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Final Report

Finite Element Evaluation of Two Retrofit Options to Enhance the Performance of Cable Median Barriers

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16. Abstract

This report summarizes the finite element modeling and simulation efforts on evaluating the performance of cable median barriers including the current and several proposed retrofit designs. It also synthesizes a literature review of the performance evaluation of cable median barriers, existing finite element modeling and simulation work on roadside safety, and an analysis of crash data collected by the North Carolina Department of Transportation.

Two retrofit options were proposed for this project, and several designs for each option were evaluated using the full-scale finite element simulations of a vehicle crashing into a cable median barrier. The simulation results showed that the potential of vehicle under-riding in back-side impacts was higher than that for front-side impacts, because the vehicle's suspension was compressed and there was less median traversal width for back-side impacts. The evaluation of different retrofit options indicated that lowering the middle and bottom cables and changing the sides of all cables on the posts could increase the likelihood of redirecting small vehicles for back-side impacts without sacrificing the CMB's performance for front-side impacts and for large vehicle impacts. For each of the two retrofit options, a new design was developed and evaluated. The simulation results showed that the newly developed three-cable and four-cable retrofit designs could improve the performance relative to the current design in back-side impacts without sacrificing its performance in front-side impacts.

The simulation results of this project should only be used to investigate performance trends for evaluating the CMBs; they should not be used to draw definitive conclusions about CMB performance for a specific crash event, because many factors affecting CMB performance were not considered in the simulations. Finite element analysis was shown to be a useful tool in crash analysis and could be used in future research to investigate these remaining issues.

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EXECUTIVE SUMMARY

This report summarizes the finite element (FE) modeling and simulation efforts on evaluating the performance of cable median barriers (CMBs) including the current and several proposed retrofit designs. A literature review is provided on the performance evaluation of CMBs and FE modeling in roadside safety research. An analysis is conducted on CMB crash data collected by the North Carolina Department of Transportation (NCDOT). Based on the literature review and crash data analysis, two retrofit options are selected and evaluated using FE simulations.

In the first retrofit option, the current design was modified by lowering the middle and bottom cables (25.25 and 20.5 in., respectively, above grade in the current design) to provide better retention of small vehicles. Five different designs are first evaluated for front- and back-side impacts at different vehicle speeds and impact angles. The simulation results are analyzed and a new retrofit design is proposed. Evaluation of the new design shows that it has the same performance as the current NCDOT design for front-side impacts, but a reduced likelihood of vehicle under-riding for back-side impacts. In the second retrofit option, the current design was modified by adding a fourth cable below the current bottom cable. The best height (17 in. above grade for the fourth cable) was determined and this four-cable design was found to have similar performance to that of the new design of the first retrofit option.

The FE simulation results show that cable-vehicle engagements are related to the cable heights, impact location, impact speed, and impact angle. The use of FE simulations in the exploration of new designs has been shown to be both effective and efficient. FE modeling and simulation are recommended in future investigations of remaining research issues such as the effects of impact locations, post spacing, and soil-foundation interactions.

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1. INTRODUCTION

Roadside barrier systems are important devices to enhance transportation safety. Different types of barriers have been developed over the years including rigid, semi-rigid, and flexible systems. Barriers serve the purpose of safely redirecting run-out-of-way vehicles and preventing vehicles from intruding into oncoming traffic. All barriers used on U.S. highways are designed following the guidelines of the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 2002, 2005) and must be tested to satisfy the safety requirements specified by the National Cooperative Highway Research Program (NCHRP) Report 350 (Ross et al. 1993).

1.1 Background

Commonly used barrier systems include concrete barriers, W-beam and thrie-beam guardrails, and cable barriers. Concrete barriers belong to the rigid category; they have higher initial costs, require less maintenance, and are less forgiving in severe crashes than other barrier systems. The W-beam or thrie-beam guardrails consist of steel rails mounted on wood or steel posts with end treatments and transitions. W-beam and thrie-beam guardrails are intended to be sacrificial; therefore, substantial replacements and/or repairs are required after major vehicle crashes. Even low-energy impacts can bend and damage the rails and displace the posts enough for the barrier not to perform properly in a subsequent crash event. The cost of maintaining these systems is generally high.

Fig. 1.1: Three-strand CMBs.

Cable barriers are cost-effective, flexible systems that are ideal for retrofit designs to prevent cross-median crashes in existing, relatively wide medians. Cable barriers differ from concrete and W-beam barriers in that they can be installed on sloped terrain and still perform effectively. They are more forgiving when struck by an off-roadway vehicle, because the cables deflect laterally and reduce impact forces transmitted to the vehicle and occupants. The high flexibility of cable barriers, however, requires that the medians have sufficient widths to allow for lateral cable deflections. For a single-run, low-tension cable median barrier (CMB) shown in Fig. 1.1, the median is required to have a minimum width of 24 ft (7m), with 12 ft (3.5 m) on each side of the CMB (AASHTO 2002, 2005).

North Carolina had approximately 550 miles of low-tension CMBs by 2006 (Murphy 2006). These CMB systems dramatically reduced cross-median crashes and fatalities since their installation in 1994. Although all of the CMBs satisfied the safety requirements of NCHRP Report 350, penetrations of CMBs were still found in certain situations. For example, the crash data analysis performed by research engineers of the North Carolina Department of Transportation (NCDOT) showed that there was approximately a 3.6 percent penetration occurrence for NC CMBs, with the majority of penetrations being vehicle under-riding (Troy 2007). Although these CMBs had very good safety performance (less than five percent penetrations), NCDOT officials believed that CMB performance could be improved by retrofitting the current designs. Due to the high cost and destructive nature of crash testing, it was not possible to use physical experiments to explore better retrofit designs.

With the rapid development of computer technology and parallel computing algorithms, it is now possible to perform full-scale finite element (FE) simulations of vehicular crashes using commercial software packages such as LS-DYNA (LSTC 2007) and PAM-CRASH (ESI 2003). Crash simulations using finite element analysis (FEA) are being increasingly used to design and evaluate the safety performance of roadside safety devices. Use of simulation has progressed from modeling crash tests to supporting hardware design decisions and to providing guidance for roadside hardware placement. Effective use of simulation permits design optimization and minimizes the number of crash tests required to achieve acceptable safety performance, thus reducing the costs of development, installation, and retrofit of roadside safety devices. Additionally, simulations provide a tool for assessing the performance limits of roadside hardware devices under conditions that full-scale crash testing cannot readily accommodate.

In this project, FE crash simulations were used to evaluate the performance of the current NCDOT CMB design and different designs of two retrofit options. The two retrofit options are: 1) determining the optimum locations of the middle and bottom cables in the three-cable system of the current NCDOT design; and 2) adding a fourth cable to the current NCDOT three-cable system below the current bottom cable and determining the optimum location for this fourth cable. Based on an analysis of the simulation results, recommendations were made to NCDOT officials for developing economical and effective retrofit solutions for existing CMB systems in North Carolina to enhance their safety performance.

1.2 Research Objectives and Tasks

The main objective of this research was to evaluate two retrofit options for the current low-tension CMBs in North Carolina. This project was divided into the following four tasks:

<u>Task 1: Literature Review and Analysis of Crash Data</u>

Literature on crash data analysis, crash testing, modeling, and simulation related to performance evaluations of CMBs was identified, collected, and reviewed to assist the FE modeling and crash simulations in this project. The following sources were used in searching for the literature:

- AASHTO Technology Implementation Group (TIG) on CMBs
- Midwest Roadside Safety Facility (MwRSF)
- National Cooperative Highway Research Program (NCHRP) ongoing projects
- National Crash Analysis Center (NCAC)
- State DOT research reports
- Texas Transportation Institute (TTI)
- Transportation Research Board (TRB) Roadside Safety Committee (AFB20) website

- Transportation Research Information Services (TRIS)
- Transportation Research Record (TRR)
- Other technical journals (searchable by Google Scholar)

An analysis of crash data provided by NCDOT was performed to aid in the selection of FE vehicle models and impact conditions (e.g. initial vehicle speeds and impact angles). The literature review and crash data analyses provided a comprehensive knowledge base for conducting other tasks of this project. The FE models of CMBs and vehicles were obtained from the NCAC model library.

Task 2: Validation and Modification of Finite Element Models

The NCAC CMB model was based on the Washington State Design; it was adjusted to meet the NCDOT design specifications (NCDOT 2006). FE simulations of the vehicle running on and crossing a 6:1 sloped median were performed to confirm the validity of the modified CMB and vehicle models.

Task 3: Evaluation of Two Retrofit Options

The two retrofit options considered in this project were:

1) Lowering the middle and bottom cables of the current CMB design and determine the best cable heights (see Fig. 1.2)
2) Adding a fourth cable below the bottom cable of the current three-cable system and determine the optimum location for this fourth cable (see Fig. 1.2)

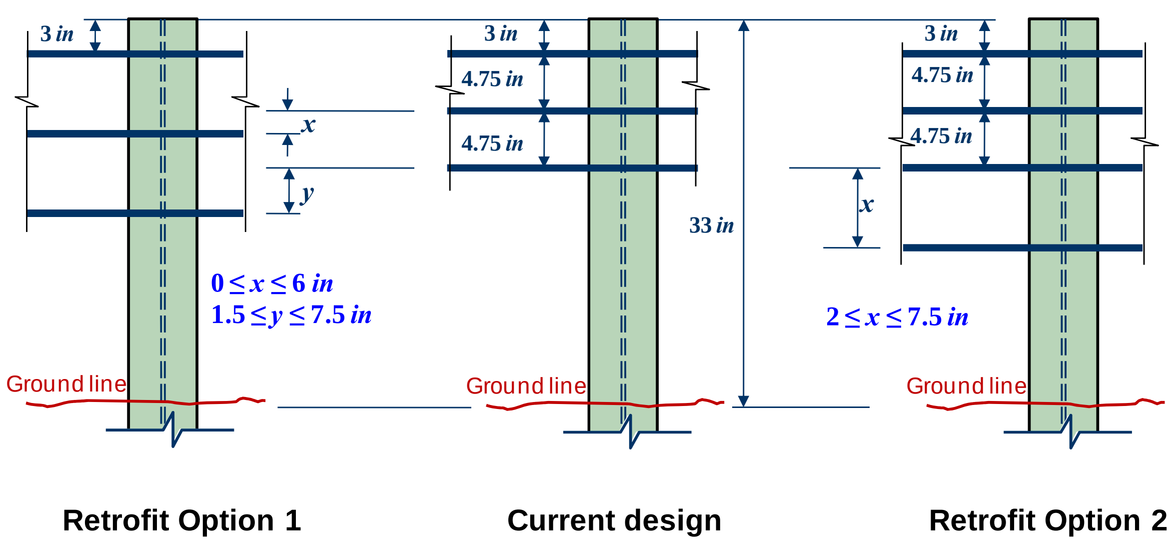


Fig. 1.2: Two retrofit options for the current three-cable system.

Different designs of the two retrofit options were evaluated using FE crash simulations with the following constant conditions for both options:

- Median width: 46 ft (14 m) including two 6-ft (1.83 m) shoulders and a 34-ft (10.4 m) wide ditch (17-ft wide on each side of the median centerline)

- Median slope: 6:1 (Horizontal : Vertical) on both sides of the ditch
- CMB location: 4 ft (1.22 m) from the ditch centerline
- Effective CMB length: approximately 400 ft (122 m) between the third post from the anchor on both ends
- Post spacing: 16 ft (4.88 m) within the effective CMB length
- Impact point: at the midpoint of the effective length of the CMB and midway between two adjacent posts
- Vehicle's initial state: fully landed on the sloped ditch before impact

Since under-riding CMB penetrations were the focus of this project, a small vehicle (1996 Dodge Neon) was selected from the available FE vehicle models. Based on the analysis of the NCDOT crash data, the vehicle's initial impact speeds were set to 55, 65, 70, and 75 mph (88.5, 104.6, 112.6, and 120.7 km/hr) and the impact angles were set to 20, 30, and 40 degrees.

Both back-side (vehicle coming from the side with the ditch) and front-side (vehicle coming from the side without the ditch) impacts were considered in the FE simulations.

<u>Task 4: Final Report</u>

This final project report provides a comprehensive summary of research activities, findings, and outcomes of the above mentioned tasks of this project. It synthesizes findings from the literature and NCDOT data, FE simulations, evaluation of the two retrofit options, and the implementation plan.

2. LITERATURE REVIEW

Cable barriers have been used since the 1960's. In the 1980's, some state DOTs started using modified cable rails as median barriers. Today, many states (Arizona, Colorado, North Carolina, Ohio, Oklahoma, Oregon, South Carolina, Utah, Washington, etc.) have installed cable barriers in highway medians. In this section, a comprehensive summary is provided on studies related to CMBs and other guardrail systems. The topics cover performance evaluation (in-service and crash testing) and the application of FEA to highway safety research.

2.1 Performance Evaluation of Median Barriers

Early in the 1960's, New York State pioneered the development of weak-post barrier systems through analytical models and full-scale vehicle crash testing. In 1965, the state guardrail and median barrier standards were changed to include only weak-post barriers. In the early 1970's, a study was performed to evaluate the field performance of the older strong-post barriers and newly developed weak-post barriers based on accident data collected in New York State from 1967 to 1970 (Zweden and Bryden 1977). Statistical analysis was performed to compare the performance of the investigated barriers based on occupant injury, vehicular responses, and after-impact maintenances. This study generated a number of significant conclusions on the performance of weak- and strong-post barriers. Although there was no significant difference in fatality rates between the two barriers, weak-post barriers exhibited a combined fatality/serious injury rate significantly lower than the strong-post barriers. The resulting occupant injury appeared to be linked to barrier stiffness since the cable barriers (both strong and weak post versions) had lower injury severity rates, while the stiffer median barriers had the highest injury rates. With respect to barrier penetration, the weak-post barriers demonstrated a lower penetration rate than the strong-post barriers (with the exception of the W-beam), which may be due to the lack of consistency between early strong-post barrier designs. The study also indicated that barrier penetrations for the weak-post systems typically resulted from low rail heights. Barrier end terminals (the first or last 50 ft of the barrier) were observed to have higher penetration rates than their midsection counterparts and resulted in higher serious injury rates. Barrier damages were linked to their stiffness; however, weak-post barriers on average were less expensive to repair than strong-post barriers despite the former's longer damage lengths.

In the early 1980's, there were significant changes in vehicle designs with smaller and lighter vehicles constituting a large portion of road traffic. A study was initiated by the New York State DOT in 1983 to determine how impact severity on traffic barriers was affected by vehicle sizes and weights, barrier types and mounting heights, and roadway features (Hiss and Bryden 1992). Several conclusions were drawn regarding the performance of cable barriers, W-beams, and box-beam guardrails. For example, injuries were found to be insensitive for cable barriers with rail heights over 24 in. (0.61 m). For cable and W-beam median barriers, however, the sample sizes were too small to assess their performance due to their limited use and exposure to possible accidents.

Ross et al. (1984) investigated the performance of longitudinal barriers placed on sloped terrain using both crash tests and computer simulations by the highway vehicle object simulation model (HVOSM). In the study, they determined typical conditions to place longitudinal barriers on sloped terrain and evaluated the behavior of widely used barrier systems. Guidelines were developed for the selection and placement of barriers on sloped terrain. It was found from the study that W-beam and thrie-beam guardrails were more sensitive to the terrain slopes than cable barriers.

In the study conducted by Ross et al. (1993), uniform procedures were developed for evaluating the safety performance of candidate roadside hardware systems, including longitudinal barriers, crash cushions, breakaway supports, truck-mounted attenuators, and work zone traffic control devices. The report from this study, the NCHRP Report 350, was adopted as the standard guideline for evaluating the safety performance of roadside safety devices. The evaluation of safety devices was facilitated through three main criteria: 1) structural adequacy; 2) occupant risk; and 3) post-impact trajectory. Structural adequacy refers to how well the device performed its intended tasks (i.e., a guardrail preventing a vehicle from striking a shielded object). The occupant risk criteria attempted to quantify the potential for severe occupant injury. The post-impact vehicle trajectory ensured that the device would not cause subsequent harm (i.e., a vehicle being redirected back into traffic). The guideline recognized the infinite number of roadside hardware installations and crash configurations; therefore, standardized installations and practically representative impact scenarios were used to provide a basis for comparing the performance of similar devices. Of particular note was the multi-service-level concept that provides six different test levels to allow for more or less stringent performance evaluations (ideally depending on the ultimate usage/placement of the hardware).

With respect to cross-median crashes, the NCHRP Report 350 is currently the standard for testing median barriers. Although the report specifies six different test levels, the warrants for devices meeting an individual test level is outside the scope of the document and left to the judgment of the transportation agency implementing the hardware. Generally, however, devices tested to the lower test levels (1 and 2) are used on lower volume, lower speed roadways, while devices tested to higher levels (3 to 6) are typically used on larger volume, higher speed roadways. Note that the 2000P test vehicle is used to evaluate the strength and redirecting capabilities of longitudinal barriers up to and including test level 3 (TL-3). All impacts are performed at 25 degrees and at 50, 70, and 100 km/hour for test levels 1, 2 and 3, respectively. This guideline is currently under revision by the FHWA.

In the early 1990's, the Traffic Engineering Branch of NCDOT conducted a study (Lynch et al. 1993) of accidents on North Carolina's interstate highways in which vehicles crossed medians and entered opposing traffic lanes. The study analyzed accidents that occurred during the period from April 1, 1988 to October 31, 1991. The objectives of this study were to identify interstate locations with unusually high cross-median accidents, to determine possible safety improvements, to develop a priority listing of these locations with recommended improvements, and to develop a model for identifying potentially dangerous locations on North Carolina interstate highways. Data collected in the study showed that 751 cross-median crashes took place in North Carolina and resulted in 105 fatalities. These crashes represented three percent of the total crashes but 32 percent of the total fatalities on interstate highways during the study period. One of the outcomes of this study was the recommendation to construct median barriers at 24 sections of interstate highways in North Carolina.

In a subsequent safety study, Hunter et al. (2001) evaluated three-strand CMBs installed on a nine-mile stretch on I-40, an interstate freeway in North Carolina. Data extracted from the Highway Safety Information System were from 1990 to 1997 and a before-after comparison was made by developing several regression models that used a reference population (e.g., all freeway locations without CMBs) to predict the number of accidents at locations with CMB treatments. The predicted number of accidents was then compared to the actual number of collisions at sites with CMBs. Although a statistically significant increase was found in the total number of crashes on sections after the installation of CMBs, a significant reduction was also found in the number of serious and fatal collisions. These safety studies by NCDOT "provided a great deal of momentum" towards the installation of more barriers in North Carolina (Stasburg and Crawley 2005), with three-strand CMBs the most commonly used median barriers. North Carolina had approximately 550 miles (885 km) of low-tension CMBs by year 2006, with 3.6% of the impacts resulting in cross-median penetrations (Troy 2007).

Following three fatalities from a cross-median accident in 1996, Oregon DOT installed a CMB system along an I-5 section to reduce the potential of future occurrences. The study conducted by Sposito and Johnston (1998) evaluated the cost-effectiveness of this system at preventing cross-median crashes. Based on a comparison of frequency/severity data from pre- and post-barrier installations, the CMBs were found to reduce both the fatality rate and susceptibility of cross-median collisions. The study also indicated that the number of accidents with minor injuries had increased from 0.7 to 3.8 per year since the barrier installation. Based on a cost-analysis incorporating the maintenance cost, the annual cost of CMBs was found to always be less than that of concrete median barriers. The report showed that the cost-effectiveness of CMBs in reducing cross-median crashes was in agreement with similar studies performed in North Carolina, Iowa, and New York.

In the early 1990's, the Washington State DOT (WSDOT) started installing the U.S. generic low-tension CMBs on medians wider than 32 ft (9.75 m). Subsequently, the WSDOT sponsored crash tests (Albin et al. 2001) to evaluate the performance of this barrier system in accordance with the NCHRP Report 350. In the first test (Bullard and Menges 1996), a 1991 Ford Festiva impacted the CMB at a speed of 62 mph (99.76 km/hr) and an angle of 20.4 degrees. In the second test (Bullard and Menges 2000), a 1995 Chevrolet 2500 pickup truck was used to impact the CMB at a speed of 63 mph (101.4 km/hr) and an angle of 24.8 degrees. Albin et al. (2001) reported that the vehicles in both tests were contained by the cables and brought to a stop with relatively minor damages and that the occupant risk values were within the preferred limits set by the NCHRP Report 350.

Cable barriers in Washington State successfully restrained 95 percent of errant vehicles without involving a second vehicle (WSDOT 2006). By comparison, only 67 to 75 percent of crashes with W-beam guardrails and concrete barriers successfully restrained errant vehicles without involving a second vehicle. Thus vehicles striking concrete barriers and W-beam guardrails were more likely to involve a second vehicle in a collision and thus had a higher risk of injury. Despite the statewide success of CMBs, the public had significant concerns about the increasing number of crashes and cross-median collisions on I-5 in Marysville, WA. As a result, the WSDOT (2006) conducted a comprehensive review of traffic safety on I-5 in Marysville from 1999 through 2004. Researchers of this study found that these cross-median penetrations occurred where the cable barrier was placed within five feet from the bottom of the ditch. The suspension was compressed right after the vehicle passed through the bottom of the ditch and continued up the slope. Consequently, the vehicle was not able to engage with the cables, particularly the bottom cable, and thus under-rode the CMB. This situation is shown by the crash test shown in Fig. 2.1.

Fig. 2.1: A sedan on its way of penetrating under a cable barrier in a crash test (WSDOT 2006).

Following the investigation on I-5 in Marysville, the WSDOT installed a high-tension CMB system about 12 ft (3.66 m) from the southbound lanes and 2 ft (0.61 m) past the slope breakpoint. The existing low-tension CMBs, which were approximately 16 ft (4.88 m) from the northbound lane, were also kept on this 40-ft (12.2 m) median. Unfortunately, on February 13, 2007, the two lines of CMBs failed to retain an errant

SUV, which overrode the high-tension CMB, penetrated the low-tension CMB, and collided into a charter bus traveling in the opposite direction (MacDonald and Batiste 2007). There were a number of reasons for the penetration, including:

- Specific road conditions: transitioning from rural to urban surrounds, low congestion to higher congestion, higher speeds to lower speeds, and widely spaced interchanges to closely spaced interchanges
- Driver's high blood alcohol level (0.07, just below the 0.08 limit) and failure of braking before and during the impacts
- High vehicle bumper and high impact speed
- Placement of the high-tension CMB (2 ft or 0.61 m from the slope breakpoint; this effectively reduces the cable heights by 1.5 in. or 38 mm)
- Mechanical failure of the anchor of the low-tension CMB

While recommending the continuous use of CMBs, a few suggestions were also made for future research and/or further investigations including placement of CMBs on sloped medians and CMB anchor designs (MacDonald and Batiste 2007).

By observation of cross-median collisions (CMCs) that occured where median barriers were not warranted by the design policy of Pennsylvania DOT, Donnell et al. (2002) reviewed the methods used to assess median safety on interstates and expressways in Pennsylvania. A critical literature review and assessment were conducted on median safety practice by various state DOTs. Qualitatively assessed median safety practices were used to provide input for quantitative data collections. Negative binomial regression models were used to model CMC frequencies on earth-divided highways. The qualitative results from the study suggested that three-strand cable barriers, strong-post W-beam guiderails, or concrete barriers could be used as median barriers in appropriate site conditions. Quantitative results showed that CMCs were rare events and that nearly 15 percent involved fatalities and 72 percent involved nonfatal injuries. Additional findings included that CMC rates at earth-divided highways decreased with the increase of median width, that CMCs appeared more likely to occur downstream of interchange entrance ramps, and that CMCs were more likely to involve adverse pavement surface conditions (wet or icy) than other crashes.

