ice-covered pavement and deer collisions.***[12] It is very likely that collisions excluded from set ii were not related to chevron presence (these collisions would have not been avoided regardless of chevron presence). Conclusions follow the presentation of statistical findings.

Chi-square statistic

Table 23 summarizes all reported crashes during the before and the after periods on both the test and the control ramps. The numbers of crashes during the before and the after period are not statistically significantly different between the test and the control ramp; the probability that similar or larger differences between ramps could occur purely due to chance is approximately 47% as calculated by the Pearson Chi-Square and the Likelihood Ratio statistics shown in **table 24**.

Table 23. Test or Control Ramp Cross-tabulation with Analysis Period-All Crashes.

		Analysis Period		Total
		BEFORE	AFTER	
Test or Control Ramp	Test	14	8	22
	Control	73	59	132
Total		87	67	154

Table 24. Chi-Square Tests for Crash Counts presented in table 23.

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	.533	1	.465
Likelihood Ratio	.540	1	.462

[12]Such crashes were excluded from both ramps.

Table 25 presents a crash summary with crashes under snow- or ice-covered roadway conditions and deer collisions removed from consideration. Although the probability that differences as large as the ones observed were purely due to chance is much smaller here, these differences are not statistically significantly different at the 95% confidence level (but are significant at the 90% confidence level). Depending on the statistic used (**table 26**), given the numbers of crashes listed in **table 25**, there is a 9.6% (8.6%) chance that differences in crash experience between the two ramps during the analysis periods could be purely due to chance.

Table 25. Test or Control Ramp Cross-tabulation with Analysis Period-Selected Crashes.

		Analysis Period		Total
		BEFORE	AFTER	
Test or Control Ramp	Test	13	4	17
	Control	73	59	132
Total		86	63	149

Table 26. Chi-Square Tests for Crash Counts presented in table 25.[13]

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	2.765	1	.096
Likelihood Ratio	2.940	1	.086

Z-test for independent proportions

A comparison of the After/Total crash proportions between the test and the control ramp was performed for all and selected crashes, using the Z-test for independent proportions. These proportions should ideally be small, indicating that a small percentage of all crashes on a given ramp occurred during the after period. The lower the proportion (percentage) of crashes in the after period, the steepest the reduction in crashes in the after period is for a ramp. Thus, if the difference "test ramp proportion minus control ramp proportion" is negative, the test ramp outperformed the control ramp, and vice-versa.

The proportions for the two ramps were not statistically significantly different when all crashes were analyzed-**table 27**. There is a 45% probability that the observed difference in percentages (-0.08) was due to chance alone. The difference "test ramp proportion minus control ramp proportion" was -0.0833 (8.33% less crashes occurred in the after period on the test ramp). The 95% confidence interval for the difference in proportions ranges from -0.302 to +0.135, indicating that the test ramp could have anywhere from 30% less crashes to 13% more crashes in the after period than the control ramp.

[13] The Chi-square test requires a minimum expected cell count of 5. The minimum expected count is 7.30.

Table 27. Difference in Proportions Tests-All Crashes.

Z-test for Independent Proportions[14]

Test Ramp Proportion (8/22)	Control Ramp Proportion (59/132)	Z-Statistic	Significance
.36364	.44697	-.74863	.45408

95% Confidence Interval for Difference in Proportions

Difference in Proportions Test-Control	Standard Error	Lower Bound	Upper Bound
-.08333	.11132	-.3015	.13484

When selected crashes only were analyzed, the results are similar-**table 28**, only the difference in proportions (-0.21) is much closer to statistical significance: there is only a 5.8% probability that the observed difference in percentages was due to chance alone. The 95% confidence interval for the difference of the two proportions was from -0.430 to +0 .007, thus, in the worst case scenario for the test ramp, crash reductions for the two ramps in the after period were almost on par (the test ramp had 0.7% more crashes in the after period than the control ramp).

Table 28. Difference in Proportions Tests-Selected Crashes.

Z-test for Independent Proportions

Test Ramp Proportion (4/17)	Control Ramp Proportion (59/132)	Z-Statistic	Significance
.23529	.44697	-1.89656	.05789

95% Confidence Interval for Difference in Proportions

Difference in Proportions Test-Control	Standard Error	Lower Bound	Upper Bound
-.21168	.11161	-.4304	.00708

[14] Based on an SPSS macro written by David Nichols (nichols@spss.com)

Conclusions About Crashes

Crash statistics on the test ramp are very limited, given the low annual crash frequency on this ramp and the limited time that has elapsed since chevron installation. Thus, it is rather early to tell with certainty whether the chevron markings had a statistically significant effect in crash reduction for that ramp. What further complicates the issue, is that it is virtually impossible to separate the individual effects that the freeway resurfacing project and the chevron marking installation had on crash experience. The crash analysis and the review of loop detector speed information indicated that the combination of these two treatments was very appropriate for this location, given the preponderance of non-daylight, heavier vehicle, single-vehicle-wet pavement crashes, leading one to assume that crashes were the result of higher speeds and/or lower pavement friction conditions. The chevron markings were effective in reducing speeds, and the resurfacing project provided better wet pavement friction, addressing both safety concerns.

Comparisons between the test and the control ramp in the before and the after period indicate statistically significant differences, at the 90% confidence level, but not at the 95% confidence level,[15] when crashes that occurred on snow- or ice-covered pavement and deer collisions were excluded from consideration. Both ramps had a lower number of crashes in the after period, however the test ramp experienced a higher percentage reduction in the after period. **When all crashes were taken into consideration, differences between the two ramps in the before and the after period were not statistically significantly different, based on the same test**.

The proportion of after/total crashes for the control ramp (45%) is higher than the after/total proportion for the test ramp (36%). These proportions indicate that both ramps experienced crash reductions in the after period, since each proportion is less than 50%. The test ramp experienced a greater reduction in the after period, since a smaller percentage of the total crashes occurred in the after period. The difference of test minus control ramp proportion is -21% and it is almost to the point of the 95% level of significance,[16] when crashes that occurred on snow- or ice-covered pavement and deer collisions are excluded from consideration. The 95% confidence interval for this difference of proportions ranges from -43% to +1%. In other words, the percentage of crashes in the after period for the test ramp ranges from being 43% lower to 1% higher than the percentage of crashes in the after period for the control ramp. When all crashes were included in the analysis, the difference of the two proportions was not found to be statistically significant.

Although there are indications that crash reductions in the after period were statistically significantly higher for the test ramp, compared to the control ramp, given the small number of crashes in the before and the after period for the test ramp, it would be preferable to defer a

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[15] Based on the Chi-square test.

[16] Significance = 0.06, based on the z-test for independent proportions.

definitive conclusion until a few more years of crash experience have accumulated and a before-after comparison with control can be based on more years of data.

CHEVRON INSTALLATION COST

The original chevron installation was performed by Century Fence[17] for the Wisconsin Department of Transportation, as part of a pavement resurfacing project. Chevron location stationing was completed by WisDOT. Installation started in the late afternoon, on May 11, 1999 and was completed the following evening. No traffic control measures, specific to the pavement marking installation were included in the chevron installation expenditures, because such measures were already in place for the construction project. The installation cost was $40,000.

WisDOT specifies an epoxy two-component paint system with zero volatile organic compounds for pavement markings. Quoting from the WisDOT Facilities Development Manual:

> *"Epoxies offer excellent durability, better night visibility and good adhesion on both concrete and asphaltic pavements. Epoxy is considered to have an average life of 3-4 years dependent upon the amount of traffic.[18] Epoxy is suitable for all types of markings. On new pavement, epoxy is placed directly on the pavement surface. On concrete, if curing compound is present, it must be removed prior to epoxy application. On existing pavement the existing non-epoxy markings must be removed prior to remarking with epoxy. Existing epoxy markings can remain in place unless they are chipping and peeling such that a bond with the pavement is not present."[19]*

The paint can be applied at ambient temperatures between 50ºF and 100ºF; curing time is not affected by humidity.[20] The painting operation stopped in the middle of the night to allow enough curing time for the paint so traffic could drive over it the next morning.