In a project funded by the New Jersey DOT, Gabler et al. (2005) evaluated the post-impact performance of two median barrier systems in New Jersey: a three-strand CMB and a modified thrie-beam guardrail. FE modeling was used as a major tool for the investigation. The project also included field investigation of crashes involving the subject barriers and a survey of median barrier experiences of other state DOTs. This study concluded that three-strand cable barriers were capable of containing and redirecting passenger vehicles, that cable barriers were effective at reducing the incidence of CMCs in wider medians, and that cable barriers reduced the overall collision severity despite the typically increased total number of accidents.

Ray and McGinnis (1997) provided a synthesis of information regarding the use of guardrails and median barriers in the U.S. and their performance with respect to the testing standards specified by the NCHRP Report 350. Comprehensive background information was provided for the evolution of testing procedures, selection and placement procedures, and in-service evaluation of longitudinal and median barriers. The notable advantages of steel-post cable guardrails or median barriers, as indicated in the report, were their compliance to the TL-3 of NCHRP Report 350, inexpensive installation, minimized sight distance problems, reduced occupant forces in the event of a collision, and reduced snow drifting and accumulation. Disadvantages of this system included periodic monitoring of cable tensions, a large clear area for barrier deflections, and increased barrier damage in the event of a collision.

Using data collected in Connecticut, Iowa, and North Carolina from 1997 to 1999, Ray and Weir (2001) performed an in-service performance evaluation of four guardrail systems: the G1 cable barriers, G2 weak-post W-beams, and the G4-1S and G4-1W strong-post W-beams. The study particularly focused on estimating the number of unreported collisions and the true distribution of occupant injuries. The performance was evaluated in terms of collision characteristics, occupant injury, and barrier damage. With the limited data samples collected in the study, no statistically significant difference was found on performance of the guardrails in the three states, and there was no significant performance difference between the G1 and G2 and between the G1 and G4-1W. However, occupant injuries were less common in collisions with a G1 cable guardrail than with G4-1S or both G4 types combined.

Ray et al. (2003) reviewed literature on in-service evaluations and identified previously used, effective methods. The in-service performance of common barriers and terminals was examined by collecting data in the following three areas: crash, maintenance, and inventory information. A procedure for planning and conducting in-service evaluations of roadside hardware was developed based on methods used and lessons learned in the evaluation study. This procedure was subsequently used as a guide for a project on in-service evaluations performed by a different research team in Washington State and modified based on their experiences and recommendations.

In the work by Bligh and Mak (1999), they evaluated the crashworthiness of roadside devices across vehicle platforms. The impact performances of roadside safety devices were evaluated through full-scale crash testing with two vehicles selected from the extremes of the passenger vehicle fleet in terms of weight and size. The implicit assumption was that if a roadside safety device successfully passed the test requirements for vehicles at the extremes for the fleet, it would perform satisfactorily for all other vehicles in between. Since many vehicular parameters could influence the performance during an impact, this assumption might or might not be valid. The safety performances of roadside devices for various passenger car platforms and light-truck subclasses were evaluated in the study. The study consisted of evaluations of the frequency and severity of roadside crashes for these generic platforms and subclasses by using recent crash data from the Fatal Accident Report System, the General Estimates System, and the Highway Safety Information System.

A median barrier guideline was developed for Texas to assist highway engineers evaluating median barriers with the intention of achieving the highest practical level of median safety (Miaou et al. 2005; Bligh et al. 2006). Based on analysis of crash data in Texas, statistical crash models for various types of median-related crashes were developed. An economic analysis of median barrier needs was performed based on estimates from the frequency and severity models and crash costs used by TxDOT. A guideline for installing median barriers on divided, access-controlled freeways was developed as a function of the average annual daily traffic and median width. Guidance to assist engineers evaluating median barriers on existing highway facilities was developed based on the mean cross-median crash rate.

Based on a review of previous research and testing of CMBs, Alberson et al. (2003) developed a new terminal to improve the lateral deflection, maintenance, and crash performance of the generic low-tension CMBs. By replacing the single, large concrete anchorage block with three specially designed posts, the new terminal eliminated spring connectors and was expected to withstand higher tensile loads. Full-scale crash testing on the new terminal showed reduced lateral cable deflections and suggested a performance improvement. This newly developed cable barrier system was expected to (partially) address the issue of cable heights in backside hits by changing the cable heights in the terminal section. A recommendation was made for further investigation of cable heights in the length-of-need sections in relation to vehicle profiles.

Recently, Alberson et al. (2007) completed a study in which a preliminary guideline was developed for the selection of CMB systems. The project reviewed cable barrier installations in the U.S. and overseas including the generic low-tension CMBs and five proprietary high tension cable systems. A survey was also conducted in the study to identify experiences, practices, and design and construction standards for cable barrier systems in various states. The study indicated a continuously increased usage of CMBs with a total of 1,645 miles of installation. As expected, the severity of accidents was found to decrease at locations where CMBs were installed, while the total number of accidents was found to increase. The study indicated that the placement of CMBs was critical to minimizing the number of accidents and maximizing the performance of the systems, and that these issues were sometimes at odds and deserved further research.

Placement of median barriers has been and will continue to be an area that deserves more research. In the NCHRP Project 17-14 (BMI-SG 2004), researchers attempted to develop a guideline for using median barriers and selecting median widths and slopes. Unfortunately, the collection of data for this project turned out to be very expensive, and the data limitations hampered the strength of the recommendations. The project results were not incorporated into practice, but should be very beneficial to future research. To avoid some of the obstacles that the NCHRP Project 17-14 faced, the NCHRP Project 22-21 set its focus on typical cross-section designs for a construction or reconstruction project rather than the exact cross-section design at a particular point. The typical cross-section designs were determined fairly early in the design process before adjustments were made to account for variations along the alignment (e.g., horizontal and vertical curvatures, interchanges and intersections, and special drainage requirements). The NCHRP Project 22-21 was started on January 24, 2006 and was to be completed by January 23, 2009.

The NCHRP Project 22-22, "Placement of Traffic Barriers on Roadside and Median

Slopes," was planned and the project results were to be incorporated into the final product of NCHRP Project 22-21. An analysis performed in the 1970's indicated that most guardrails did not perform well when placed on 6:1 and steeper slopes. Since that time, the vehicle fleet has changed dramatically with a significant increase in the popularity of light trucks and sport utility vehicles. In addition, there has been a significant change in the design of roadside barriers in recent decades. It is unclear how these changes affect the behavior of longitudinal barriers placed on sloped terrain. Information from the NHTSA FARS database indicated that some cross-median crashes occurred where median barriers were in place. A full-scale crash test also showed that a passenger vehicle could penetrate a CMB on the backside of a depressed median. With the dramatic increase in the use of CMBs in depressed medians, a more detailed study on the performance of barriers in depressed medians is needed to achieve acceptable safety performance.

During the 2007 Summer Meeting of the TRB AFB20 (Committee on Roadside Safety Design), placement of CMBs on sloped medians was considered one of the most important and urgent issues for roadside safety research. Research was suggested to consider the safety and maintenance aspects, impact angles, impact speeds, critical impact points, cable heights and spacing, post spacing and deflections, and soil conditions.

2.2 Crash Modeling and Simulations

Macherle (2003) provided a bibliography of 271 references published from 1998 to 2002 on crash simulations using FEA and impact-induced injuries. This bibliography categorized the references into four different topic areas: 1) crash and impact simulations without occupants; 2) impact-induced injuries; 3) human surrogates; and 4) injury protection. The first topic area included crashworthiness of aircrafts, helicopters, automobiles, and vehicle rail structures. The second area of research utilized two major types of models for humans, crash dummies and real human bodies. Research topics in this area were mainly on biomechanics and impact analyses for various human injuries. Topics on human surrogates focused on the development of FE models of hybrid and other types of human dummies. These dummy models were used to obtain dynamic responses of human bodies during impacts, which were difficult to measure experimentally. In the fourth area, FE modeling was utilized to analyze and simulate injury protection systems such as seat belts, air bags, and collapsible structures to reduce serious and fatal injuries. The references included in Mackerle's bibliography are generally useful to the work on FE crash simulations; however, only a few references under injury protection are related to roadside safety and none is related to CMB simulations.

Most of the publically available FE models of vehicles and roadside safety structures were developed at the NCAC. Since the 1990's, significant effort has been put into the development of FE models that are available as LS-DYNA input files (NCAC web1). A list of references of these modeling efforts and simulation work performed at NCAC is also available (NCAC web2). The modeling and simulation efforts at NCAC can be found in several representative studies. Marzougui et al. (2000) developed the FE model of an F-shaped portable concrete barrier and validated the model with data of a full-scale crash test. With the proven fidelity and accuracy of the modeling methodology, the models of two modified designs were created and used in FE simulations to evaluate their safety performance. A third design was then developed based on the simulation results and its performance was analyzed. In the work by Zaouk et al. (2000a, 2000b), a detailed FE model of a 1996 Plymouth Neon was developed. The three dimensional geometric data of each component was obtained using a passive digitizing arm and then imported into a preprocessor for mesh generation, parts connection, and material properties. Tensile tests were conducted on specimens to obtain the material properties of the various sheet metal components. The body-in-white model was used in the simulation of a frontal impact and the results were compared with test data to evaluate the accuracy and validity of the model. Kan et al. (2001) developed an integrated FE model that included the vehicular structure, interior components, an occupant (Hybrid III dummy), and an airbag for crashworthiness evaluation. The integrated model was then used in a case study to demonstrate the potential benefit of the integrated simulation and analysis approach, which would further improve the engineering practice with cost saving and more accurate and consistent analysis results.

In the work by Marzougui et al. (2004), a detailed suspension model was developed and incorporated into the previously developed FE model of a Chevrolet C2500 pickup truck (Zaouk et al. 1997). Pendulum tests were conducted at the FHWA Federal Outdoor Impact Laboratory and compared with simulation results on displacements and accelerations at various locations. Crash simulations were also performed using the upgraded vehicle model and the results were compared with crash data from previously conducted full-scale tests.

Mohan et al. (2005) developed a detailed FE model for the three-strand low-tension cable barriers. The model addressed the important issues with cable modeling for crash simulations by defining soil and post, post and hook-bolt, and cable and hook-bolt interactions. The CMB model was then combined with the FE model of a Chevrolet C2500 pickup truck and used in the simulation of a CMB impact on flat terrain. The simulation results were compared to data from a full-scale crash test with the same setup. Cable pullout and soil-post dynamic deflections from the simulation were found to correlate well with the crash test data. Angular displacements of the pickup truck in the simulation were similar to those of the crash test. Recorded test data such as the maximum dynamic deflection and the vehicle's acceleration at the center of gravity compared well with simulation results.

To facilitate the use of FE simulations to evaluate roadside safety structures at higher test levels specified by the NCHRP Report 350, Mohan et al. (2007) improved and validated a previously developed FE model of a 1996 Ford F800 single unit truck. This 18,000 lb (8,165 kg) truck was used by the NCHRP Report 350 as the standard vehicle for test level 4. Simulations were performed using the improved model and the results were compared with those from a full-scale crash test. The global kinematics and time histories of accelerations of the truck from simulation results correlated well with test data. Mohan et al. suggested further improving the model to correlate well on the vehicle's yaw by considering frictions between tires and barriers and between tires and the ground.

In the most recent work by Marzougui et al. (2007), they investigated penetrations of low-tension CMBs placed on flat and sloped medians using FEA and vehicle dynamics simulations coupled with full-scale crash testing. The FE model of a Chevrolet C2500 pickup truck was used in the simulation of a CMB placed on flat terrain and the results showed that the vehicle was retained by the barriers. The FE model of a Ford Crown Victoria was used in the simulation of a CMB placed four feet from the ditch centerline on a 6:1 median. The Crown Victoria was found to under-ride the CMB with minimum resistance from the cables. The simulation results using the Crown Victoria model were confirmed by the full-scale crash tests (No. 04010 and 04011) performed at the FHWA FOIL. A conclusion from the simulation results was that the sloped terrain caused the vehicle to be relatively lower than the cable and hence reduced the effectiveness of the CMB. In both simulations, the initial vehicle speed was 62 mph (99.76 km/hr) and the impact angle was 25 degrees.

Marzougui et al. (2007) also performed vehicle dynamics simulations using the above two vehicle models along with the model of a small sedan, a Mitsubishi Mirage, to further investigate the effect of sloped (6:1) terrain on the CMB performance. It was determined that suspensions of mid-sized vehicles tended to be fully compressed due to dynamic forces imposed by the ground when the vehicle started going up the slope on the opposite side of the ditch. Under this condition, the nose of the vehicle was likely to be below the lowest cable and under-rode the CMB. Future work recommended by Marzougui et al. (2007) was to analyze alternative designs and barrier placement retrofits to improve CMB performance on sloped medians. Their suggested retrofits included adding a fourth cable, using a narrower post spacing, using a stronger cable-post connection, and incorporating ties to connect the three cables.

Researchers from the roadside safety group at Worcester Polytechnic Institute (WPI) utilized FE models in a number of roadside safety studies. Ray (1996a) analyzed data of full-scale crash tests and developed a criterion using statistical parameters to assess the repeatability of full-scale crash tests and to evaluate simulation results compared to crash data. Ray (1996b) also reviewed the history of using FEA in roadside safety research, and presented the vehicle, occupant, and roadside hardware models that had been developed to date. Ray and Patzner (1997) developed a nonlinear FE model of a modified eccentric loader breakaway cable terminal and used it to simulate a full-scale crash test involving a small passenger car. Simulation results were analyzed and compared to crash data, and the FE model was recommended to be used in the evaluation of new design alternatives. Plaxico et al. (1997) developed a 3D FE model of a modified thrie-beam and simulated the impact of a compact automobile against it. The computational model was then calibrated with data from an actual field test that was previously conducted as part of a full-scale crash test program carried out under the auspices of FHWA. Plaxico et al. (1998) developed the FE model of a breakaway timber post and a soil model for a breakaway cable terminal (BCT) and the modified eccentric loader BCT. Simulation results were compared and found to correlate well to data from physical tests. Patzner et al. (1999) examined the effects of post strength and soil strength on the overall performance of the modified eccentric loader terminal using a nonlinear FE model. A matrix of twelve simulations of full-scale crash test scenarios was used to establish the combinations of post and soil strengths that produce favorable results. The parametric study showed that certain combinations of soil and post strengths increased the hazardous possibilities of wheel snagging, pocketing, or rail penetration, while other combinations produced more favorable results.

In the work of Plaxico et al. (2000), the impact performance of two strong-post W-beam guardrails, the G4-2W and G4-1W, were compared. After validating the FE model of the G4-2W guardrail with data of a full-scale crash test, the FE model of the G4-1W guardrail was developed. The two guardrails were compared with respect to deflection, vehicle redirection, and occupant risk factors. The two systems were found to perform similarly in collisions and satisfy the TL-3 requirements of the NCHRP Report 350. Using LS-DYNA simulations and laboratory experiments, Plaxico et al. (2003) investigated the failure mechanism of the bolted connection of a W-beam rail to a guardrail post, which could have a significant effect on the performance of the guardrail system. A computationally efficient and accurate FE model of the rail-to-post connection was developed and used in the analysis of guardrail system performance. As observed in real-world crashes and full-scale crash tests, deflated tires had a significantly different behavior from inflated tires. Since vehicle kinematics is strongly coupled with the behavior of deflated tires, modeling this behavior is critical in simulations involving roadside hardware devices. Orengo et al. (2003) presented a method to model tire deflations in LS-DYNA simulations along with examples to use the model. Ray et al. (2004) used LS-DYNA simulations to determine if an extruded aluminum bridge rail would pass the full-scale crash tests for TL-3 and TL-4 conditions of the NCHRP Report 350. The simulation results, which were supported by a subsequent AASHTO LRFD analysis, indicated a high likelihood of passing the crash tests.

FE simulations were also used by researchers at the Midwest Roadside Safety Facility (MwRSF). Reid (1996) utilized FEA in the study of the influence of material properties on the performance of vehicular structures and attempted to develop a crashworthiness guideline for design engineers. In one of his later works, Reid (1998) demonstrated through two simple examples the potential modeling issues that could be easily overlooked in FE impact simulations: contact definitions and damping. He also suggested ways to check for modeling errors and to make improvements. In the work of Reid and Bielenberg (1999), FE simulations were performed for a bullnose median barrier impacted by a 4,409 lb (2000 kg) pickup truck to determine the cause of failure and to evaluate a potential solution to the problem. Reid and Coon (2002) presented details on the development of a hook-bolt model used in the CMB model. In a collaborative work (Reid and Marzougui 2002; Tiso et al. 2002), the FE model of a Chevrolet C2500 pickup truck was improved through refining meshes, using better material models, adding details to simplified components, and improving connections between components. Suspension modeling, which is critical to the correct vehicle dynamic responses, was also investigated in this collaborative work and a new model was successfully developed with significant improvements.

To educate roadside safety engineers and promote the use of simulations, Reid (2004) summarized ten years of the simulation efforts at MwRSF on the development of new roadside safety appurtenances. Reid and Hiser (2004) studied friction effects, particularly between solid elements, on component connections and interactions in crash modeling and analysis. In their work on modeling bolted connections that allowed for slippage, Reid and Hiser (2005) investigated two modeling techniques that are based on discrete-spring clamping and stressed clamping models, respectively, with deformable elements. The simulation results for both models compared well with test data, with the stressed clamping model having better accuracy accompanied by significantly increased computational cost. Hiser and Reid (2005) also investigated FE models for slip base structures, which could potentially reduce the amount of crash resistance and thus occupant injury when struck by errant vehicles. They developed and evaluated two models for bolt preloading, with one using discrete spring elements and the other using pre-stressed solid elements. Similar to their findings in the work of modeling hook-bolts, they found that the solid-element model was more accurate than the discrete-spring model under severe impact conditions. As a result, the model using pre-stressed solid elements was incorporated into the FE model of a cable guardrail system. The results showed that the slip base model was acceptable in both end-on impact and length-of-need impact simulations.

FE simulations were also found in the work of other researchers in the area of roadside safety. Whitworth et al. (2004) evaluated the crashworthiness of a modified W-beam guardrail using detailed FE models of the guardrail and a Chevrolet C2500 pickup truck. The simulation results were compared to crash test data and found in good agreement in terms of vehicle roll and yaw angles. Simulations were also performed to evaluate the effect of certain guardrail design parameters, such as rail mounting height and routed/non-routed blockouts, on the crashworthiness and safety performance of the system. In the work of Bligh et al. (2004), FEA was utilized to develop new roadside devices to address three roadside safety issues. An alternative to the popular T6 tubular W-beam bridge rail was developed to address problems with vehicle instability observed in full-scale crash testing. A retrofit connection to the grid-slot portable concrete barrier of TxDOT was developed to limit the dynamic barrier deflections to levels that were more practical for work zone deployment. Finally, crashworthy mow strip configurations were developed for use when vegetation controls around guardrail systems were desired to reduce the cost and risk associated with hand mowing. In the work of Gabler et al. (2005), they evaluated the post-impact performance of a three-strand CMB and a modified thrie-beam median barrier. FE modeling was adopted as the primary method for the investigation. In their study, Gabler et al. indicated that cables were particularly difficult to model due to their small cross-sectional geometry compared to other structures such as the vehicle. The LS-DYNA contact algorithms were found not robust with the narrow contact characteristic of the cables under the high severity of crash conditions. More importantly, they investigated the larger discrepancies between simulation results and crash tests on CMB deflections, vehicle exiting conditions, and occupant risk parameters. They concluded that the large discrepancies were attributed to the complex nature of the interactions between the vehicle and the cables.

FE simulations, particularly those with LS-DYNA, have been increasingly used in roadside safety research. In addition to the abovementioned references, FHWA recently published several manuals on using LS-DYNA material models and evaluations of these models (Lewis 2004; Reid et al. 2004; Murray et al. 2005; Murray 2007). These references are useful in crash modeling using LS-DYNA.

2.3 Analysis of NCDOT Crash Data

An analysis was performed on crash data of historical vehicle penetrations that occurred on North Carolina's CMBs from 2001 to 2004. Tables 2.1 and 2.2 give a summary of CMB penetrations, which were used to select impact conditions for the simulations of this project.

Table 2.1: Back-side CMB penetration information

No.	Crash Date	County	Route	Cable offset (ft)	Median width (ft)	Distance to barrier (ft)	Impact speed (mph)	Impact angle	Vehicle
1	11/13/01	Durham	I-40	4	48	28	55	11	2000 Mercury Grand Marquis
2	2/19/02	Johnston	I-40	7	49	31	65	27	2000 Daewoo Nubria SE
3	8/16/02	Warren	I-85	3	36	21	80	17	1993 Lincoln Town Car
4	4/3/03	Edgecombe	US 64	5	46	28	55	35	1991 Buick LeSabre Custom
5	10/17/03	Sampson	I-40	4	46	27	50	21	1995 Honda Civic EX Coupe
6	8/23/03	Duplin	I-40	5	46	28	75	12	1998 Volkswagon Jetta (GLS)
7	9/1/03	Duplin	I-40	4	45	26	70	21	1995 Saturn SL
8	1/9/04	Nash	US 64	4	68	38	40	28	1998 Ford Escort
9	2/13/04	Wake	US 64	3	67	37	55	28	1994 Oldsmobile Cutlass Ciera S
10	2/17/04	Pender	I-40	3	45	25	65	30	1994 Honda Civic EX Coupe
11	6/5/04	Robeson	I-95	3	35	21	55	14	1988 Honda Civic CRX
12	6/6/04	Johnston	I-40	7	45	29	80	23	1998 Acura 3.2 CL
13	6/9/04	Cabarrus	I-85	6	69	41	30	26	1999 Cheverolet Camaro
14	6/26/04	Johnston	I-40	4	45	27	45	22	1994 Oldsmobile Eighty Eight
15	11/19/04	Warren	I-85	4	36	22	70	5	2003 Oldsmobile Alero

Table 2.2: Front-side CMB penetration information

No.	Crash Date	County	Route	Cable offset (ft)	Median width (ft)	Distance to barrier (ft)	Impact speed (mph)	Impact angle	Vehicle
1	8/28/02	Robeson	I-95	2	35	15	60	20	2001 Ford Focus ZX3
2	1/25/04	Duplin	I-40	4	46	19	45	11	1996 Saturn SL
3	2/19/04	Johnston	I-40	8	46	15	80	12	2004 Dodge Intrepid SE
4	2/24/04	Nash	US 64	4	68	30	70	26	2003 Toyota Corolla S
5	4/16/04	Sampson	I-40	2	45	21	65	13	2000 Oldsmobile Alero
6	3/26/04	Wake	I-40	2	69	32	50	39	1997 Acura Integra
7	5/19/04	Sampson	I-40	3	46	20	65	14	1995 Mitsubishi Montero
8	6/1/04	Duplin	I-40	4	47	19	70	20	2003 Honda Civic

Tables 2.1 and 2.2 contain 23 CMB penetrations that include eight front-side and 15 back-side impacts. The cable offsets relative to the ditch ranged from two to eight feet, with an average offset of four feet. Therefore, the cable offset relative to the ditch was held constant at four feet for all simulations of this project. Median widths at impact locations range from 35 to 69 ft (10.7 to 21.0 m), where the average median width is approximately 49 ft (14.9 m). The standard 46-ft (14.0 m) median (NCDOT 2002, 2006), which include two 6-ft (1.83 m) shoulders and two 17-ft (5.18 m) slopes on both sides of the ditch, was decided to be used in the simulations of this project. Since a narrower median would likely be more critical, the selected median width would be representative of worst case of the observations. The shoulders were assumed to be flat and the grassy

parts of the median had a 6:1 downward slope on both sides of the drainage ditch. The CMB placement and median conditions for this project are illustrated in Fig. 2.2.