Century Fence constructed the chevron templates from plywood. Because of the complexity of the markings, two crews were used: one applied the longitudinal markings, and the other applied the chevron markings.

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[17] Century Fence Company, N11 W24711 Hy TJ Pewaukee, WI, telephone 1 800 242 2288 CenturyF@execpc.com.

[18] This statement refers mainly to longitudinal lane markings. The shorter end of this useful life was expected of the chevrons, given that they were placed within the traffic lanes (personal communication with WisDOT District 2 maintenance personnel, November 2001).

[19] Procedure 11-50-1

[20] Personal communication with Mr.Frank Both, Century Fence Company, December 2001.

In the spring of 2001 an attempt was made to wash traffic grime from the markings with high pressure hoses and detergents, but the effort was not successful. The markings were subsequently repainted with the same type of epoxy paint on October 30, 2001, at a cost of $38,000 which, this time, included traffic control costs specific to the painting operation. Work took two evenings to complete this time, as well.

CONCLUSIONS

The test ramp was a well-chosen location for the converging chevron pattern installation, from a traffic, roadway geometry and safety point of view. The ramp was sufficiently isolated from merging/diverging effects of adjacent ramps; traffic volumes were not such that congestion alone would force lower speeds during most hours of the day; and, ramp curvature required that drivers reduce their speeds as evidenced by crash experience preceding device installation. The period before chevron installation was dominated by non-daylight, heavier vehicle, single-vehicle-wet pavement crashes, crashes that occurred during higher speed hours. The combination of pavement resurfacing and converging chevron marking installation, applied on the test ramp, appears to have been effective in addressing these safety issues.

Chevron installation on the test ramp contributed to a statistically significant average speed reduction on the ramp, estimated at approximately 12.5 mph, when the effects of higher traffic volumes were accounted for, between the before- and the after- chevron installation periods. The 95% confidence interval for this reduction extends approximately 0.1 mph on either side of this value. This speed reduction was close to the anticipated speed reduction of 15 mph, (from 65 mph before, to 50 mph after chevron installation), stated in the Wisconsin Department of Transportation letter to the Federal Highway Administration requesting permission to install this experimental device.

The chevron pattern device was expected to affect speeds during the least congested parts of the day, when speeds were not influenced by higher levels of congestion, however, speeds were lower during each hour of the day, both during weekdays and weekends.

Both the test and the control ramps had lower numbers of crashes in the after period, despite higher traffic volumes (test ramp +10%, control ramp +7%). When all crashes were examined, no statistically significant differences were found between the test and the control ramp during the before and the after period. However, when crashes that occurred on snow- or ice-covered pavement and deer collisions were excluded from consideration (because they would have occurred regardless of whether the chevrons were present or not), the number of crashes on the test ramp in the after period was statistically significantly lower than that on the control ramp at the 10 percent level of significance (but not at the 5 percent level of significance).

Although both ramps had less crashes in the after period, the percentage of all crashes that occurred in the after period was lower for the test ramp (36.3% compared to 44.7% for the control ramp), indicating a larger reduction in the number of crashes in the after period for the test ramp. The 95 percent confidence interval for the difference of these percentages (test minus control percentage ≈ -8%) ranges from -30% to +13% when all crashes are included, and from -43% to +7% when crashes on snow- or ice-covered pavement and deer collisions were excluded. Thus, it is very likely that the measured difference between crash reductions was not due to chance, but was a result of ramp treatment. However, one cannot be 95% sure that this conclusion is correct, unless the upper limit for the confidence interval for the difference is negative.

No detrimental effects from the installation of the converging chevron marking installation were identified in terms of the analyzed traffic flow characteristics or crash experience.

RELATED INFORMATION FROM RECENT PUBLICATIONS

In the period following submission of the draft version of this report to WisDOT in December 2001, additional related sources of information became available to the investigators:

- A 1997 Japanese article on chevron evaluation was received from Japanese colleagues and translated by Marquette University; summaries of three published evaluations of chevron and other pavement marking applications were received from Japan, accompanied by pictures of anti-skid markings used for chevron, "comb" and transverse markings.
- The final report on an evaluation of a freeway sign, installed at another freeway curve (in the southbound direction of I-43, just north of downtown Milwaukee) in Milwaukee County, Wisconsin, was published by Marquette University. The evaluation provided carefully documented information[21] about truck speed change as trucks approached the freeway curve with comparable characteristics to the test location at the Mitchell Interchange.
- A 1995 Transport Research Laboratory (TRL)-published evaluation of a chevron-based device was received. Methodology and findings provide insights for future chevron-related crash analyses.

Information from Japan

An article entitled " A Study of the Accident Reduction Effectiveness of Speed Reduction Lane Markings" was authored by Mr. Kazuyuki Terada and published in Japan, in June 1997. The author included in this study discussions about:

- Crash experience
- Lane change behavior
- Vehicle position within lane
- Driver questionnaire results

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[21] A large sample of vehicle speeds was collected by laser gun (n = 2,830) at the curve PC; the accuracy of detector information was verified by laser gun; and an additional 31,151 observations were collected through pavement-embedded detectors at a point 860 feet upstream of the curve PC.

The following tables provide selected information from the paper. **Table 29** provides a crash summary based on six segments where chevrons were installed. An overall reduction in crash frequencies can be seen, however: i) the numbers are very small for the first four locations, especially for the after period; ii) the last two locations have adequate sample sizes and show consistency between the two before and the two after years, but the overall reduction of crashes from the before to the after period is not statistically significant. Chevron effectiveness is not uniform among the summarized locations–more years of information would be necessary in order to arrive at definitive conclusions.

Findings by crash type are presented in **table 30**. The discussion about vehicle position within the lane is not presented here (the article abstract indicates that drivers tend to position their vehicles closer to the center of their lane); neither are driver questionnaire statistics.

Speed observations from opposite traffic directions of a tangent highway segment are presented in **table 31**. Average speeds ranged between 64 mph (102 km/h) and 86 mph (138 km/h). Speeds, **in general**, were **lower** in the direction the chevrons were installed–they were **higher**, however, in the slow and middle lanes, during the AM period. Fast lane speeds were **lower** by 8.75 mph (14 km/h) for autos in the AM and by 6.88 mph (11 km/h) for trucks in the PM peak. However, speeds were **higher** by 7.5 mph (12 km/h) for trucks in the middle lane in the AM period.

Table 32 presents a lane changes for small vehicles and trucks, based on data collected at six locations (three with chevrons and three without). Each set of three locations included a curve to the left, a curve to the right and a tangent segment. Passenger car lane changes were fewer where chevrons were present. Findings for trucks were mixed (small truck lane change samples were analyzed).

The provided excerpts indicate that a lower number of crashes was present after chevron installation, however the study periods were short (two years before, two years after); additional years of safety performance are needed for conclusive results. A degree of uncertainty about the speed reduction effectiveness of the chevron patterns is present because of the mixed results for the AM period. Fewer passenger car lane changes occurred where chevrons were installed. There were very few lane change observations for trucks for definitive conclusions.

Based on these findings, it may be desirable that future U.S. chevron pattern evaluations include speed change, vehicle lane positioning and lane change studies for autos and trucks. Reporting speed change results for each lane of traffic would be desirable.

Mr. Kazuhiko ANDO[22] provided summaries for three papers published in Japan (A. Kozaki, T.Fukui, 1991, N. Takada, 1997, and U.Kurosaki et al., 1997). The papers address the speed-reduction effectiveness of chevron markings and "comb" markings–an accompanying sketch demonstrates the appearance of these markings. Chevron signs used in conjunction with delineators and arrow markings had the effect of reducing speeds before vehicles entered a curve (results were not quantified in the summary). "Comb" markings were found to reduce average speeds between 1 mph (1.6km/h) and 3.6 mph (5.7km/h) in one study; results in the other study were unclear. Both studies found fewer lane changes after comb markings were in place.