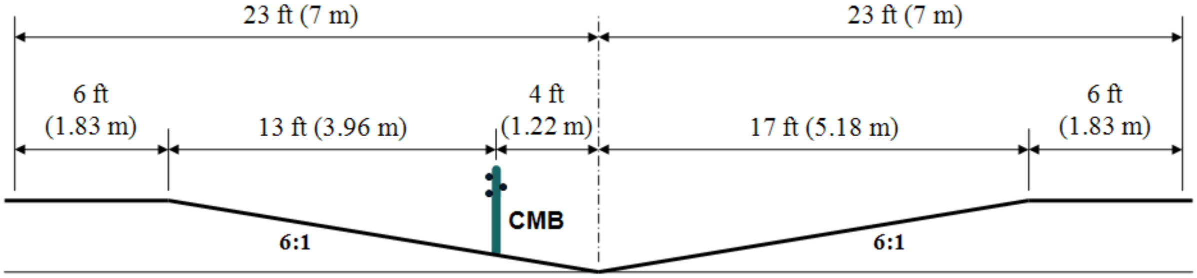


Fig. 2.2: CMB placement on a 46-ft median.

The impact speeds in Tables 2.1 and 2.2 ranged from 30 to 80 mph (48.3 to 128.7 km/hr), with the majority between 50 to 80 mph as illustrated in Fig. 2.3. Based on this distribution, four impact speeds - 55, 65, 70, and 75 mph (88.5, 104.6, 112.6, and 120.7 km/hr) - were selected and used in the simulations of this project. Impact angles given in Tables 2.1 and 2.2 ranged from 5 to 39 degrees, with only one penetration below 10 degrees. Four impact angles - 10, 20, 30, and 40 degrees - were initially considered and the three large angles - 20, 30, and 40 degrees - were selected after consultation with NCDOT officials.

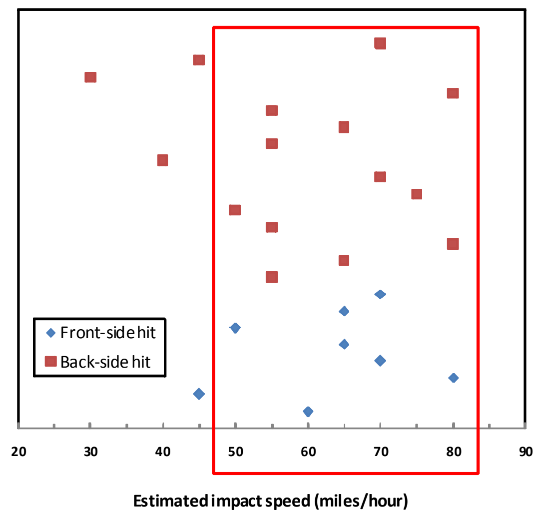
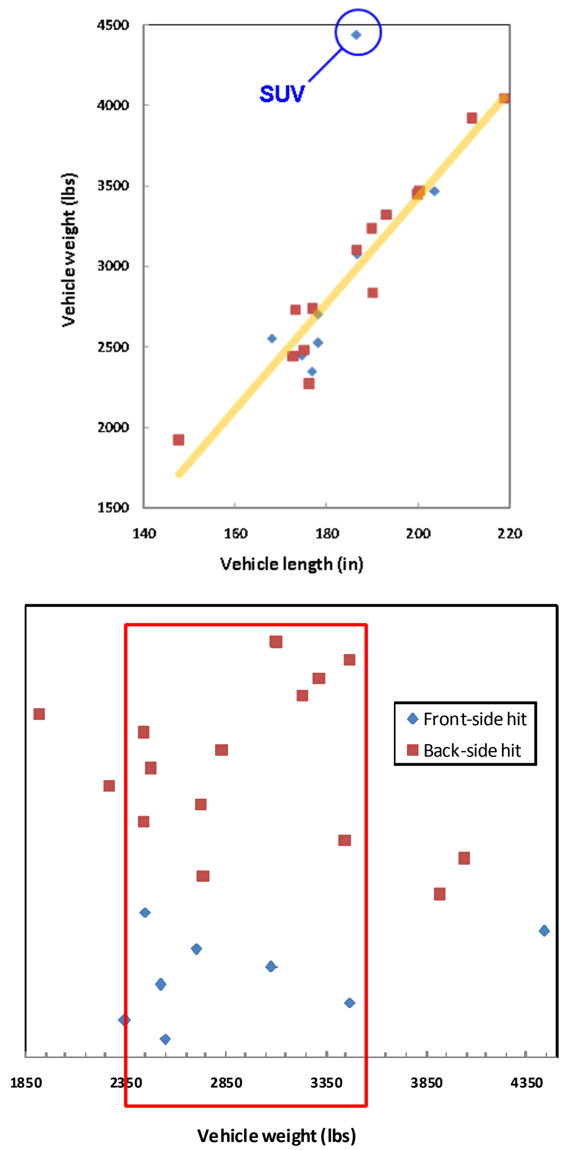


Fig. 2.3: Estimate impact speeds from crash data.

The last columns of Tables 2.1 and 2.2 give the makes, models, and years of the vehicles that penetrated the CMBs. The masses and important dimensions of these vehicles were obtained from the manufacturer specifications and internet sources. Vehicle masses ranged from 1922 to 4436 lb (872 to 2012 kg) and vehicle lengths ranged from 148 to 219 in. (3.76 to 5.56 m). An analysis on the vehicle masses and lengths showed a strong linear correlation between the two quantities, as shown in Fig. 2.4a with the exception of one outlier, which was an SUV. Therefore, the selection of vehicle models for the FE simulation was based on vehicle mass. The range of vehicle masses was decided to be from 2450 to 3450 lb (1111 to 1565 kg), because this range covered the majority of vehicles in the set of crash data as shown in Fig. 2.4b. Since vehicle under-riding was the major concern of this project, the selection of vehicle models was focused on small to medium sized vehicles.



a. b.

Fig. 2.4: Vehicle masses and lengths in crash data.
a. Correlation of vehicle masses and lengths; and b. range of vehicle masses.

3. FINITE ELEMENT MODELING AND SIMULATIONS

The FE models of the CMB and vehicles were obtained from NCAC and modified according to the CMB designs, median conditions, and impact scenarios considered in this project. Both front- and back-side impacts were simulated in this project. In both cases, the vehicle was assumed to be fully landed on the sloped median; therefore, vehicle trajectories were not considered in these simulations. Figure 3.1 shows the simulation setups for both front- and back-side impacts.

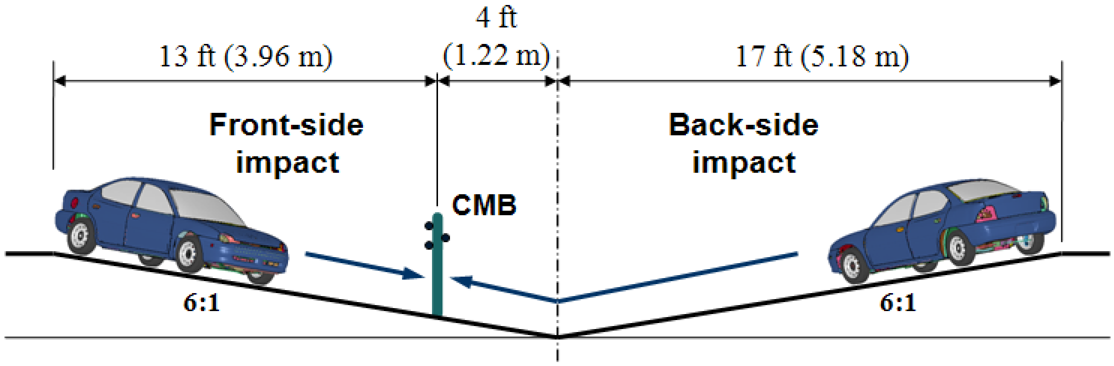


Fig. 3.1: Front-side and back-side impacts.

For each of the front-side and back-side impacts, four vehicle speeds and three angles were selected. This means that a total of 12 (4×3) impact scenarios were considered for either a front-side or a back-side impact. The impact speed was defined in the vehicle's travel direction, and the impact angle was defined as that between the vehicle's travel direction and the longitudinal direction of the CMB (Fig. 3.2). The four selected impact speeds were 55, 65, 70, and 75 mph (88.5, 104.6, 112.6, and 120.7 km/hr) and the three impact angles were 20, 30, and 40 degrees. In this project, the vehicle's initial contact point with the CMB was at the middle of the effective CMB length and midway between the two adjacent posts.

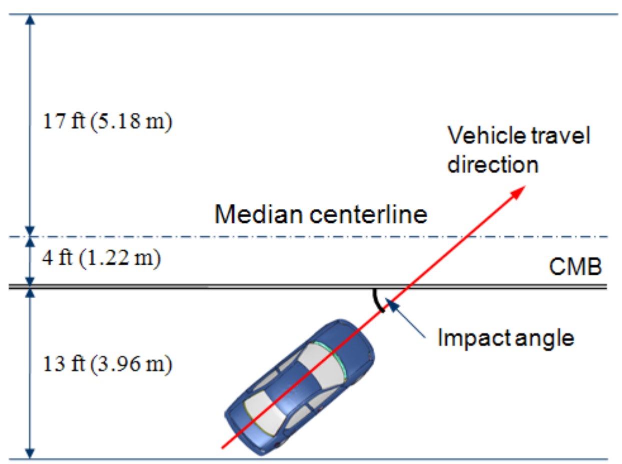


Fig. 3.2: Definition of an impact angle.

3.1 Current CMB Design and Retrofit Options

In this project, two retrofit options for the current NCDOT CMB were investigated: 1) lowering the middle and bottom cables and determining the optimum cable heights; and 2) adding a fourth cable and determining its optimum height. The CMB section being investigated was placed on a 46-ft (14 m) wide, 6:1 sloped median with an effective length of 400 ft (122 m). According to the current NCDOT design, post spacing was 16 ft

(4.88 m) within the effective length. At each end, there was a transitional post that was 100 in. (2.54 m) from the end post of the effective CMB length and was 200 in. (5.08 m) from the anchor post. The longitudinal placement and effective length of the CMB is illustrated in Fig. 3.3.

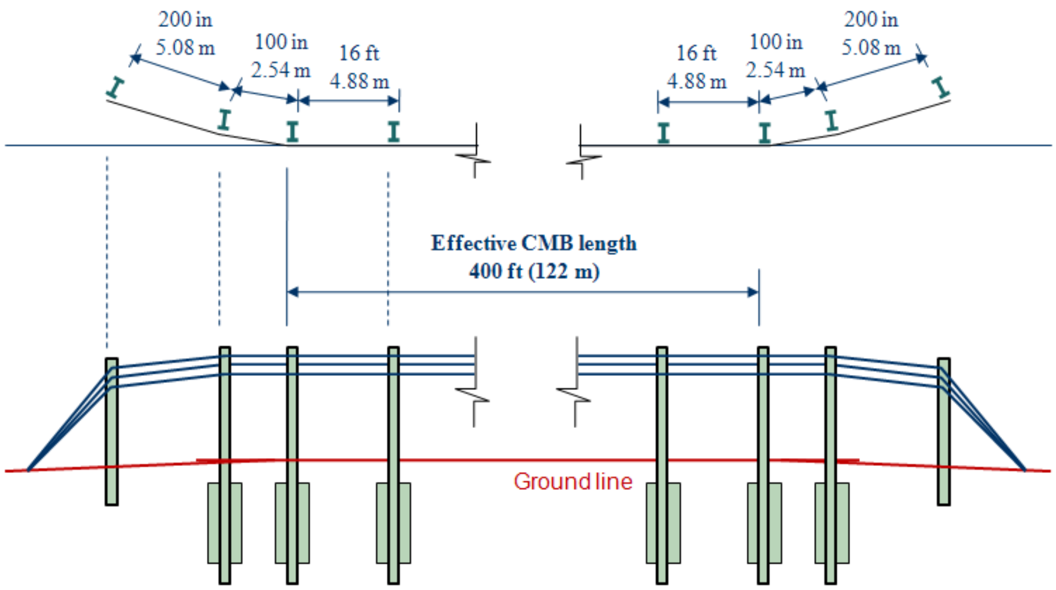
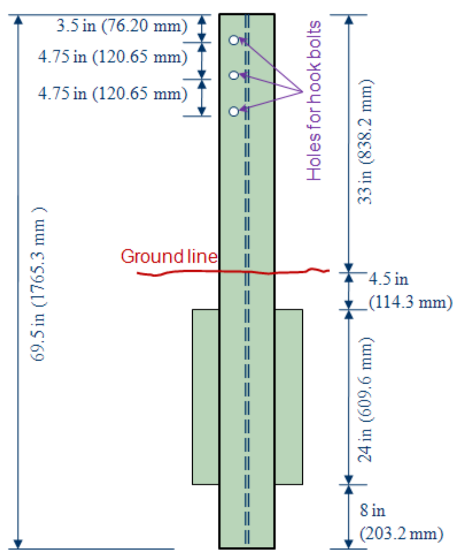


Fig. 3.3: Longitudinal placement and effective length of the CMB.

Figure 3.4 shows the post geometry and cable positions in the current NCDOT design in which the total length of the post is 69.5 in. (1.765 m) and the portion above the ground is 33 in. (0.838 m).



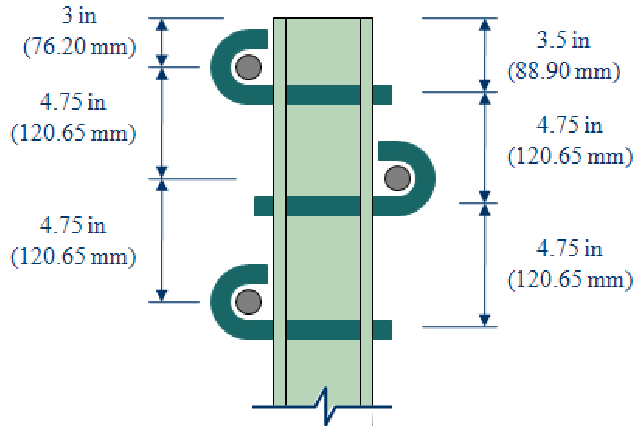
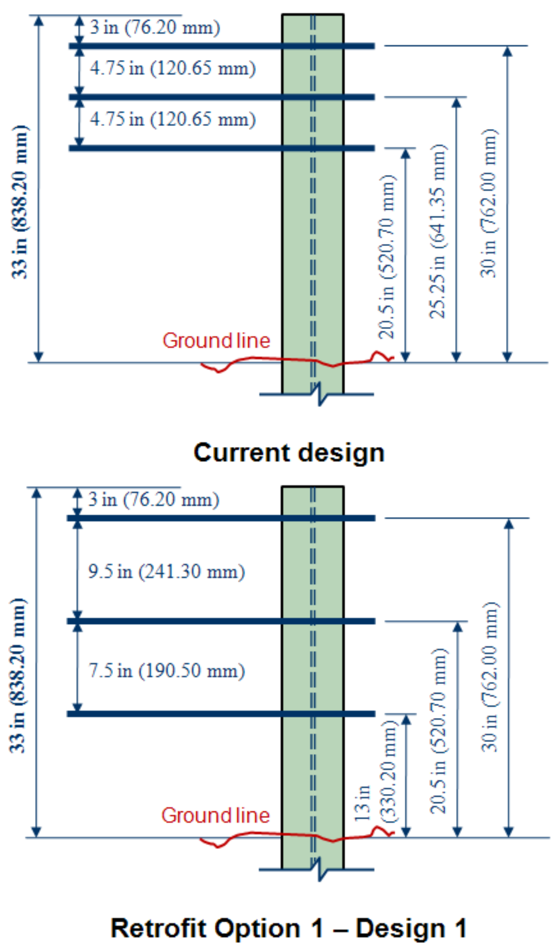
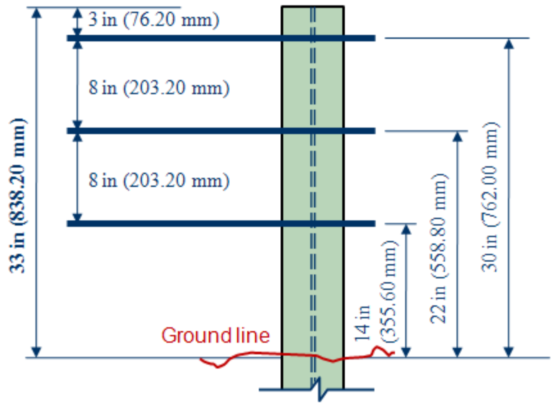


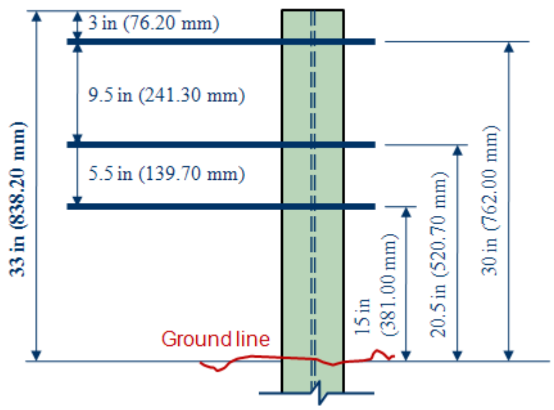
Fig. 3.4: Post geometry and cable positions in the current NCDOT design.

For Retrofit Option 1, five new designs were proposed and evaluated in this project. Cable heights of the current and retrofit designs are shown in Fig. 3.5 and given in Table 3.1.

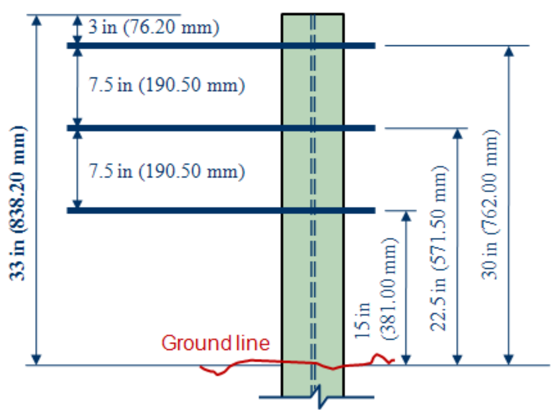




Retrofit Option 1 – Design 2



Retrofit Option 1 – Design 3



Retrofit Option 1 – Design 4

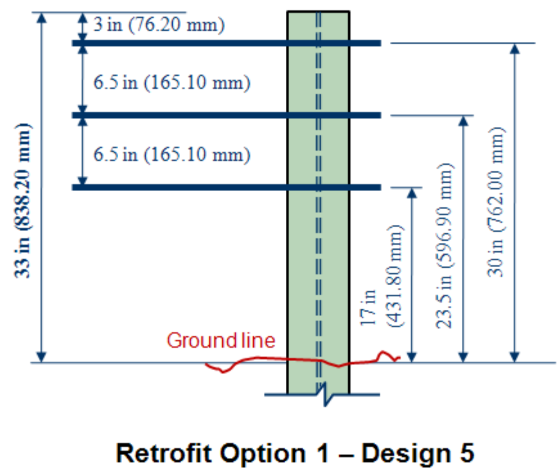


Fig. 3.5: Cable heights of the current NCDOT design and the five designs of Retrofit Option 1.

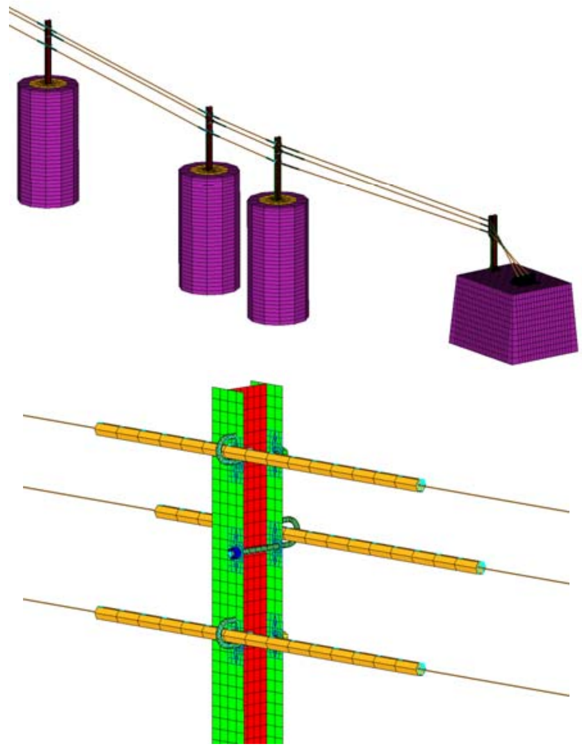
Table 3.1 Cable heights in the current design and five designs of Retrofit Option 1

CMB Design	Cable height			Comment
	Top	Middle	Bottom	
Current design	30” (762 mm)	25.25” (641.35 mm)	20.5” (520.7 mm)	
Option 1 – Design 1	30” (762 mm)	20.5” (520.7 mm)	13” (330.2 mm)	Utilize existing hole
Option 1 – Design 2	30” (762 mm)	22” (558.8 mm)	14” (355.6 mm)	
Option 1 – Design 3	30” (762 mm)	20.5” (520.7 mm)	15” (381 mm)	Utilize existing hole
Option 1 – Design 4	30” (762 mm)	22.5” (571.5 mm)	15” (381 mm)	
Option 1 – Design 5	30” (762 mm)	23.5” (596.9 mm)	17” (431.8 mm)	

For Retrofit Option 2, the height of the fourth cable was determined based on an analysis of simulation results of Retrofit Option 1. This analysis will be presented along with simulation results of Retrofit Option 2 in Section 3.6.

3.2 FE Models of Cable Median Barriers

The FE model of the CMB was obtained from NCAC (Fig. 3.6a). This model was developed based on the Washington State design; therefore, it was modified to conform to the NCDOT design specifications (NCDOT 2002, 2006). Several modifications were made to the NCAC CMB model. First, the post spacing was changed from 16 ft - 4.85 in. (5 m) to 16 ft (4.88 m) as per the NCDOT specifications. Secondly, shell elements were used in the cable model around posts for contact purposes (Fig, 3.6b). Due to the change of post locations (spacing), the cable model in the region of the posts was regenerated. Finally, the CMB in the NCAC model was placed on flat terrain and thus was modified to a 6:1 sloped median for the simulations of this project.



a. b.

Fig. 3.6: The NCAC FE model of a CMB.
a. The CMB model; and b. detailed cable model around a post.

3.3 FE Models of Vehicles

The FE models of four passenger cars and two pickup trucks were obtained from NCAC and were considered for use in this project. These models are shown in Figs. 3.7 and 3.8. Table 3.2 gives the number of nodes, number of elements, and the mass of each vehicle model.

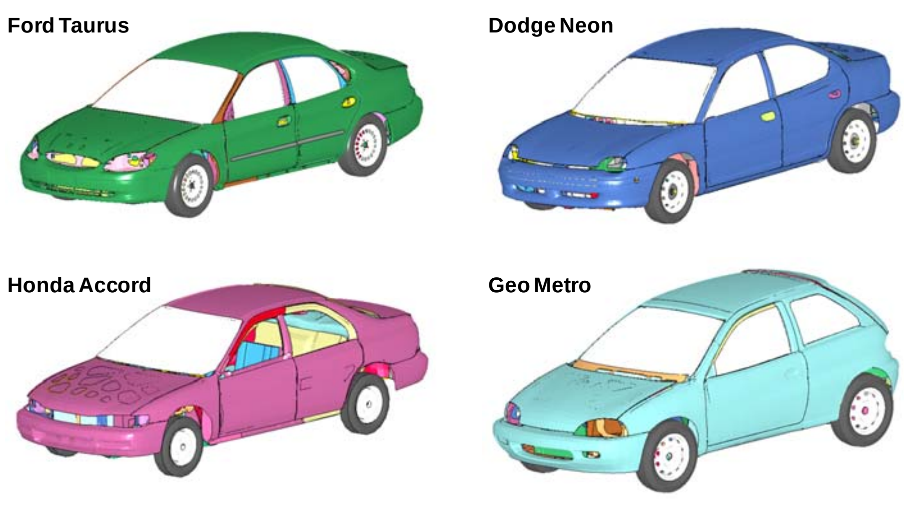


Fig. 3.7: Four NCAC FE models of passenger cars.

Ford F250 Chevrolet S10

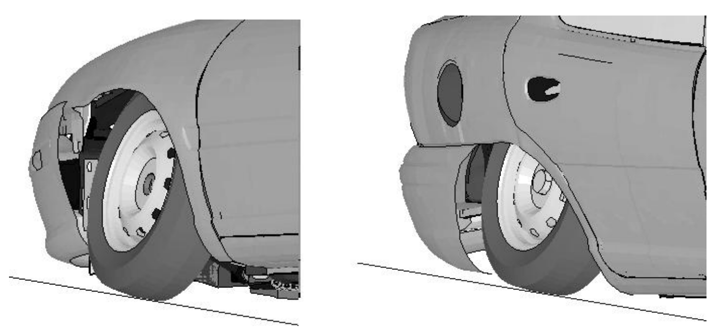
Fig. 3.8: Two NCAC FE models of pickup trucks.

The masses of the Geo Metro and the Ford F250 did not fall in the previously determined range, 2450 to 3450 lb (1112 to 1566 kg). The FE model of the Honda Accord was last updated in 2001; it was an old model with coarse meshes. The mass of the Ford Taurus was above the upper limit. Therefore, the models considered for this project were the Dodge Neon and the Chevrolet S10. The Dodge Neon had a lower profile and thus higher likelihood of under-riding the CMB than the Chevrolet S10. In addition, the FE model of the Dodge Neon was newer than the Chevrolet S10. Based on the above considerations, the FE model of the Dodge Neon was selected for the simulations of this project.

Table 3.2: Information of FE vehicle models

Model	Number of nodes	Number of elements	Mass (lbs / kg)
Ford Taurus 2001	874,835	863,844	3,654 / 1,659
Dodge Neon 1996	283,859	275,992	2,901 / 1,317
Honda Accord	130,837	125,591	2,921 / 1,326
Geo Metro	200,352	196,099	1,203 / 546.2
Ford F250	738,005	730,391	6,608 / 3,000
Chevrolet S10	220,442	220,409	2,482 / 1,127

The FE model of the 1996 Dodge Neon was originally developed at NCAC for the full-frontal crash test specified by the Federal Motor Vehicle Safety Standards and Regulations (FMVSS). Since the FMVSS full-frontal test was conducted on flat terrain, the vehicle suspension models were validated before they were used in crash simulations involving sloped medians. To validate the suspension models, simulations of the Dodge Neon running across a 6:1 sloped median were performed. The simulation results showed that both the

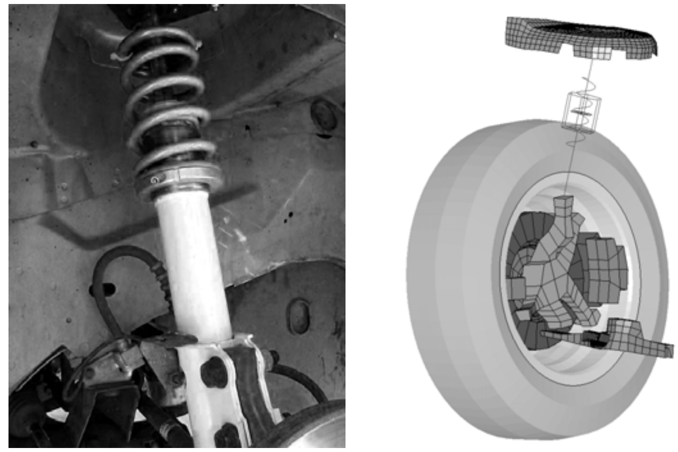


a. b.

Fig. 3.9: Original suspension models on a 6:1 sloped median. a. Front suspension; and b. rear suspension.

front and rear suspension models did not exhibit realistic dynamic behaviors as shown in Fig. 3.9. Unrealistic titling was observed on the front and rear wheels of the vehicle during and after crossing the median centerline.

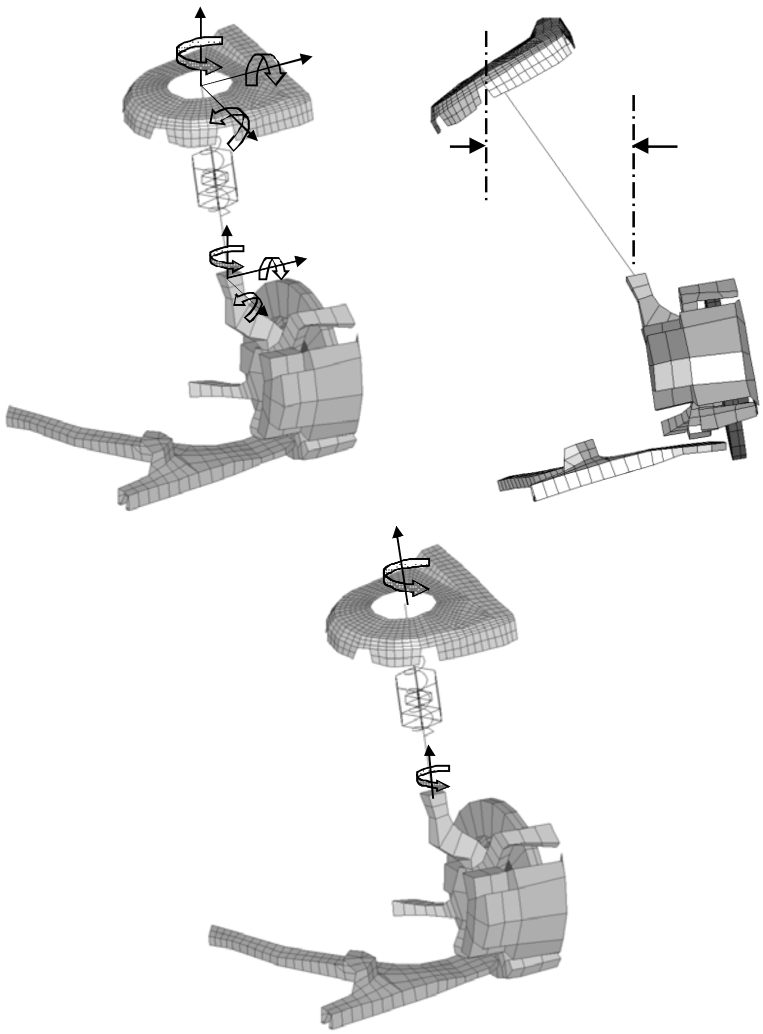
To correct the unrealistic tilting, the suspension models were compared with the real suspensions of the vehicle. Figures 3.10a and 3.10b show the real front suspension and the FE model, respectively, of the Dodge Neon. The front suspension consisted of a coil spring, a shock absorber, and a strut. The upper end of the strut was held by the strut tower brace and the lower end was held by the knuckle that only allowed for rotations about the strut when the wheel was turned (see Fig. 3.10a). The spring constants of the front and rear spring coils were 150 lbf/in. (26.7 N/mm) and 120 lbf/in. (21.0 N/mm), respectively.



a. b.

Fig. 3.10: The front suspension of the 1996 Dodge Neon. a. Real suspension; and b. FE suspension model.

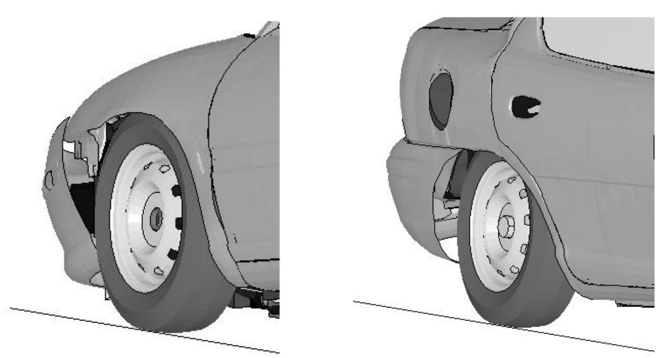
In the FE model of the front suspension, spherical joints were used to model the connections on both ends of the strut. The spherical joints allowed for rotations of the strut in all of the three directions and thus did not accurately represent the real connections, which only allowed for rotation about the strut. Figure 3.11a shows the three allowable rotations on each of the two joints in the original model. Figure 3.11b shows the large lateral displacement using the original suspension model in the simulation shown in Fig. 3.9. Figure 3.11c shows the modified suspension model using cylindrical joints that confine two rotations at the joints of the strut. Similar analyses and modifications were also performed on the rear suspension model. The modified suspension models were used in a simulation of the vehicle crossing the median, and the simulation results showed that the unrealistic tilting was corrected, as shown in Fig. 3.12.



a. b. c.

Fig. 3.11: Modeling of the front suspension joints.
a. Suspension model with spherical joints; b. large lateral displacement due to unconfined rotation; and c. suspension model with cylindrical joints.

To check the robustness and stability of the modified suspension models, the vehicle models with the original and modified suspension models were also used in simulations of the vehicle crossing medians with larger slopes. Figure 3.13a shows one of the simulations in which the vehicle is launched from the shoulder on the side with a 2.5:1 slope and lands on the side



a. b.

Fig. 3.12: Modified suspension models on a 6:1 sloped median.
a. Front suspension; and b. rear suspension.

with a 4:1 slope of the median. Figures 3.13b and 3.13c show the suspension behaviors of the original and modified models, respectively.

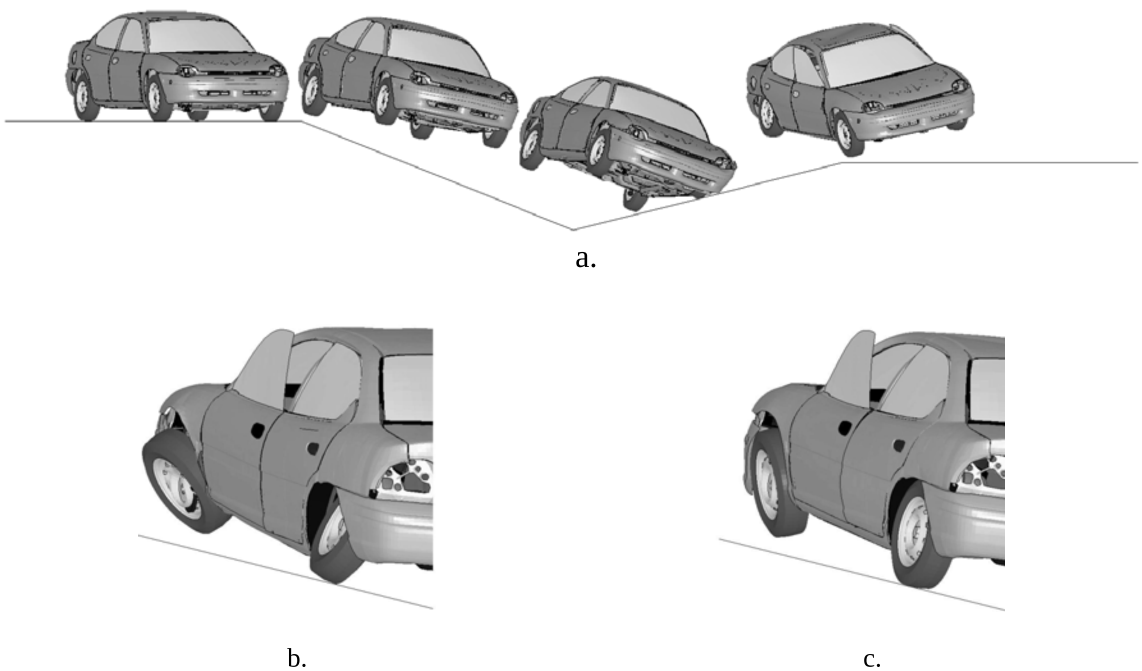


Fig. 3.13: Suspension behaviors of the original and modified models on a sloped median.
a. Vehicle trajectory; b. original suspension model; and c. modified suspension model.

There were several modeling issues that caused numerical instabilities and abortion of the simulations using the original vehicle model. For example, there were several disconnected elements on the front bumper of the vehicle model as shown in Fig. 3.14. Similar situations also existed in other parts of the vehicle model. Furthermore, contacts between various vehicle components were found to function improperly due to severe deformations. For example, the contact between the front-wheel rim and the brake disk did not work after the vehicle crossed the ditch centerline. The brake penetrated into the rim on the front wheel as shown in Fig. 3.13b. The above mentioned problems did not cause numerical instabilities in simulations of full-frontal impacts in which the vehicle ran on flat terrain. However, on sloped medians, the FE simulations became unstable and terminated prematurely due to the presence of these modeling issues. All of these problems were resolved before the Neon model was used in the simulations of this project. The commercial software package, Hypermesh (Altair 2006), was used in the modification of all models.

3.4 Simulation Results of the Current Design

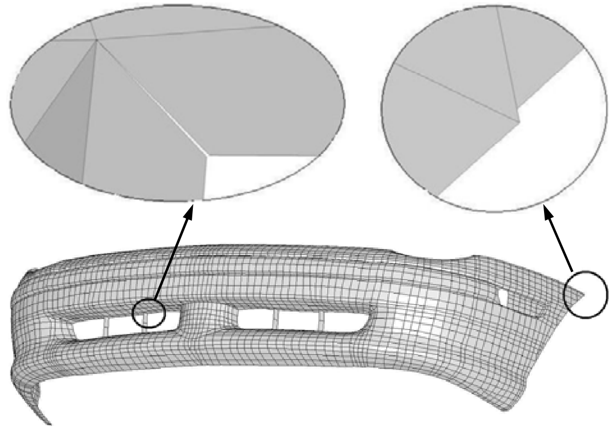


Fig. 3.14: Disconnected elements on the front bumper.

The current NCDOT CMB design was first examined using FE simulations to provide a basis for evaluating the performance of the retrofit designs. The FE model of the 1996 Dodge Neon was used in the simulations of both front- and back-side impacts. CMB performance was evaluated by characterizing the vehicle's behavior into the following four categories.

1. Redirected (RD): the vehicle engaged with one or more cables and was redirected within the 34-ft (10.4 m) sloped median.
2. Redirected on shoulder (RD_S): the vehicle engaged with one or more cables and was redirected on the shoulder of the 46-ft (14 m) median.
3. Redirected out of median (RD_O): the vehicle engaged with one or more cables and was redirected outside the 46-ft (14 m) median.
4. Penetrated (PT): the vehicle penetrated the CMB and entered into the oncoming traffic lane without engaging with any cable.

The cable's behavior in cable-vehicle engagements was defined as follows.

1. Engaging (E): a cable was engaged with the vehicle for the entire impact duration.
2. Sliding (S): a cable was first engaged with the vehicle, slid along it, and finally lost engagement. The cable had some contribution to redirecting the vehicle.
3. Over (O): a cable slid over the vehicle without significant contribution to redirecting it.
4. Under (U): a cable slid under the vehicle without significant contribution to redirecting it.

The cable-vehicle engagement was characterized in the order of bottom, middle, and top for the three cable system. For example, (SU, E, O) meant that the bottom cable had an initial engagement with the vehicle, but eventually slid under the vehicle; the middle cable engaged with the vehicle during the entire impact event; and the top cable simply slid over the vehicle offering negligible resistance.

The results of all FE simulations for the current design impacted by the Dodge Neon are summarized in Table 3.3 using the definitions given above.

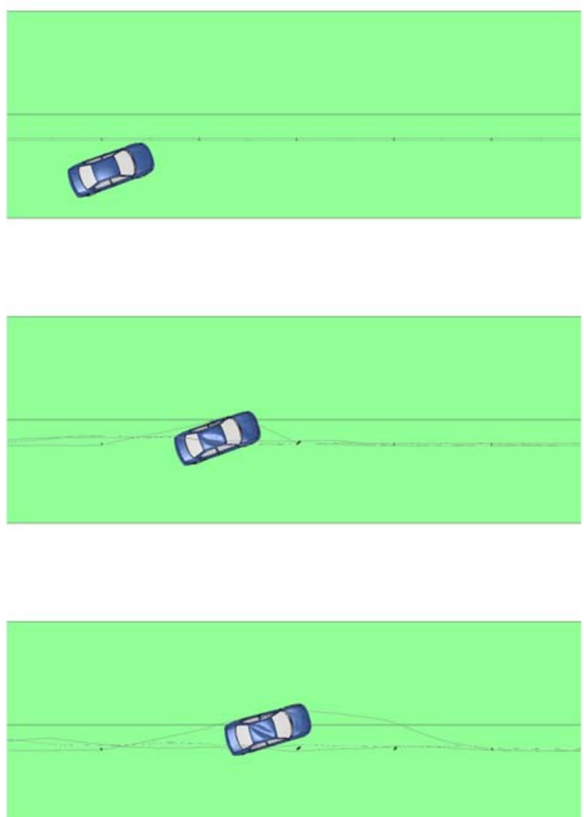
Table 3.3: FE simulation results of current design impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Front	20	RD (E, O, O)	RD (E, O, O)	RD (E, O, O)	RD (E, O, O)
	30	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
	40	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
Back	20	RD (E, O, O)	RD_S (E, O, O)	RD_S (E, O, O)	RD_S (E, O, O)
	30	RD_S (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

For all of the front-side impacts, the vehicle was completely redirected within the 34-ft (10.4 m) sloped median. Depending on the impact angles, the vehicle engaged with one or two cables. For the 20° impacts, the vehicle only engaged with the bottom cable, while it engaged with both the middle and bottom cables for the 30° and 40° impact angles.

Figures 3.15, 3.16, and 3.17 show the simulation results of front-side impacts with an initial speed of 65 mph (104.6 km/hr) and impact angles of 20°, 30°, and 40°, respectively. For each case, four snapshots are shown before and after the vehicle impacting the CMB. Figure 3.18 shows the traversal displacements measured at the front (hood) and rear (trunk) locations on the vehicle for the case of 30° and 65 mph (104.6 km/hr). The displacement curve becomes flat at 0.5 seconds, indicating that the vehicle has been redirected. The simulation results for all other front-side impacts of the current design are given in Appendices A and B. The simulation results show that the current CMB design is effective in preventing penetrations of small vehicles for front-side impacts, even at higher impact speeds and larger impact angles than specified by the NCHRP Report 350.



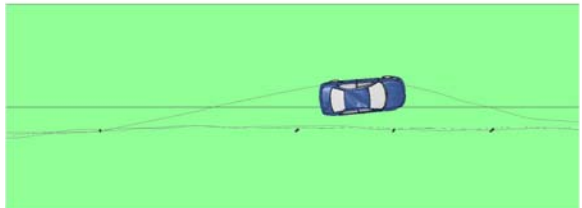


Fig. 3.15: Front-side impact by Dodge Neon at 20° and 65 mph for the current design.

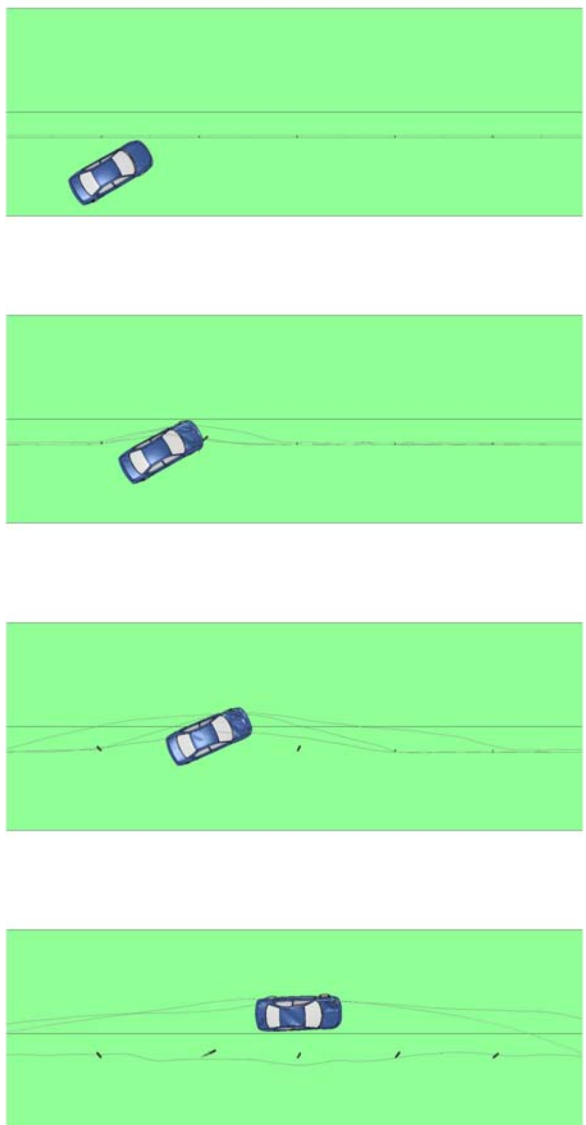


Fig. 3.16: Front-side impact by Dodge Neon at 30° and 65 mph for the current design.

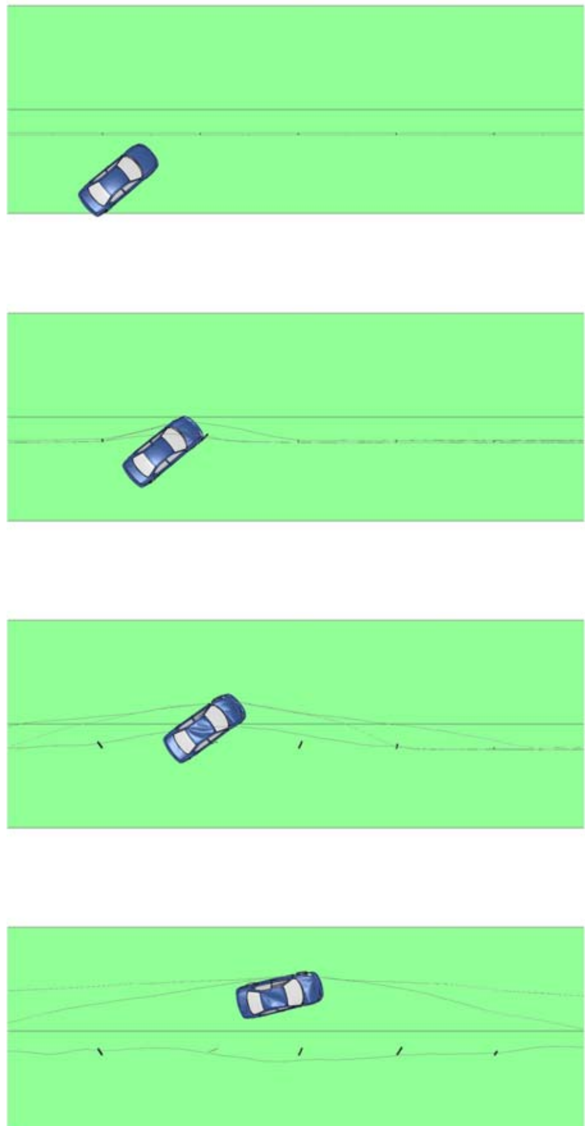


Fig. 3.17: Front-side impact by Dodge Neon at 40° and 65 mph for the current design.