Mr. ANDO provided pictures of chevron and transverse markings applications on two-lane rural highways, noting that anti-skid markings were used at both locations. All original materials provided by Mr. ANDO are provided in **Appendix 13.**

I-43 Sign Evaluation

The study site for this evaluation presented some similarities with the I-94 chevron evaluation test ramp, as shown in **table 33**: Both freeway curves were preceded by tangent segments of substantial length; the I-43 sign evaluation site was in the southbound direction of I-43 at North Avenue, just North of downtown Milwaukee. The chevron evaluation site was in the I-94 westbound (northbound) direction, approximately 5 miles South of downtown Milwaukee. The I-43 site was a basic freeway segment with three lanes of traffic; the I-94 chevron evaluation site was a two-lane directional ramp between two freeways. Both sites had concrete shoulders on either side.

Vehicle speed information presented in **table 34** from the I-43 site reflects drivers unaffected by the presence of the evaluated sign. Speed data were collected through (accurate) laser guns or pavement-embedded vehicle classification detectors[23] during off-peak hours.

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[22] Senior Researcher, Advanced Road Design and Safety Division, Road Department, National Institute for Land and Infrastructure Management Ministry of Land, Infrastructure and Transport, ADDRESS: 1-Asahi, Tsukuba-shi, Ibaraki-ken, 305-0804, JAPAN, TEL: +81-298-64-4539 FAX: +81-298-64-0178 URL: http://www.nilim.go.jp/lab/gdg/top-e.htm E-mail: andou-k92gi@nilim.go.jp

[23]Detector accuracy had been verified by laser gun for each lane of traffic and each vehicle class.

Table 34 shows that:

1. Auto and semi-truck speeds 860 feet upstream of the freeway curves differed by approximately 3 mph at each location (speed reduction plus speed at PC).
2. Auto and semi-truck speeds at the PC differed by approximately 4.6 mph at the I-43 location.
3. Auto and semi-truck speeds at the PC differed by approximately 6.0 mph at the I-94 location.
4. Notwithstanding the larger radius and superelevation on one hand, but higher traffic volumes on the other, at I-43, speed reductions approaching a curve were of much larger magnitude in the presence of the chevron pattern.

Based on these observations, separate analyses of the chevron pattern speed-reduction effects for autos and semi-trucks (other truck categories, as well) may be desired. If, indeed speed reduction effects are more pronounced for trucks, the device may be recommended for use at locations with many speed-related truck crashes.

The U.K. M1 Chevron Trial - Accident Study

A different type of chevron device was experimented with in the U.K. Results were summarized in the Transport Research Laboratory Project Report 118, authored by R.D. Helliar -Symons and N.R. Butler, and published in 1995.

This device originated in France where it was used successfully for the first time in 1983. The U.K.-installed device, shown in **figure 17** consists of chevrons painted on the roadway surface approximately every 122 feet (40 meters) and is supplemented by with a roadside post-mounted sign, instructing drivers to keep two chevrons apart, intending to increase vehicle headways. If drivers adhered to the sign message, headways would be 2.4 seconds at speeds of 70 mph.

The primary objective of the device was to reduce rear-end crashes. The device was installed in the slow and middle lanes of two three-lane rural freeways. A comparison of three years of before and two years of after data identified a 56% reduction in total crashes, and over 40% reduction in multi-vehicle collisions, when compared to control sites. The authors were surprised to find an unexpected reduction in single-vehicle crashes (from 8 per year to a total of two such crashes).

The authors investigated whether the chevrons caused crashes to "migrate" further downstream, but did not find any evidence of such a migration.