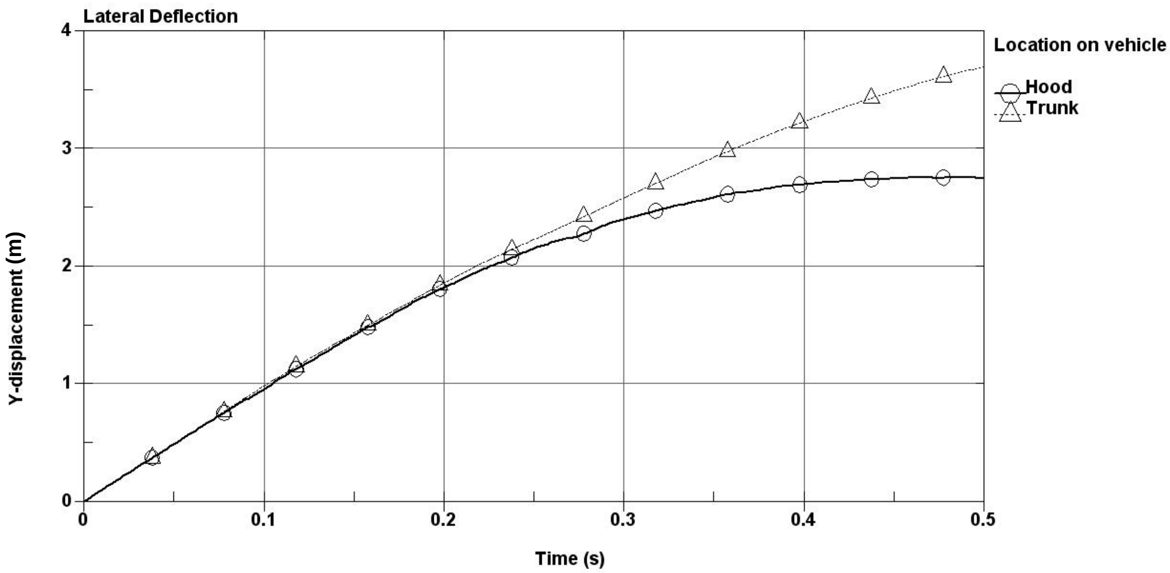
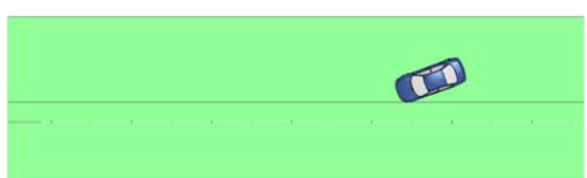


Fig. 3.18: Vehicle's traversal displacements in front-side impact at 30° and 65 mph.

Simulations for back-side impacts were performed under the same vehicle speeds and impact angles as those for the front-side impacts. In all of these cases, the vehicle engaged only with the bottom cable. This was because the vehicle's profile was lower than that in the front-side impacts due to suspension compression upon crossing the median centerline. The results showed that the vehicle was redirected within the median (on the slope or shoulder) for 20° impacts at all speeds. Also, the vehicle was redirected on the shoulder of the median for the 30° impact at 55 mph (88.5 km/hr). In all other cases, which had more severe impact conditions (higher speeds and larger angles) than that of NCHRP Report 350, the CMB was not able to redirect the vehicle within the median. Figures 3.19, 3.20, and 3.21 show the results of back-side impacts at a speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively.



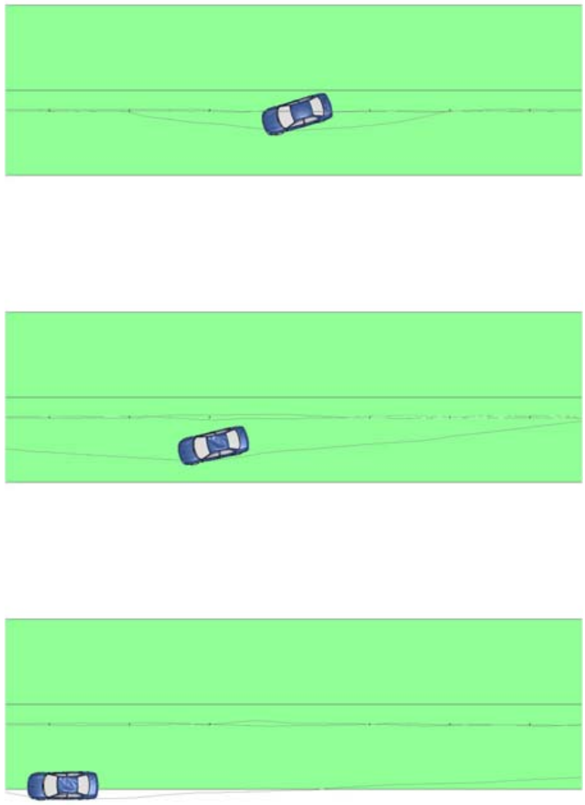
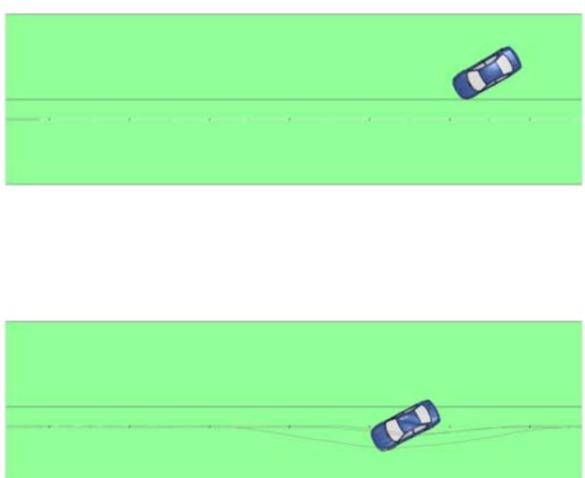


Fig. 3.19: Back-side impact by Dodge Neon at 20° and 65 mph for the current design.



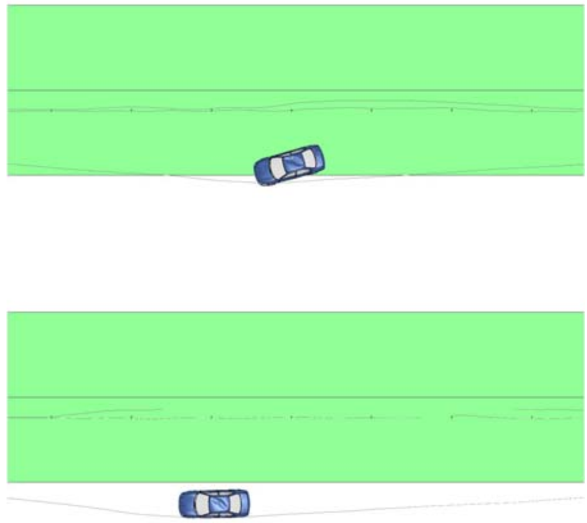
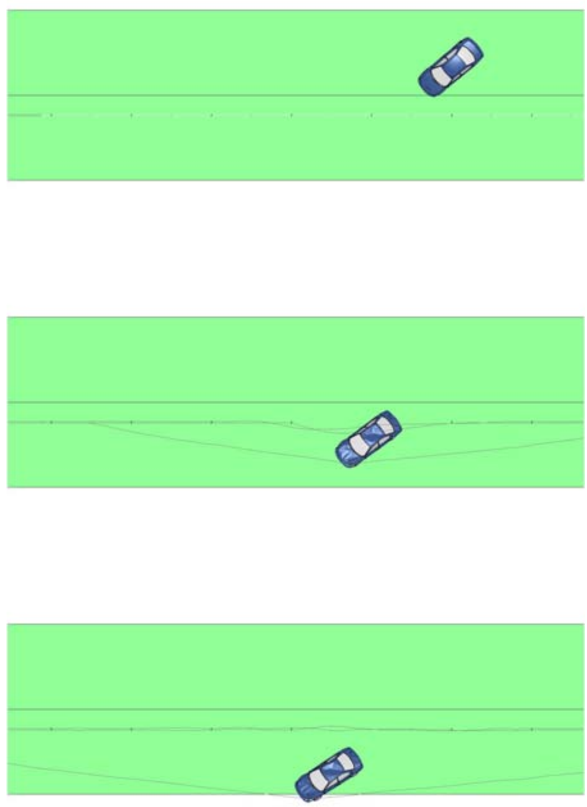


Fig. 3.20: Back-side impact by Dodge Neon at 30° and 65 mph for the current design.



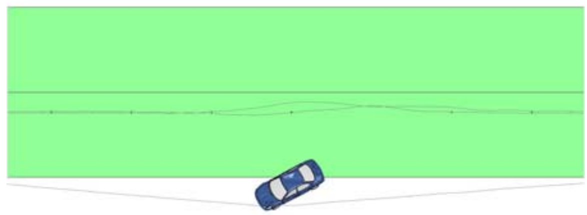


Fig. 3.21: Back-side impact by Dodge Neon at 40° and 65 mph for the current design.

Figure 3.22 shows the traversal displacements measured at the front and rear locations on the vehicle. The simulation results for all other back-side impacts of the current design are given in Appendices A and B.

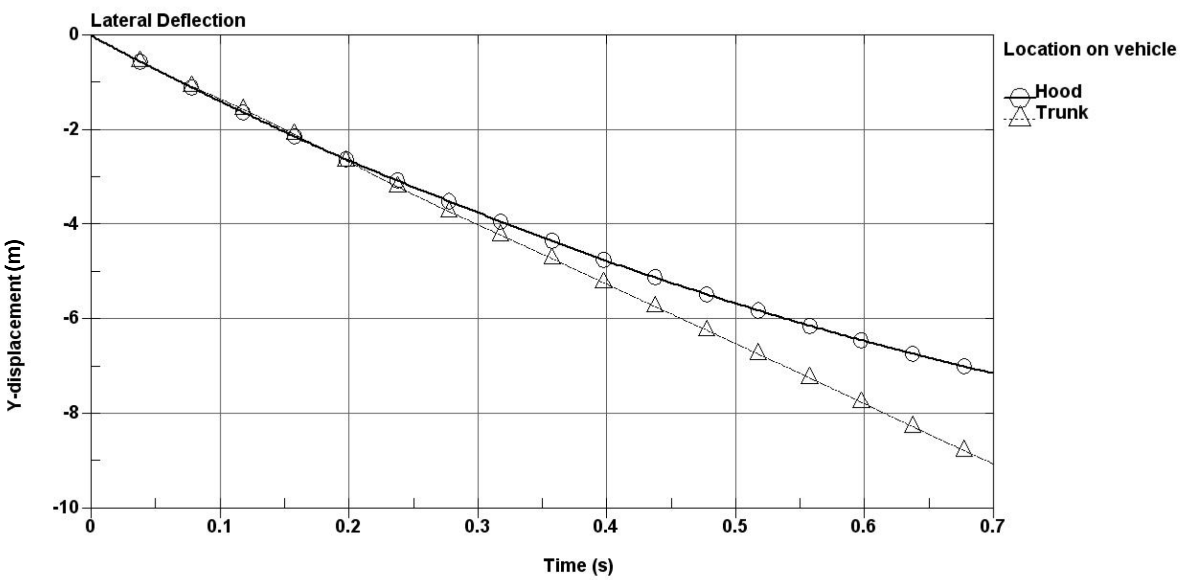


Fig. 3.22: Vehicle's traversal displacements in back-side impact at 30° and 65 mph.

The performance of the CMB was not equal for front- and back-side impacts. There are several reasons for the unsuccessful redirection of the vehicle in back-side impacts. First, the traversal distance to redirect the vehicle in back-side impacts was 8 ft (2.44 m) shorter than that in front-side impacts. Secondly, the vehicle did not engage with the middle cable due to the vehicle's lower profile after crossing the median centerline. It was observed from the simulation results that the larger the impact speed and angle, the lower the vehicle's profile after crossing the ditch centerline. Figure 3.23 shows traces of three nodes located on the vehicle's front for front- and back-side impacts at 30° and 65 mph (104.6 km/hr). The three nodes were selected from the top of the front corner of the fender, top of bumper, and bottom of bumper. The bumper, upon hitting the cable in the back-side impact, was approximately 8.7 in (220 mm) lower than that in the front-side impact. All other traces on these three nodes are included in Appendix C. Finally, the redirection force of the bottom cable in a back-side impact was less than that in a front-side impact. In the current design, the forces to hold the bottom cable to the posts in back-side impacts were due to the strength of the hook-bolts, while the forces in front-side impacts were due to the strength of the posts (See Fig. 3.24).

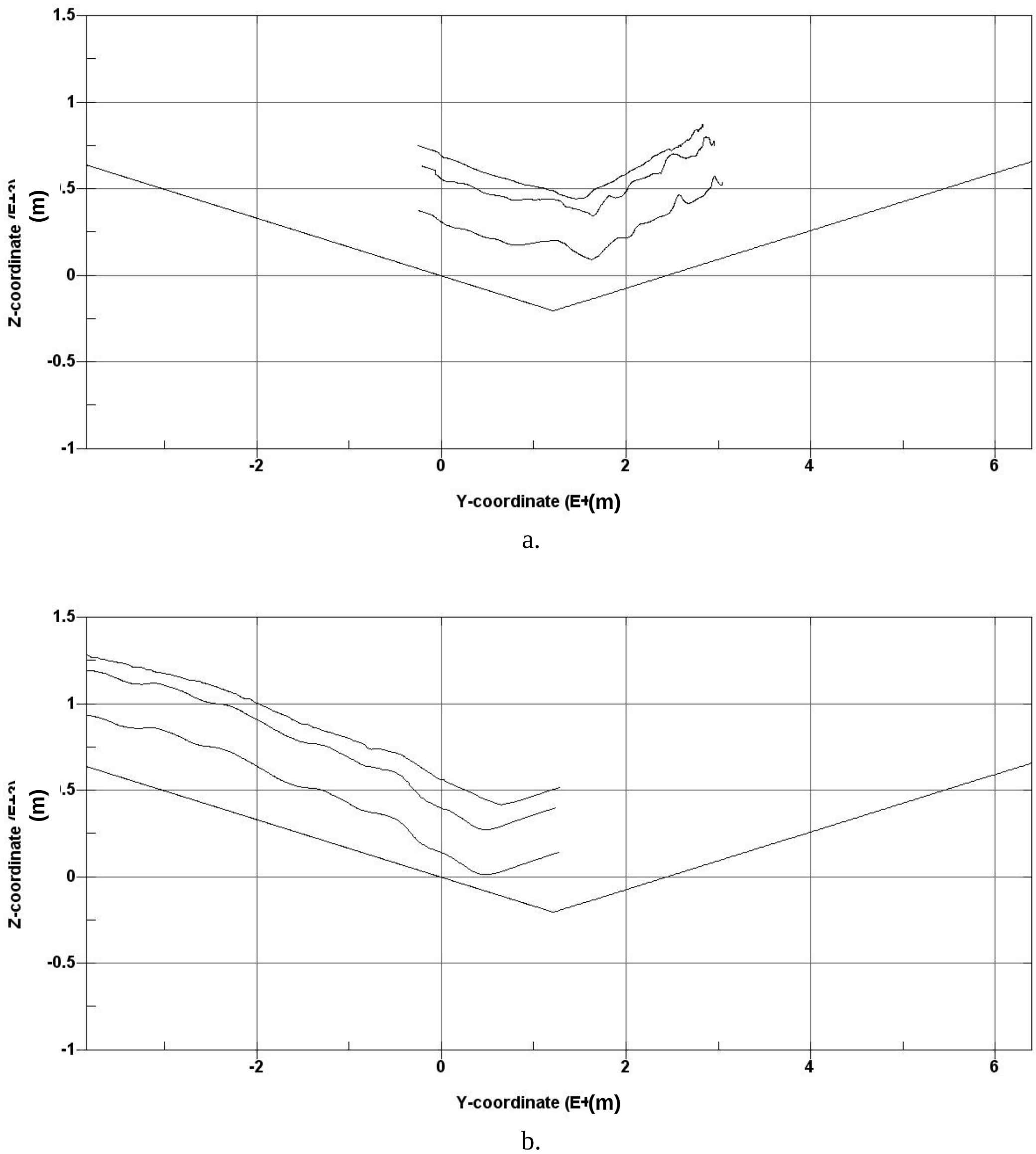


Fig. 3.23: Vehicle's bumper heights during impacts at 30° and 65 mph for the current design.
a. Front-side impact; and b. Back-side impact.

For a front-side impact, the bottom cable had to bend or ride up a post before it detached from it. This explained the increased redirection force of the bottom cable for front-side impacts. In contrast, the bottom cable only needed to yield a hook-bolt in a back-side impact before it detached from it; the bottom cable thus provided less redirection force.

It should be noted that the simulation results only served as a means of finding potential improvements on the current design to prevent under-riding of small vehicles. Since the results were based on a vehicle model that was smaller and had a lower profile than the vehicle used in the TL-3 test of the NCHRP Report 350, the results should not be used as an indication of the actual performance of the current design. The simulation results showed that cable heights affected vehicle-cable engagements and that cable and hook-bolt configurations affected the traversal displacements of the vehicle before it was redirected. Based on an analysis of simulation results, five new designs were proposed for Retrofit Option 1 and evaluated using FE simulations. In all of the five retrofit designs, the middle and bottom cables were adjusted to lower locations as shown in Table 3.1. These simulation results are presented next.

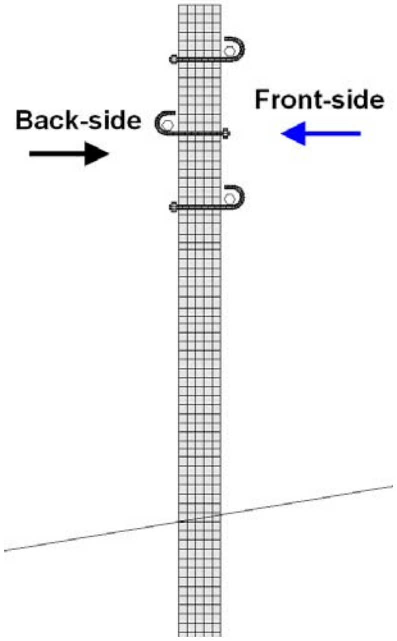


Fig. 3.24: Configurations of cables and hook-bolts in the current design.

3.5 Simulation Results of Retrofit Option 1

The goal of retrofitting the current CMB design was to prevent potential under-riding of small vehicles. In Retrofit Option 1, the middle and bottom cables in the current design were lowered to increase the likelihood of engaging with small vehicles. Five retrofit designs were proposed and evaluated using FE simulations. These designs are schematically shown in Fig. 3.5 and the cable heights of the five designs are given in Table 3.1. Based on an analysis of simulation results of the five designs, a new retrofit design, the sixth design, was proposed and evaluated for Retrofit Option 1.

3.5.1 First Design

In the first retrofit design, the bottom and middle cables were lowered to 13 in (330 mm) and 20.5 in (521 mm), respectively, above grade. Simulations were performed for both front- and back-side impacts at 20°, 30°, and 40° with initial speeds of 55, 65, 70, and 75 mph (88.5, 104.6, 112.6, and 120.7 km/hr). The results of cable-vehicle engagements are summarized in Table 3.4. Figures 3.25, 3.26, and 3.27 show the simulation results for front-side impacts at an initial speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. Figures 3.28, 3.29, and 3.30 show the simulation results for back-side impacts at an initial speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. The results showed that the first retrofit design performed better in 20° and 30° back-side impacts but worse in 40° front-side impacts than the current design. It had similar performance for all other impact scenarios in terms of cable-vehicle engagement.

Table 3.4: FE simulation results of the first design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75

Front	20	RD (U, E, O)	RD (SU, E, O)	RD (U, E, O)	RD (SU, E, O)
	30	RD (U, E, O)	RD (SU, E, O)	RD (SU, E, O)	RD_S (SU, E, O)
	40	RD_S (SU, E, O)	RD_O (SU, E, O)	RD_O (SU, E, O)	RD_O (SU, E, O)
Back	20	RD (U, E, O)	RD (U, E, O)	RD (U, E, O)	RD (U, E, O)
	30	RD (SU, E, O)	RD (E, E, O)	RD_O (E, O, O)	RD_O (E, O, O)
	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

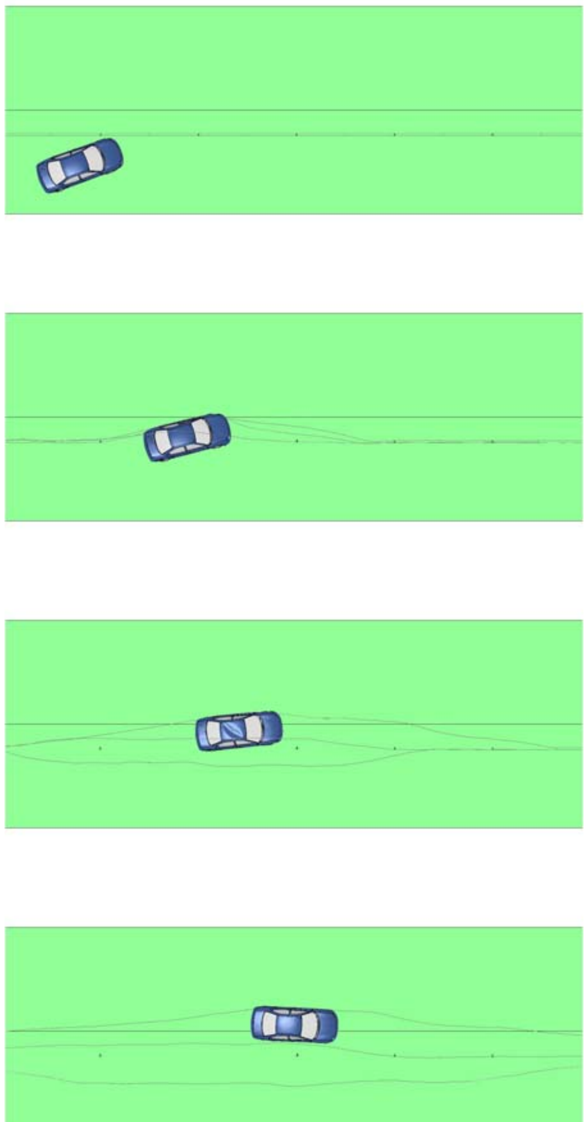


Fig. 3.25: Front-side impact by Dodge Neon at 20° and 65 mph for the first design of Retrofit Option 1.

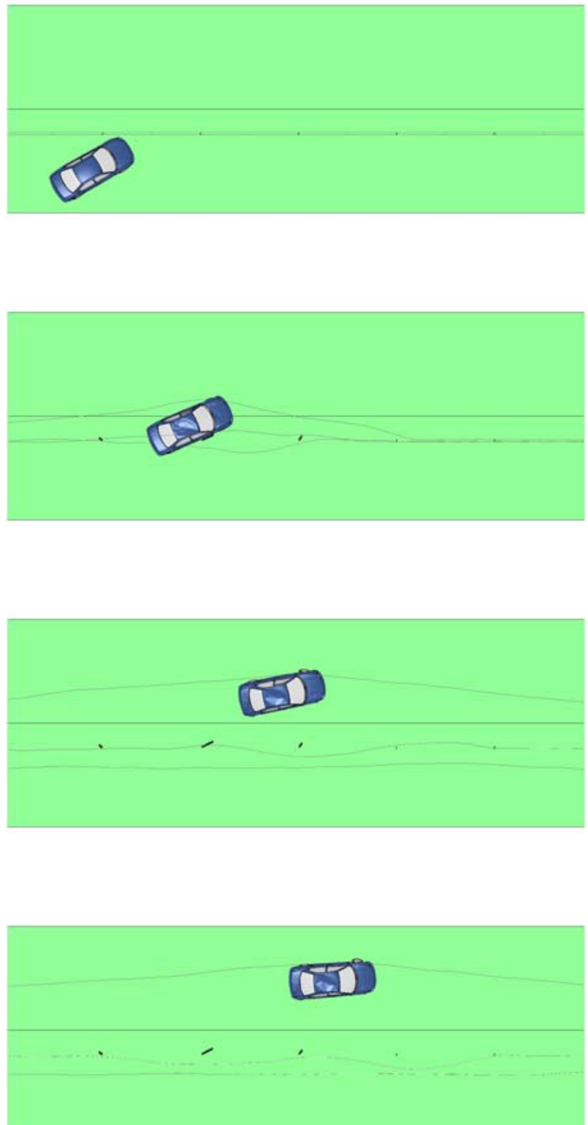


Fig. 3.26: Front-side impact by Dodge Neon at 30° and 65 mph for the first design of Retrofit Option 1.

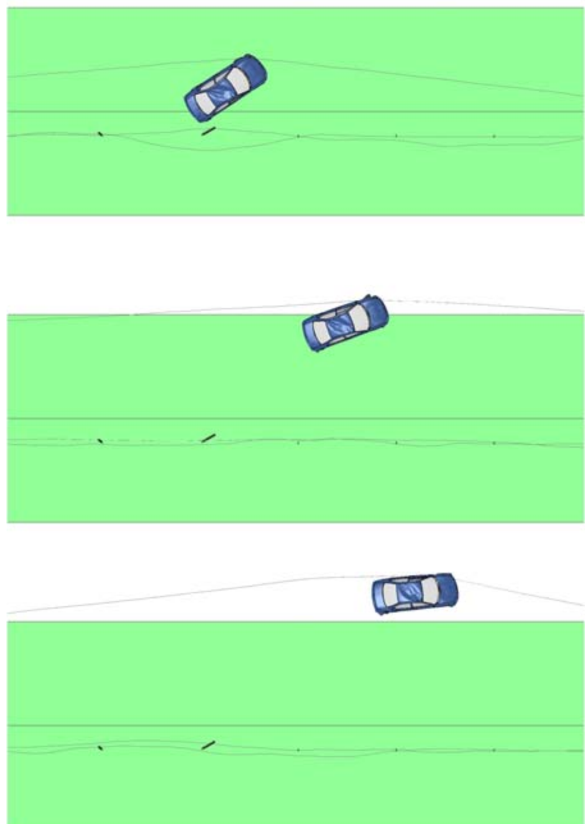
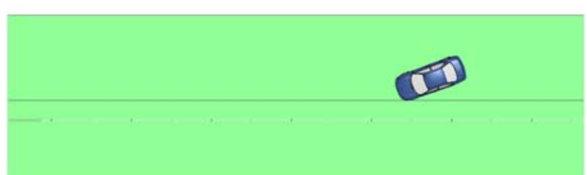


Fig. 3.27: Front-side impact by Dodge Neon at 40° and 65 mph for the first design of Retrofit Option 1.

For front-side impacts, the bottom cable of the first retrofit design did not fully engage with the vehicle during the entire crash event; the vehicle's suspension was not compressed upon impacting the CMB. As a result, the bottom cable slid down and was overridden by the vehicle. For small angle impacts, i.e., 20° and 30°, the engagement with the middle cable was able to redirect the vehicle within the median. For 40° impacts, however, the middle cable was not able to redirect the vehicle within the median due to the increased impact severity. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.



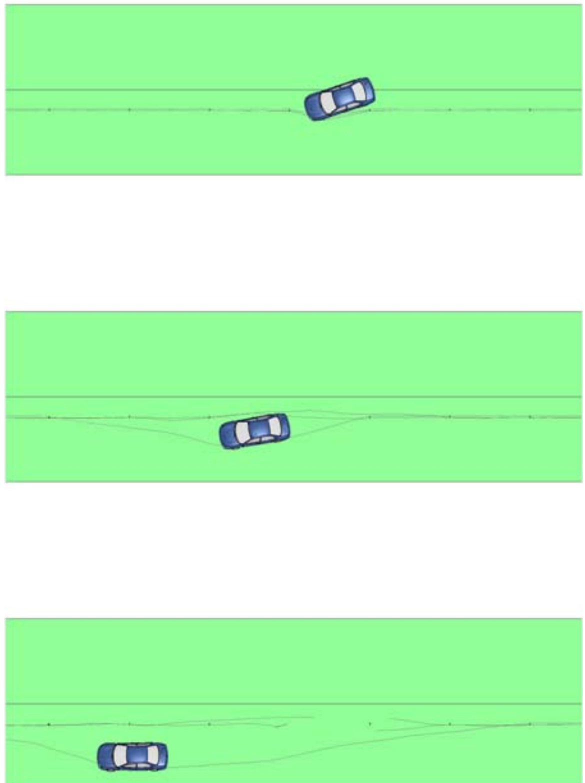
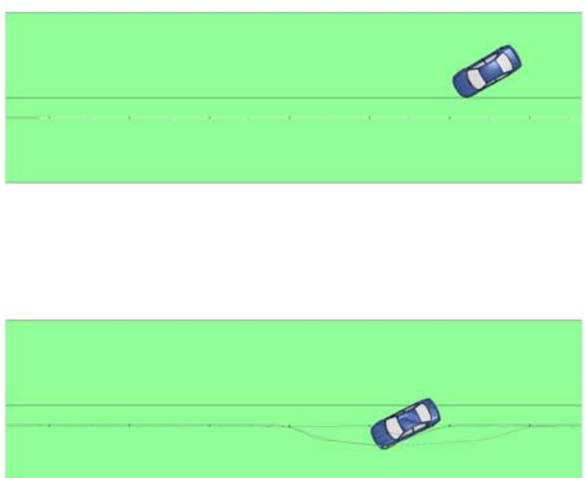


Fig. 3.28: Back-side impact by Dodge Neon at 20° and 65 mph for the first design of Retrofit Option 1.



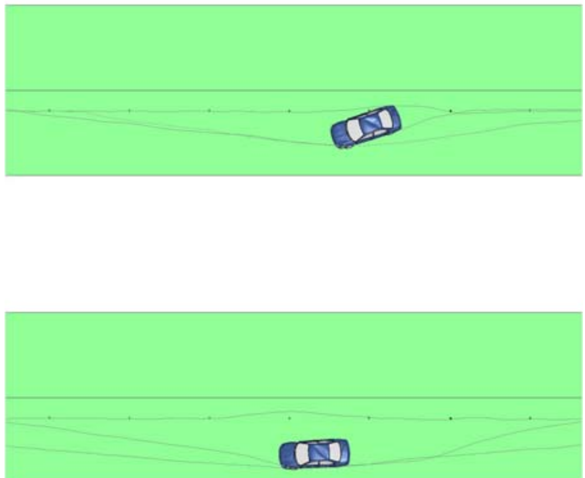
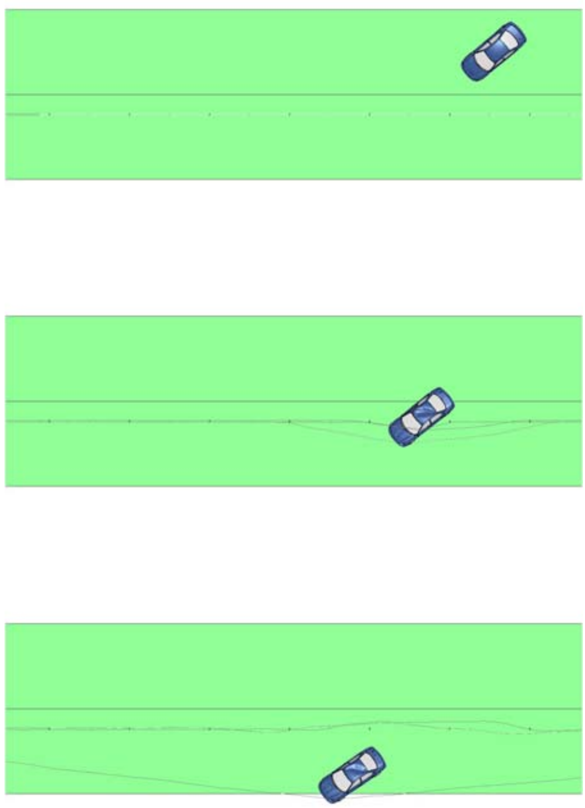


Fig. 3.29: Back-side impact by Dodge Neon at 30° and 65 mph for the first design of Retrofit Option 1.



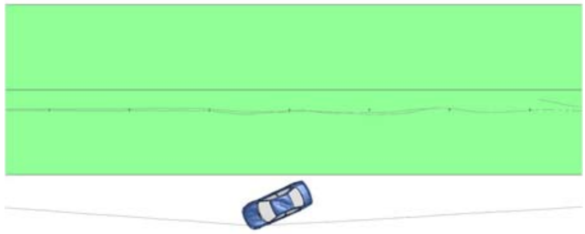


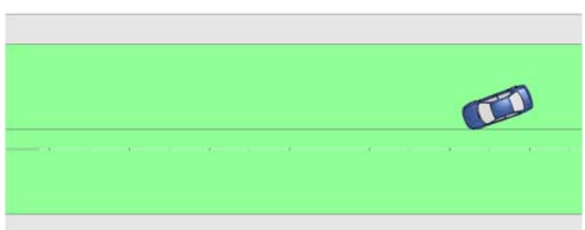
Fig. 3.30: Back-side impact by Dodge Neon at 40° and 65 mph for the first design of Retrofit Option 1.

3.5.2 Second Design

In the second retrofit design, both the bottom and middle cables were higher than those in the first design. Simulations were performed for back-side impacts at all four speeds with impact angles of 20°, 30°, and 40°. The results of cable-vehicle engagement are given in Table 3.5. Figures 3.31, 3.32, and 3.33 show the simulation results for an initial vehicle speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively. It can be seen that the change of cable heights affected the cable-vehicle engagement for the 20° and 30° impacts, but the overall CMB performance was worse than the first design. The second design did not show improvement on the current design in back-side impacts; therefore, simulations of front-side impacts were not performed for the second design.

Table 3.5: FE simulation results of the second design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Back	20	RD (SU, E, O)	RD (SU, E, O)	RD (U, E, E)	RD (U, E, E)
	30	PT (SU, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)
	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)



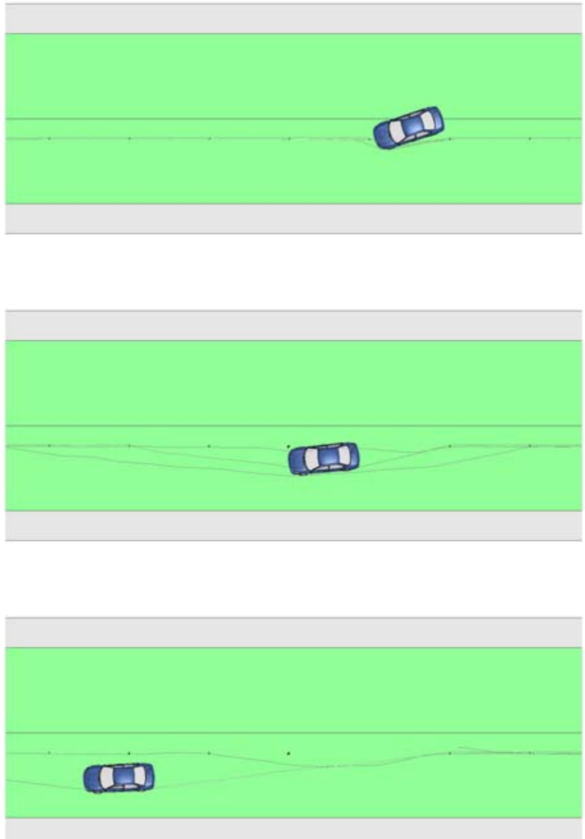


Fig. 3.31: Back-side impact by Dodge Neon at 20° and 65 mph for the second design of Retrofit Option 1.

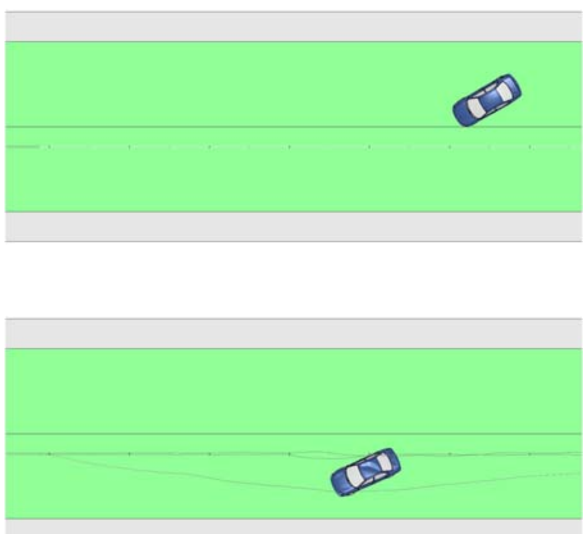
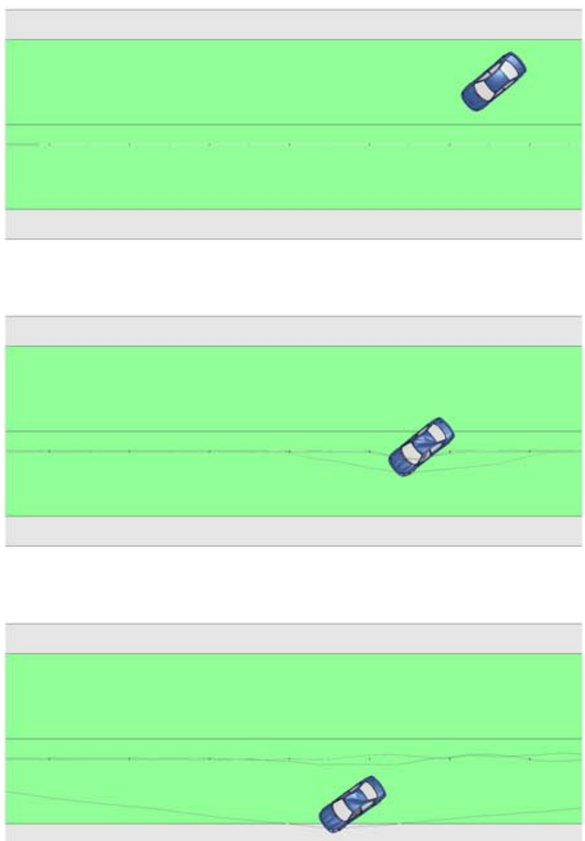


Fig. 3.32: Back-side impact by Dodge Neon at 30° and 65 mph for the second design of Retrofit Option 1.



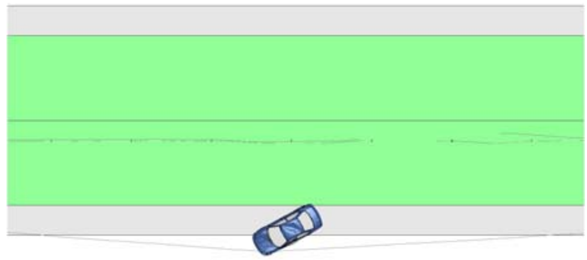


Fig. 3.33: Back-side impact by Dodge Neon at 40° and 65 mph for the second design of Retrofit Option 1.

3.5.3 Third Design

For the first two retrofit designs, the bottom cables were found to be overridden by the vehicle in some front- and back-side impacts. In the third design, the bottom cable was set higher and the middle cable was set lower than the second design. The results of cable-vehicle engagement for both front- and back-side impacts are summarized in Table 3.6.

Table 3.6: FE simulation results of the third design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Front	20	RD (SU, E, O)	RD (SU, E, O)	RD (SU, E, O)	RD (SU, E, O)
	30	RD (SU, E, O)	RD (SU, E, O)	RD (SU, E, O)	RD (SU, E, O)
	40	RD (U, E, O)	RD_O (SU, E, O)	RD_O (U, E, O)	RD_O (SU, E, O)
Back	20	RD (SU, E, O)	RD (SU, E, O)	RD (U, E, O)	RD (U, E, E)
	30	RD (E, E, O)	RD (E, E, O)	RD_S (E, E, O)	RD_S (E, E, O)
	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

Compared to the current design, the third design showed better performance in back-side impacts. This was due to the engagement with the middle cable that had the same height above grade as the bottom cable of the current design. The middle cable in the third design was on the side facing the back-side impacts and thus provided more resistance due to bearing against the posts. In all of the front-side impacts, the bottom cable could not fully engage with the vehicle; redirection of the vehicle relied predominantly on the resistance provided by the middle cable. Consequently, the CMB failed in redirecting the vehicle within the median for those severe impacts, i.e. 40° impacts with vehicle speeds of 65, 70, and 75 mph (104.6, 112.6, and 120.7 km/hr). Nevertheless, the third design was shown to perform better than the first two designs and provided valuable insights on the relationship of cable heights and cable-vehicle engagements.

Figures 3.34 to 3.36 show the simulation results for front-side impacts at an initial speed of 65 mph (104.6 km/hr)with impact angles of 20°, 30°, and 40°, respectively. Figures 3.37 to 3.39 show the simulation results for back-side impacts under the same impact conditions. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.

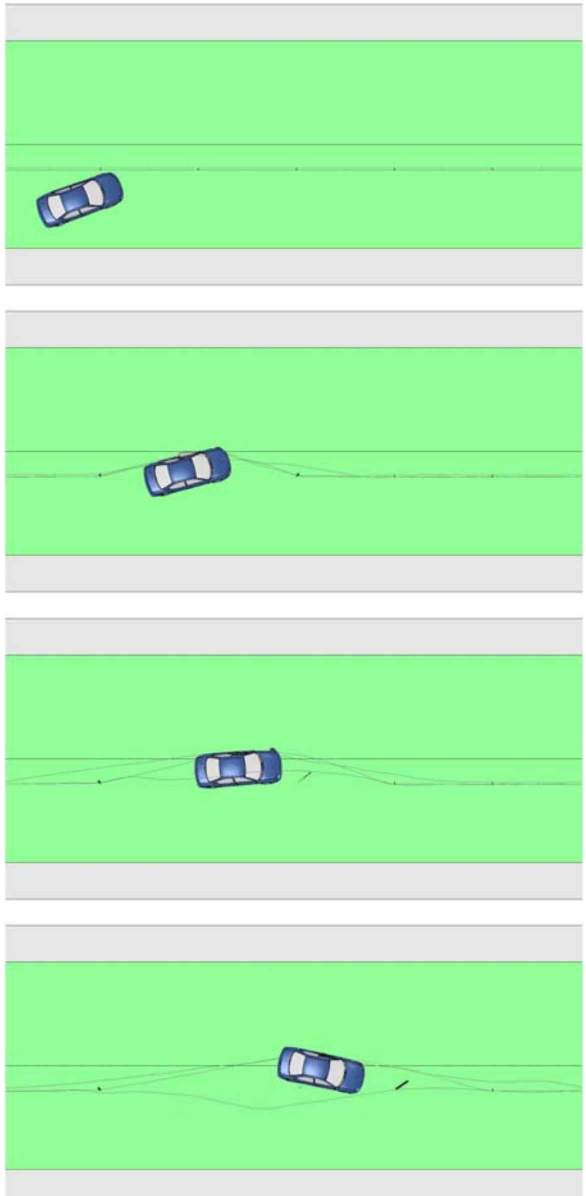
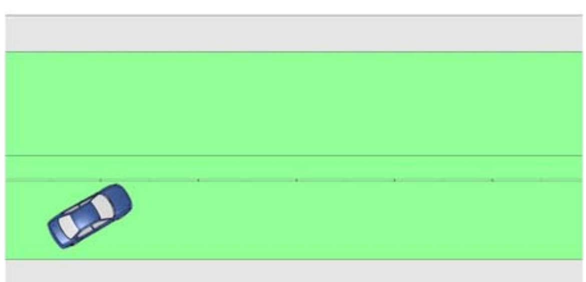


Fig. 3.34: Front-side impact by Dodge Neon at 20° and 65 mph for the third design of Retrofit Option 1.



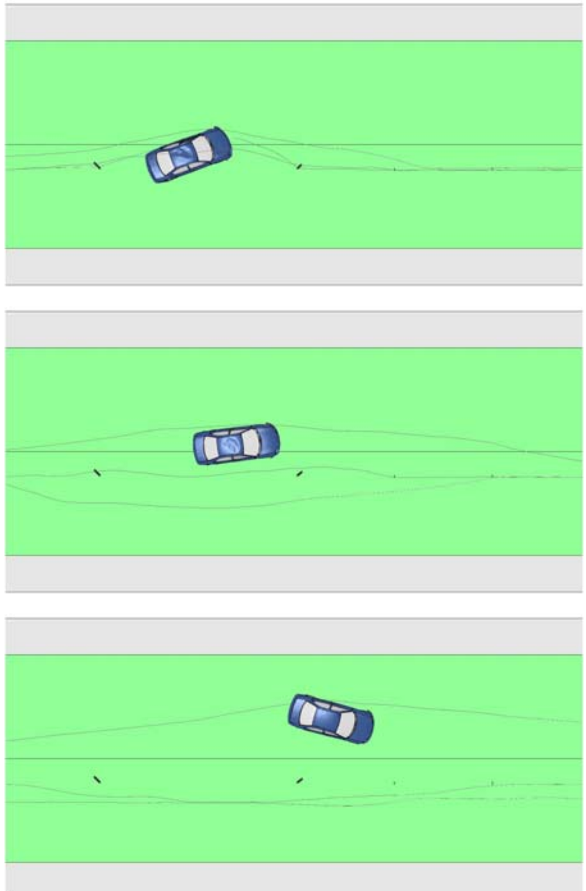
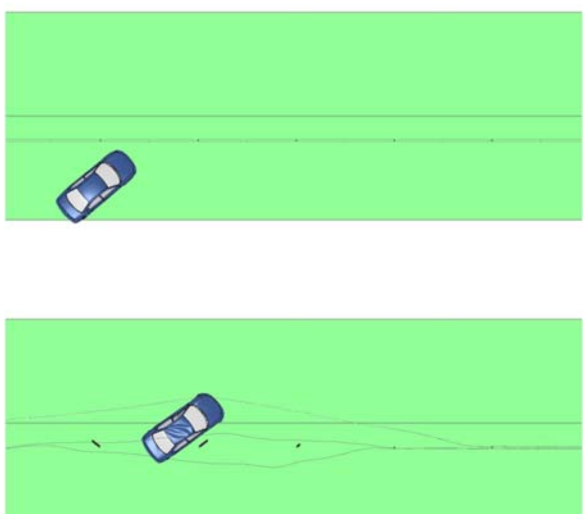


Fig. 3.35: Front-side impact by Dodge Neon at 30° and 65 mph for the third design of Retrofit Option 1.