Implications for Future Chevron Evaluations

The following additional recommendations are made, based on the cited analyses:

- It would be desirable to conduct separate speed reduction effectiveness studies for autos and trucks in order to decide conclusively whether indeed the speed reduction effectiveness of chevron installations is greater for trucks than for autos.
- It would be desirable to conduct a lane position analysis in order to determine whether drivers tend to position their vehicles closer to the center of a lane where chevron markings are present. A location with a substantial number of side-swipe and improper lane change crashes would be ideal for such an analysis in order to provide an opportunity to associate such traffic behavior with crash experience.
- It would be desirable to conduct a lane change analysis in order to determine whether the number of lane changes is smaller at locations where chevron markings have been applied. A location with a substantial number of side-swipe and improper lane change crashes would be ideal for such an analysis in order to provide an opportunity to associate such traffic behavior with crash experience.
- Based on the experience from the I-43 analysis, pavement-embedded loop detectors capable of vehicle classification and speed detection, both upstream and at the curve PC would be ideal to provide a large and reliable database. Such an arrangement will provide the opportunity to evaluate chevron effectiveness for each of a large number of vehicle classes. Speed and vehicle class will be recorded for each vehicle crossing the detectors. Results will conclusively quantify the speed change effect attributed to the chevron installation.
- Anti-skid pavement markings may be specified for any chevron installation, given the extensive application of markings required. It would be desirable to investigate the properties of such markings currently in use in Japan.
- The M-1 Chevron Trial study suggests that it may be useful to include an investigation of device effect downstream from the device installation, in order to identify whether speed reductions affected downstream safety performance. Conversely, if speed reductions due to chevrons were to occur at a location that operates at high traffic volume levels, speed reductions over the chevrons may cause unwanted upstream effects, adversely affecting crashes.

Table 29. Crash Frequencies Before and After Chevron Installation.

Segment direction and length	Year 2 before	Year 1 before	Year 1 after	Year 2 after	Curve geometry (curve direction) Horizontal (Radius in meters) Vertical (Gradient in %)
NB 3.0 km	20	18	15		R2000~R1000~R700 (LEFT) -3.000% ~+0.707%
NB 1.1 km	10	15	6	3	R1500 (RIGHT) +0.300%~-1.555%~+0.670%
NB 1.3 km	21	26	5	11	R2000 (RIGHT) -1.698%~+2.730%
SB 3.0 km	29	16	7	6	R1000~R2000~R1000~R2000 (RIGHT) +3.0%~ -3.0%~ -0.66%~ +0.95%
SB 4.1 km	27	40	29	31	R700~R700~R800~R1000~R700~R800 (LEFT) +2.9%~ -2.9%~ -1.5%~ +0.5%~ -2.7%~ +0.3%~ -1.5%
SB 1.8 km	30	40	25	26	R2000~R4000 (RIGHT) +3.0%~ -1.7%~ +0.1%~ +3.0%
Total	137	155	87	77	

Table 30. Crash Types Before and after Chevron Installation.

	Road condition		Light condition		Speed before crash	Violation type			
	Dry	Wet	Day	Night		Inappropriate maneuver	Inappropriate braking	Inattention	Follow too close
Before n = 285	52%	48%	59%	72%	96.9 km/h	45%	7%	30%	1%
After n = 165	68%	25%	72%	24%	95.4 km/h	27%	10%	38%	3%

Table 30. Crash Types Before and after Chevron Installation (continued).

	Crash type			Driver experience on this roadway			
	HD-ON	R-END	SSWIPE	First time	Once a year	Once a month	More than once a week
Before n = 285	47%	26%	21%	3%	59%	9%	18%
After n = 165	36%	30%	18%	1%	53%	11%	20%

Table 31. Speeds at Chevron Installations (km/h).

Condition	Location marker	Geometry	Period	Autos			Trucks		
				Slow lane	Middle lane	Fast lane	Slow lane	Middle lane	Fast lane
Chevrons	SB 87.3 km	Tangent Grade -1.70%	AM	115	131	132	110	123	
			PM	97	110	125	95	105	115
			Average	106	120.5	128.5	102.5	114	115
No Chevrons	NB 88.2 km	Tangent Grade -3.00%	AM	113	126	146	108	111	
			PM	103	116	130	98	108	126
			Average	108	121	138	103	109.5	126

Table 32. Lane Changes.