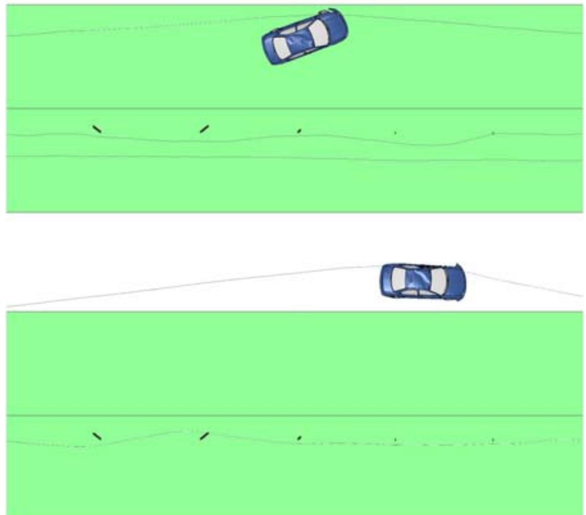
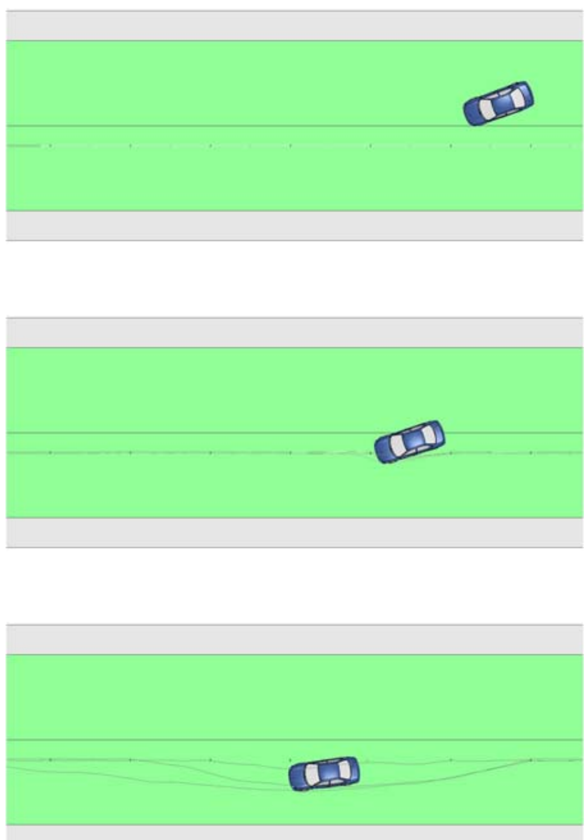


Fig. 3.36: Front-side impact by Dodge Neon at 40° and 65 mph for the third design of Retrofit Option 1.



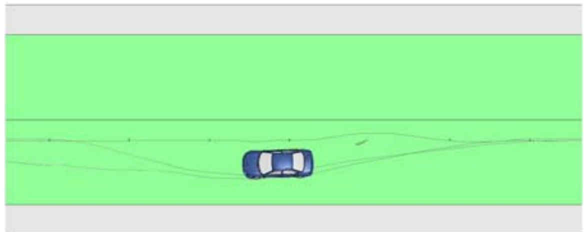


Fig. 3.37: Back-side impact by Dodge Neon at 20° and 65 mph for the third design of Retrofit Option 1.

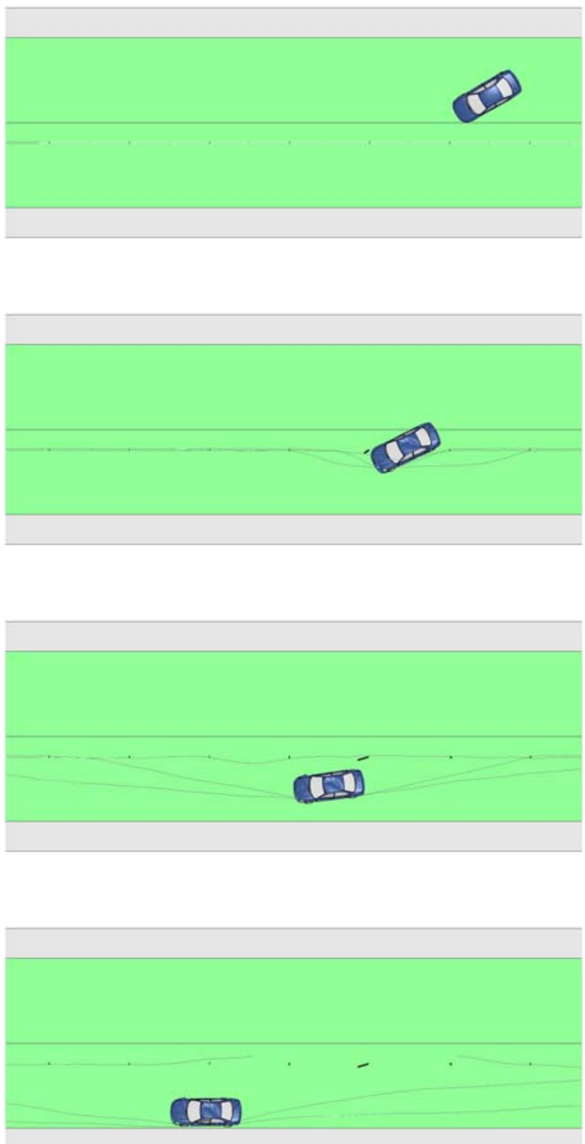


Fig. 3.38: Back-side impact by Dodge Neon at 30° and 65 mph for the third design of Retrofit Option 1.

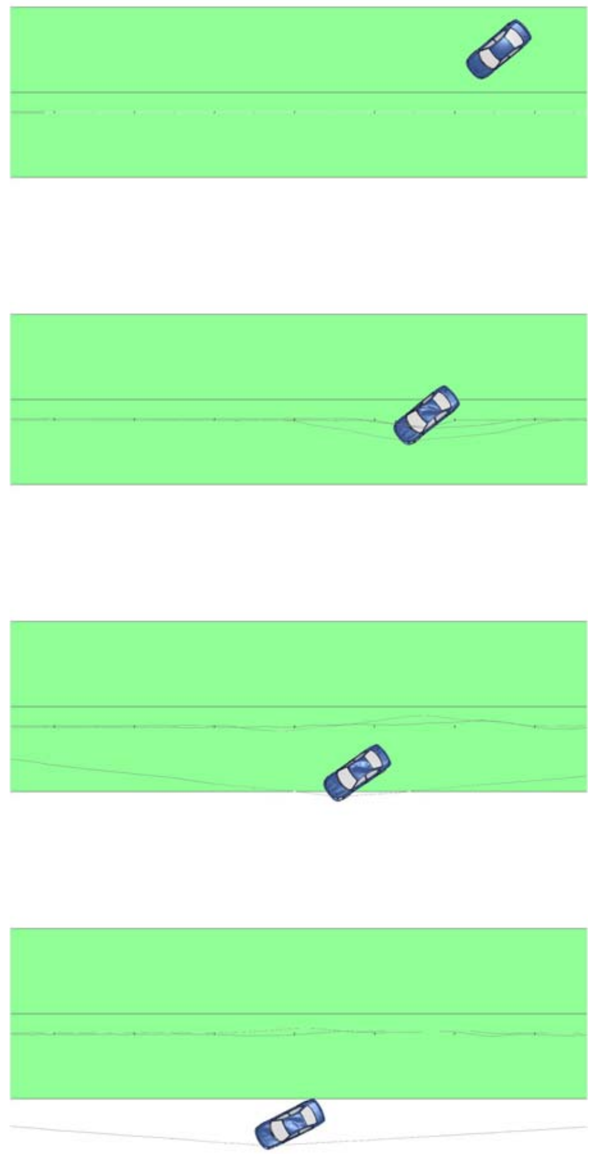


Fig. 3.39: Back-side impact by Dodge Neon at 40° and 65 mph for the third design of Retrofit Option 1.

3.5.4 Fourth Design

The fourth design differed from the third design only in the middle cable, which was two inches higher in the fourth design. Table 3.7 summarizes the cable-vehicle engagements for back-side impacts. Similar to the third design, the bottom cable was not engaged with the vehicle for all 20° impacts. For 30° and 40° impacts, the CMB did not redirect the vehicle within the grassy median even though the bottom cable was engaged. Figures 3.40, 3.41, and 3.42 show the simulation results for back-side impacts at 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.

Table 3.7: FE simulation results of the fourth design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Back	20	RD (SU, E, O)	RD (SU, E, O)	RD (U, E, E) / PT (U, O, O)*	RD (U, E, E) / PT (U, O, O)*
	30	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)
	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

* The vehicle was redirected when impacting the post first; the vehicle penetrated the CMB if it impacted the cables midway between the two posts.

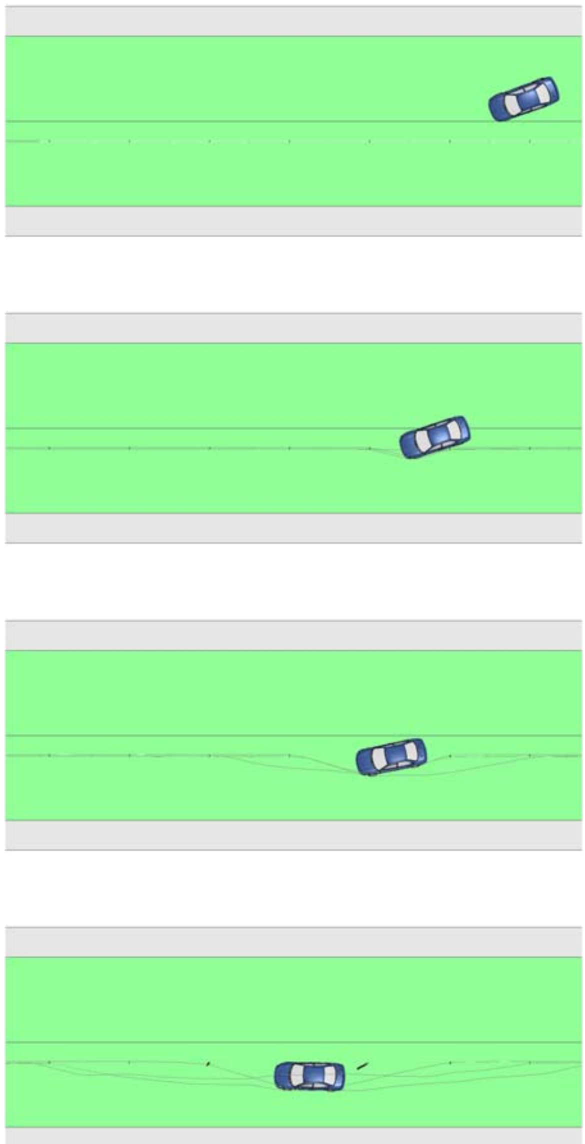


Fig. 3.40: Back-side impact by Dodge Neon at 20° and 65 mph for the fourth design of Retrofit Option 1.

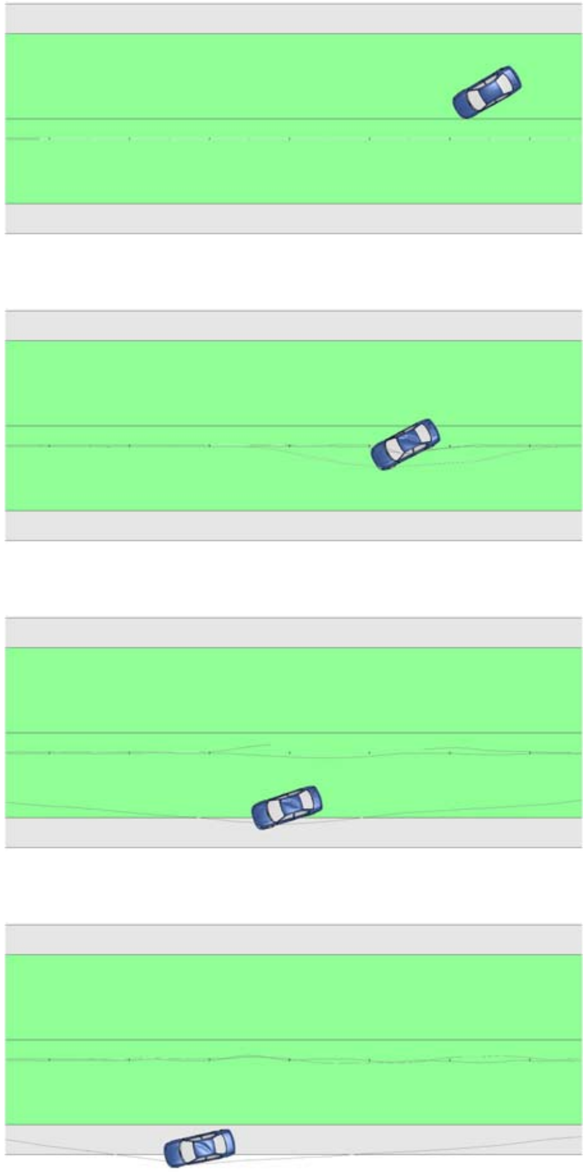
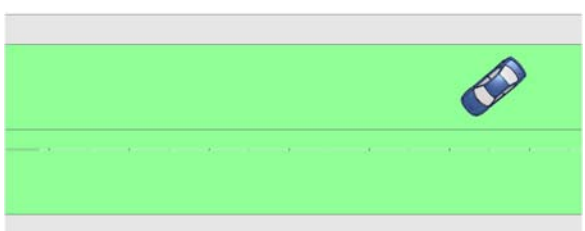


Fig. 3.41: Back-side impact by Dodge Neon at 30° and 65 mph for the fourth design of Retrofit Option 1.



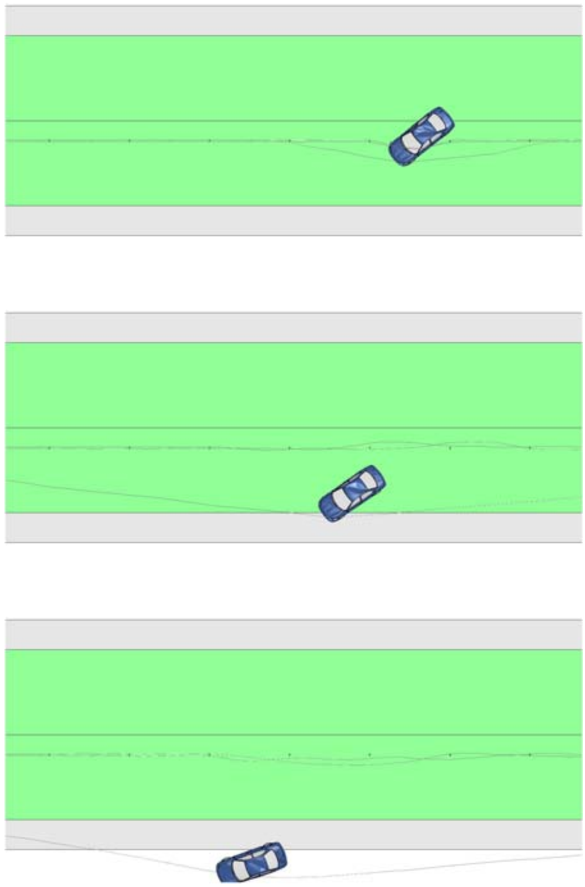


Fig. 3.42: Back-side impact by Dodge Neon at 40° and 65 mph for the fourth design of Retrofit Option 1.

For the 20° impact at 70 mph (112.6 km/hr), the simulation results showed that the vehicle did not engage with any of the three cables when it impacted the cables midway between the two posts. A simulation was then performed by changing the initial impact point to a post while maintaining the same impact speed and angle. The results showed that the vehicle engaged with the middle and top cables and was redirected within the median. This demonstrated that in addition to impact speed and impact angle the initial impact point could affect cable-vehicle engagement. Under certain impact and site conditions, the vehicle could under-ride the CMB without engaging with any of the cables. This scenario was supported by the NCDOT crash data in Tables 2.1 and 2.2. Simulations of front-side impacts were not performed for this design due to its unsatisfactory performance for back-side impacts.

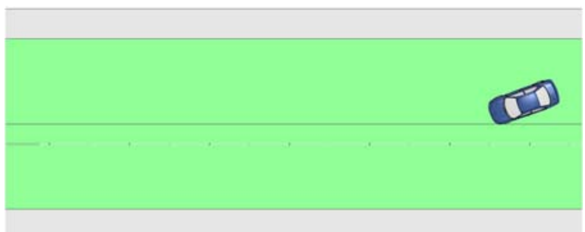
3.5.5 Fifth Design

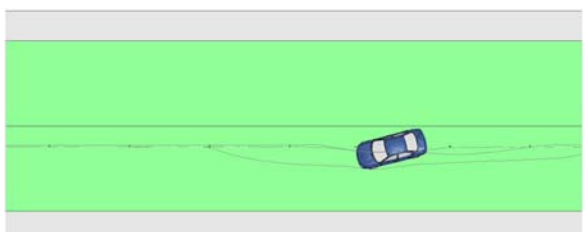
In the fifth design, the bottom cable was two inches higher and the middle cable was one inch higher than the fourth design. The results of cable-vehicle engagement for back-side impacts are summarized in Table 3.8.

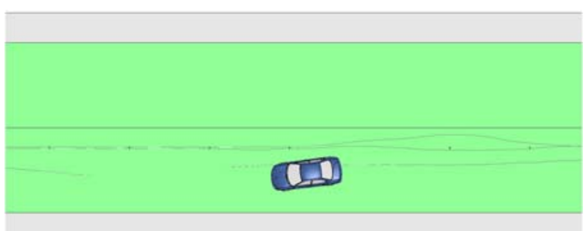
Table 3.8: FE simulation results of the fifth design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Back	20	RD_S (SU, O, O)	PT (U, O, O)	RD_O (SU, O, O)	RD_O (E, O, O)
	30	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)
	40	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)	RD_O (E, O, O)

It was observed that this design did not show any improvement over the current design for back-side impacts. Therefore, this design was not evaluated for front-side impacts. Figures 3.43, 3.44, and 3.45 show the simulation results for back-side impacts at an initial speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.







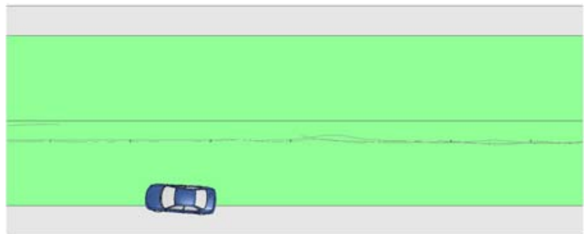


Fig. 3.43: Back-side impact by Dodge Neon at 20° and 65 mph for the fifth design of Retrofit Option 1.

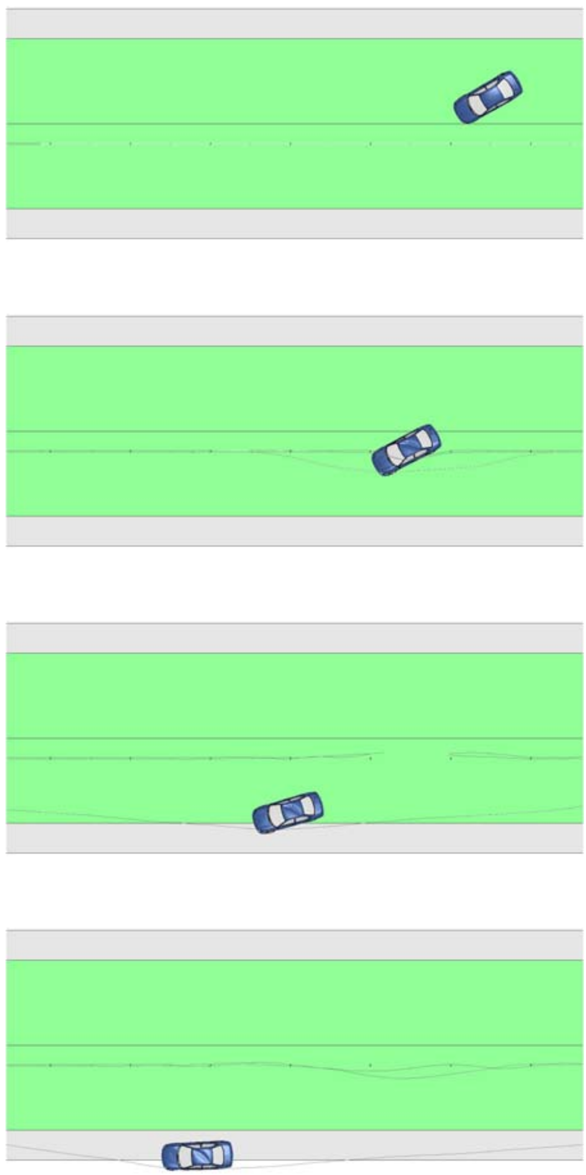


Fig. 3.44: Back-side impact by Dodge Neon at 30° and 65 mph for the fifth design of Retrofit Option 1.

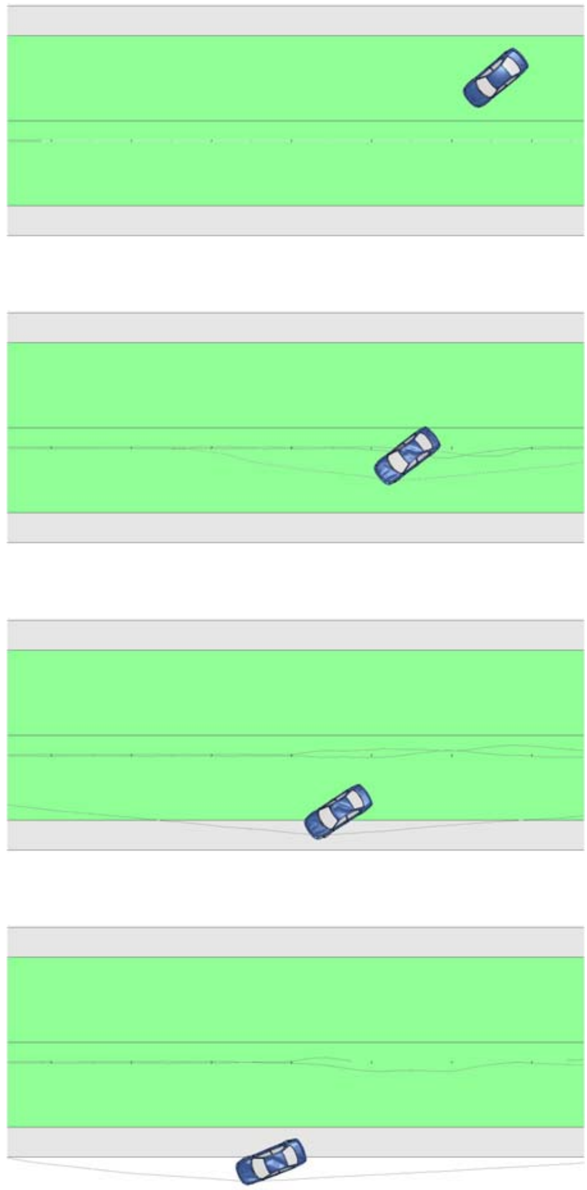


Fig. 3.45: Back-side impact by Dodge Neon at 40° and 65 mph for the fifth design of Retrofit Option 1.

3.5.6 A New Retrofit Design (Sixth Design)

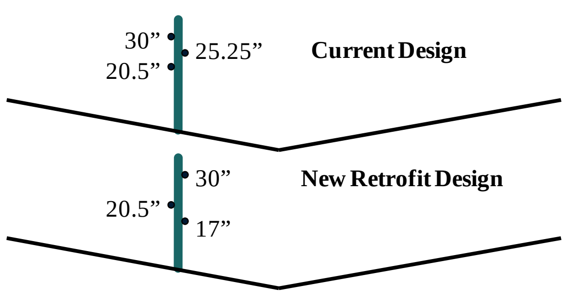
Among the five retrofit designs, the third design was found to give the best performance in back-side impacts. Compared to the current design, the third design most significantly improved the CMB's performance in back-side impacts at 30°. For front-side impacts, however, it performed worse than the current design for 40° impacts at 65, 70, and 75 mph (104.6, 112.6, and 120.7 km/hr).