	Small vehicles		Large vehicles	
Chevrons present				
Slow lane	15/896	1.7%	0/264	0.0%
Middle lane	65/2162	3.0%	9/304	3.0%
Fast lane	59/1217	4.8%	3/28	10.7%
Chevrons not present				
Slow lane	32/958	3.3%	5/259	1.9%
Middle lane	92/1799	5.1%	3/280	1.1%
Fast lane	72/839	8.6%	2/28	7.1%

Table 33. Curve Geometry, Design Speed and Speed Limit.

	I-43 Sign Evaluation Freeway mainline	**Chevron Evaluation Test ramp**
Curve Direction	Curve to Right (3 lanes)	Curve to Left (2 lanes)
Radius	1000 feet	850 feet
Max. Superelevation e_{max}	0.08 feet/foot	0.06 feet/foot
Design Speed*	55 mph	45-50 mph
Length	800 feet	1660 feet
Entering Grade	-0.54%	+3.01%
Length of preceding tangent	8,040 feet	5,170 feet
Per lane traffic volume	1,200 vph	960 vph
Speed limit	50 mph	50 mph

* A Policy on Geometric Design of Highways and Streets, AASHTO, 2001 edition.

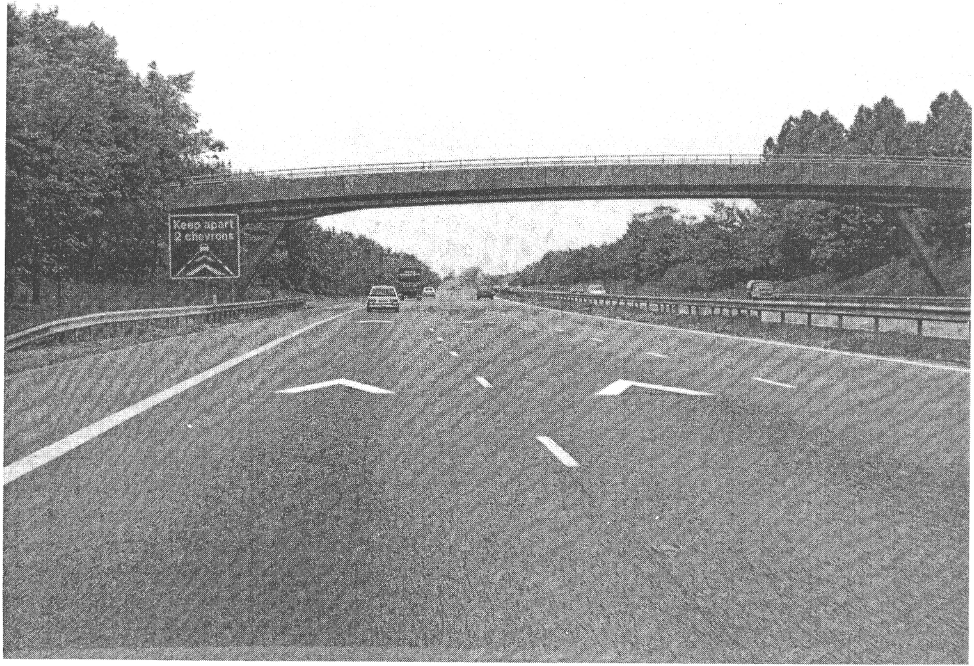
Table 34. Speeds at Two Freeway Curves in Milwaukee County, Wisconsin.

	Autos	Single-Unit Trucks	Semi-Trucks
I-43 Sign Evaluation			
Average speed at PC	57.90 mph	53.40 mph	53.29 mph
Speed reduction during 860 feet before curve PC	0.13mph	1.27 mph	1.91 mph
No of obs. 860 feet before PC (detector data)	15,027	585	606
No of obs. at PC (laser gun data)	902	166	219
Chevron Evaluation-Test ramp, After Period			
Average speed at PC	56.0 mph		50.0 mph
Speed reduction during 1531 feet before curve PC-autos Speed reduction during 1594 feet before curve PC-semi-trucks	9.0 mph		13.0 mph
Speed reduction during 860 feet before curve PC†	4.9 mph		8.1 mph
No of obs. 1541 feet before PC (laser gun data)	25*		38
No of obs. 195 feet before PC (laser gun data)	20*		41
No of obs. at PC (laser gun data)	21*		42

* Small sample sizes.

† Interpolated values from data presented in **figures 12** and **13**.

Figure 17. M-1Chevron Markings Installation, U.K. (Source: Helliar-Symons et. al.)



RECOMMENDATIONS

The absence of detrimental effects, and the strong indications of speed and initial indications of crash reduction benefits, lead to a recommendation to install converging chevron pattern devices at carefully selected locations and, in the process, validate the findings of the present evaluation with data from these new device installations. Ideally (from a device evaluation point of view), selected locations should have a substantial speed-related crash experience (thus adequate statistics will accumulate in a short period after device installation); comparable untreated sites[24] should be located within close proximity; accurate historical speed information should be available; and the facilities should be provided to continue collecting and validating speed data after device installation.

Very few crashes occurred on the test ramp, especially during the after period. It would be desirable to continue monitoring the safety performance of both the control and the test ramp, for at least another two years. Statistics based on a larger number of crashes on the two ramps will allow the derivation of narrower 95% confidence intervals for the difference of before/total crash proportions.

Device effectiveness evaluation concerns should be addressed early when choosing locations for new device installations. Speeds and volumes should be monitored for sufficiently long periods before and after device installation by accurate means.

The following additional recommendations are made, based on the two cited recent publications:

- It would be desirable to conduct separate speed reduction effectiveness studies for autos and trucks in order to identify whether the speed reduction effectiveness of chevron installations is greater for trucks than for autos. If the device is shown to induce greater speed reduction for trucks, it may be recommended as a countermeasure at locations with a preponderance of speed-related truck accidents.
- It would be desirable to conduct a lane position analysis in order to determine whether drivers tend to position their vehicles closer to the center of a lane where chevron markings are present. A location with a substantial number of side-swipe and improper lane change crashes would be ideal for such an analysis in order to provide an opportunity to associate such traffic behavior with crash experience.
- It would be desirable to conduct a lane change analysis in order to determine whether the number of lane changes is smaller at locations where chevron markings have been applied. A location with a substantial number of side-swipe crashes, and crashes attributed to improper lane changes would be ideal for such an analysis in order to correlate chevron effectiveness on lane changing behavior with crash experience.

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[24] That is, sites with similar crash experience, geometry and traffic volumes.

- Based on lessons learned from the I-43 analysis, pavement-embedded loop detectors capable of vehicle classification and speed detection, both upstream and at the end of the chevron pattern would be ideal to provide a large and reliable database. Such an arrangement will provide the opportunity to evaluate chevron effectiveness for each vehicle class based on the entire vehicle population, since speed and vehicle class will be recorded for each vehicle crossing the detectors. Results will be conclusive for the speed change effect of the chevron installation. The large speed database will allow conclusions about speed reductions on dry and wet pavement, with and without chevrons.
- Anti-skid pavement markings should be specified for any chevron installation, given the extensive application of markings required. It would be desirable to investigate the properties (friction, retroreflectivity, durability, etc.) of such markings currently in use in Japan and elsewhere in the world.
- The M-1 Chevron Trial study suggests that it may be useful to include an investigation of device effect downstream from the device installation, in order to identify whether speed reductions affected downstream safety performance. Conversely, if speed reductions due to chevrons were to occur at a location that operates at high traffic volume levels, speed reductions over the chevrons may cause unwanted upstream effects, adversely affecting crashes. Thus, a crash analysis extending on either side of future chevron installations would be desirable.

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