Although none of the five retrofit designs gave overall improvement compared to the current design, the simulation results confirmed that cable-vehicle engagement was affected by cable heights. An analysis was thus performed on the relationship of cable engagement and cable heights using the aggregate simulation results of the current design and the five retrofit designs. Table 3.9 gives a summary of cable engagements for all simulation scenarios.

Table 3.9: Cable engagements in relation to cable heights in the current and five retrofit designs

Front-side Impacts										
Impact Angle (°)	Cable Height (in.)									
	13.0	14.0	15.0	17.0	20.5	22.0	22.5	23.5	25.25	30
20	SU/U		SU		E				O	O
30	SU/U		SU		E				E	O
40	SU		SU/U		E				E	O
Back-side Impacts										
Impact Angle (°)	Cable Height (in.)									
	13.0	14.0	15.0	17.0	20.5	22.0	22.5	23.5	25.25	30
20	U	SU/U	SU/U	SU/U/E	E	E	E/O	O	O	O
30	SU/E	SU/E	E	E	E/O	O	O	O	O	O
40	E	E	E	E	E/O	O	O	O	O	O

The results in Table 3.9 showed that the cable was unlikely to fully engage with the vehicle in a front-side impact if its height was 15 in. (381 mm) or lower. For back-side impacts, it was preferred that the cable height was 17 in. (432 mm) or higher so as to become engaged at all impact angles. It was also observed that a cable at 20.5 in. (521 mm), which was the height of the bottom cable in the current design, was likely to engage with the vehicle in both front- and back-side impacts. Based on the above analysis, a new retrofit design was proposed and evaluated. This new design was referred to as the <u>sixth design of Retrofit Option 1</u> as schematically shown in Fig. 3.46b relative to the current design (Fig. 3.46a).



a. b.

Fig. 3.46: Cable heights and placement of the sixth retrofit design in comparison with the current design. a. Current design; and b. the sixth retrofit design.

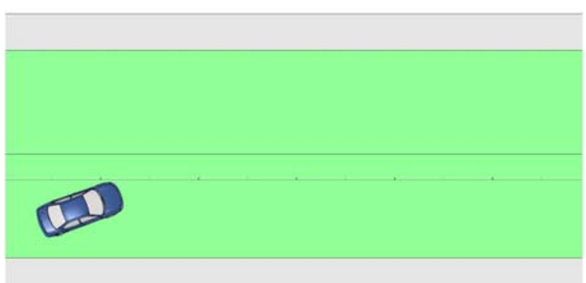
In the sixth retrofit design, the bottom and middle cables were located at 17 in. (432 mm) and 20.5 in. (521 mm), respectively, above grade. A major difference of the sixth design from all other designs was that the three cables were on the opposite sides of the posts. This change utilized post bearing to enhance cable resistance and reduce the traversal displacements of the vehicle being redirected. A cable on the side of a post facing the impacting vehicle was termed a “strong cable” because it provided more resistance due to post bearing. In the sixth design, the top and bottom cables were strong cables for back-side impacts, while the middle cable was the strong cable for front-side impacts. As implied in Table 3.9, the sixth design was expected to lead to more effective cable-vehicle engagements for both front- and back-side impacts.

Simulations of both front- and back-side impacts were performed for the sixth design. The results of cable-vehicle engagement are given in Table 3.10. The sixth design showed the same performance as the current design for front-side impacts. The middle cable of the sixth design had the same height as the bottom cable of the current design and it was engaged with the vehicle for all front-side impacts. For back-side impacts, both the bottom and middle cables were engaged with the vehicle. Consequently, the CMB redirected the vehicle within the median for all back-side impacts. Only for the 40° impacts at 65, 70, and 75 mph (104.6, 112.6, and 120.7 km/hr), did the CMB safely redirect the vehicle on the shoulder of the 46-ft (14 m) median.

Table 3.10: FE simulation results of the sixth design of Retrofit Option 1 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Front	20	RD (SU, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
	30	RD (SU, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
	40	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
Back	20	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
	30	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)	RD (E, E, O)
	40	RD (E, E, O)	RD_S (E, E, O)	RD_S (E, E, O)	RD_S (E, E, O)

Figures 3.47, 3.48, and 3.49 show the simulation results for front-side impacts at an initial speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. Figure 3.50 shows the traversal displacement time histories of the front and rear ends of the vehicle for a front-side impact of 30° and 65 mph (104.6 km/hr).



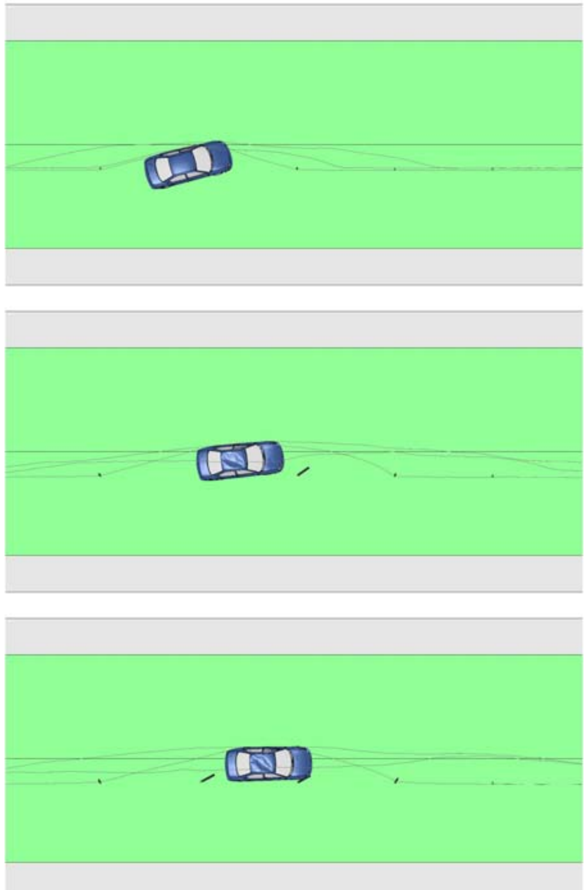
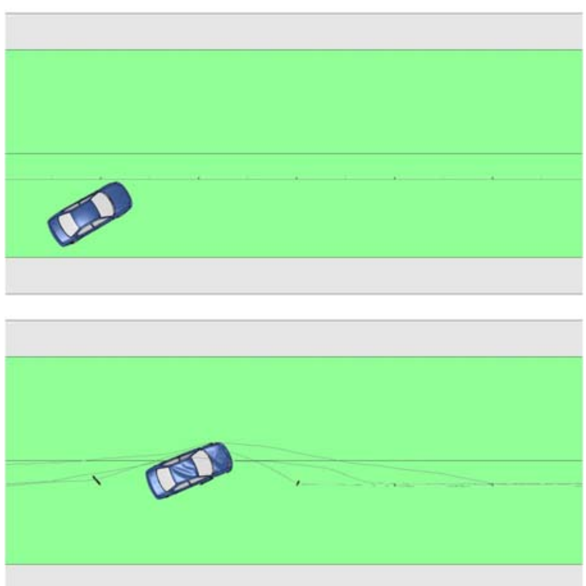


Fig. 3.47: Front-side impact by Dodge Neon at 20° and 65 mph for the sixth design of Retrofit Option 1.



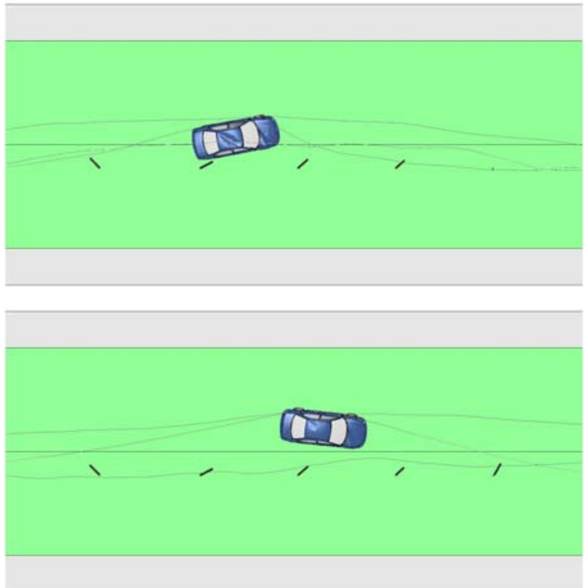
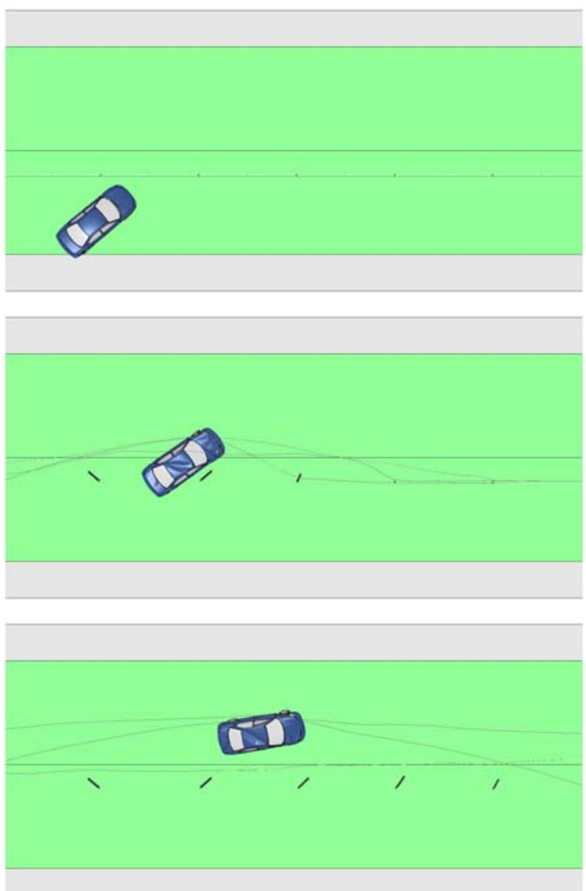


Fig. 3.48: Front-side impact by Dodge Neon at 30° and 65 mph for the sixth design of Retrofit Option 1.



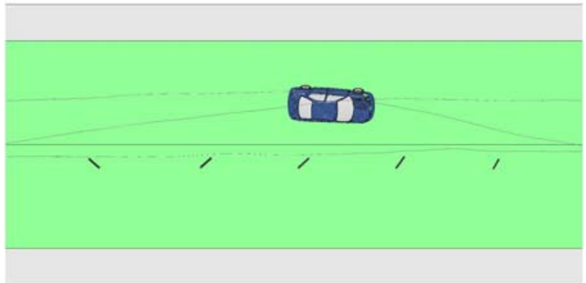


Fig. 3.49: Front-side impact by Dodge Neon at 40° and 65 mph for the sixth design of Retrofit Option 1.

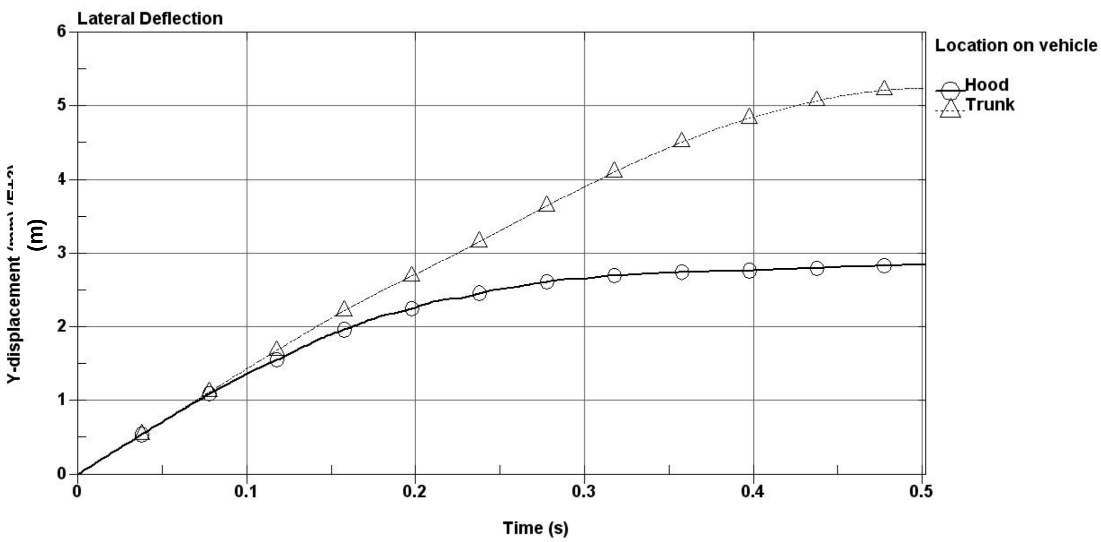
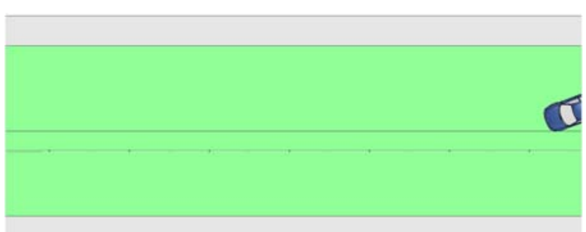


Fig. 3.50: Vehicle's traversal displacements in front-side impact at 30° and 65 mph.

Figures 3.51, 3.52, and 3.53 show the simulation results for back-side impacts at an initial speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. Figure 3.54 shows the traversal displacement time histories of the front and rear ends of the vehicle for a back-side impact of 30° and 65 mph (104.6 km/hr). The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.



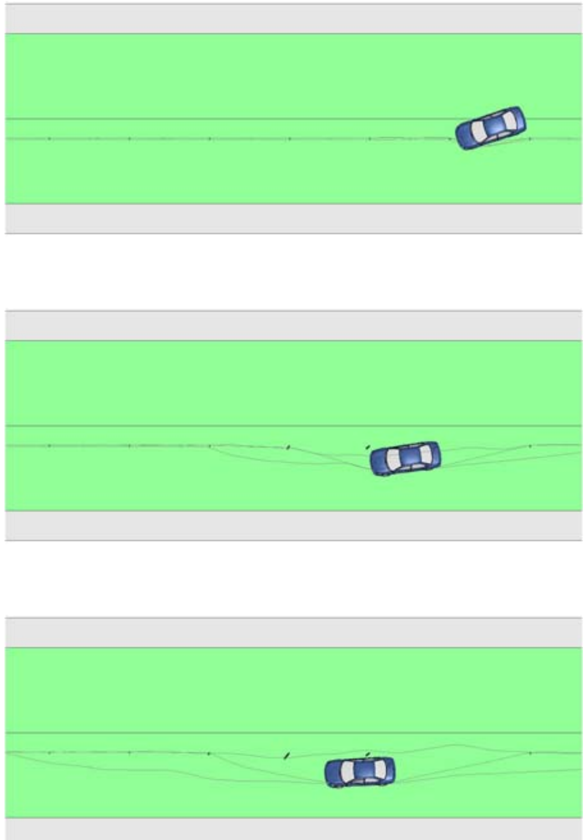
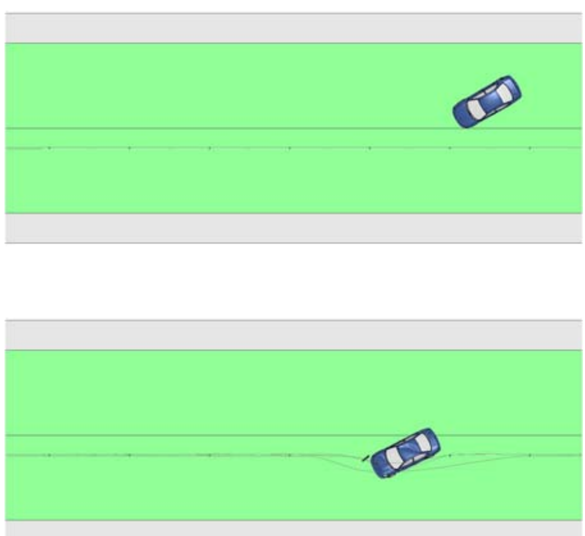


Fig. 3.51: Back-side impact by Dodge Neon at 20° and 65 mph for the sixth design of Retrofit Option 1.



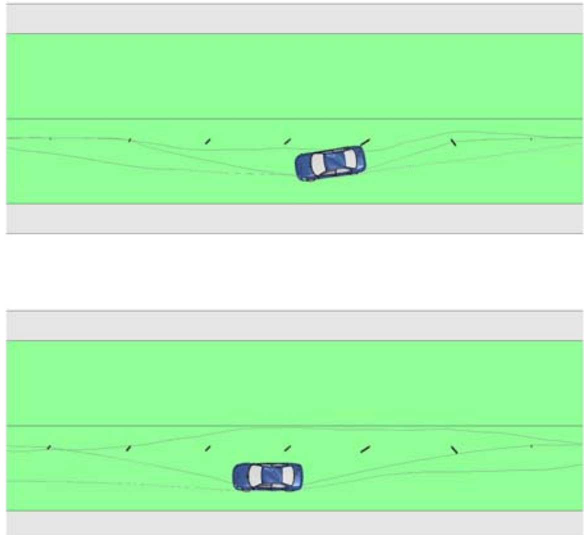
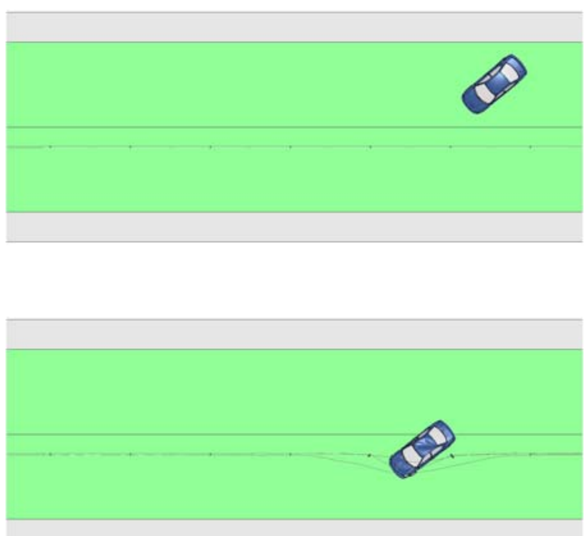


Fig. 3.52: Back-side impact by Dodge Neon at 30° and 65 mph for the sixth design of Retrofit Option 1.

The sixth design was also evaluated using a large vehicle model, a Ford F250 (Fig. 3.8), to investigate potential changes in the performance of the CMB when impacted by a large vehicle. It should be noted that this vehicle model was 1.5 times heavier than the TL-3 test vehicle used in the NCHRP Report 350. Therefore, the simulation results using the Ford F250 should not be used to determine the safety performance of the CMB as set out in the NCHRP Report 350.



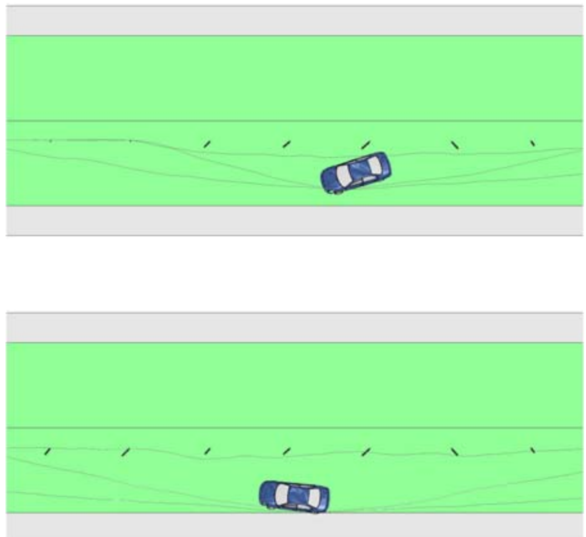


Fig. 3.53: Back-side impact by Dodge Neon at 40° and 65 mph for the sixth design of Retrofit Option 1.

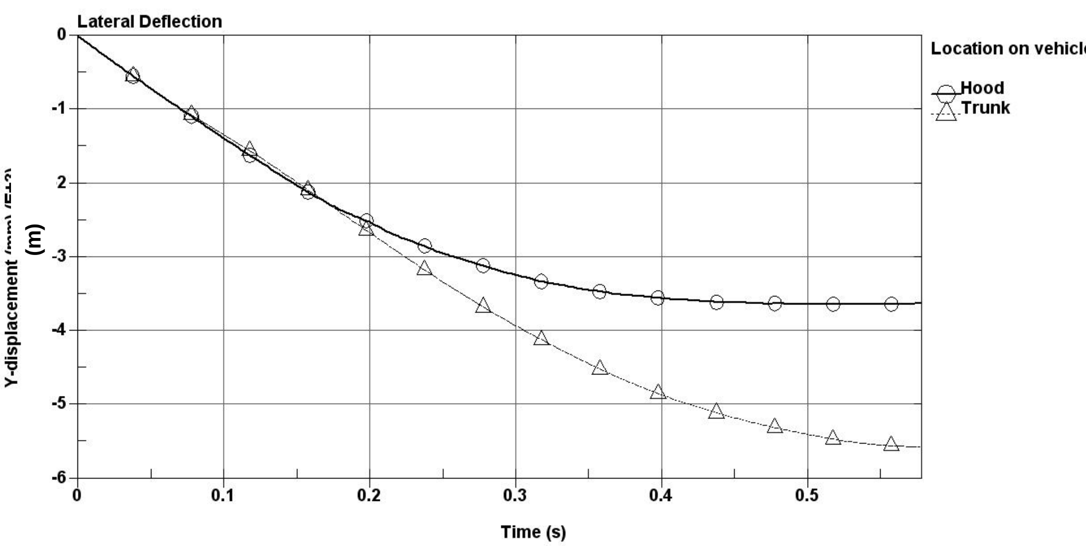


Fig. 3.54: Vehicle’s traversal displacements in back-side impact at 30° and 65 mph.

Table 3.11 summarizes the cable-vehicle engagements for the sixth design in front- and back-side impacts using the Ford F250 model. The CMB performance was as expected for all of the cases except for the 20° front-side impact at 70 mph (112.6 km/hr). In this case, the middle cable was not engaged with the vehicle and the top cable, though engaged, could not fully redirect the vehicle within the median due to the vehicle’s large mass and high speed. For 40° impacts at high speeds, the CMB was unable to redirect the vehicle within the median even though all three cables were engaged. Figures 3.55 to 3.60 show the simulation results for front- and back-side impacts at an initial vehicle speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.

Table 3.11: FE simulation results of the sixth design of Retrofit Option 1 impacted by Ford F250

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Front	20	RD (U, U, E)	RD (U, U, E)	RD_O (U, U, E)	RD (U, E, E)
	30	RD (U, E, E)	RD (U, E, E)	RD_S (U, E, E)	RD_S (U, E, E)
	40	RD (E, E, E)	RD_S (E, E, E)	RD_O (E, E, E)	RD_O (E, E, E)
Back	20	RD (E, E, E)	RD (E, E, E)	RD_S (E, E, E)	RD_S (E, E, E)
	30	RD_S (E, E, E)	RD_S (E, E, E)	RD_S (E, E, E)	RD_S (E, E, E)
	40	RD_S (E, E, E)	RD_O (E, E, E)	RD_O (E, E, E)	RD_O (E, E, E)

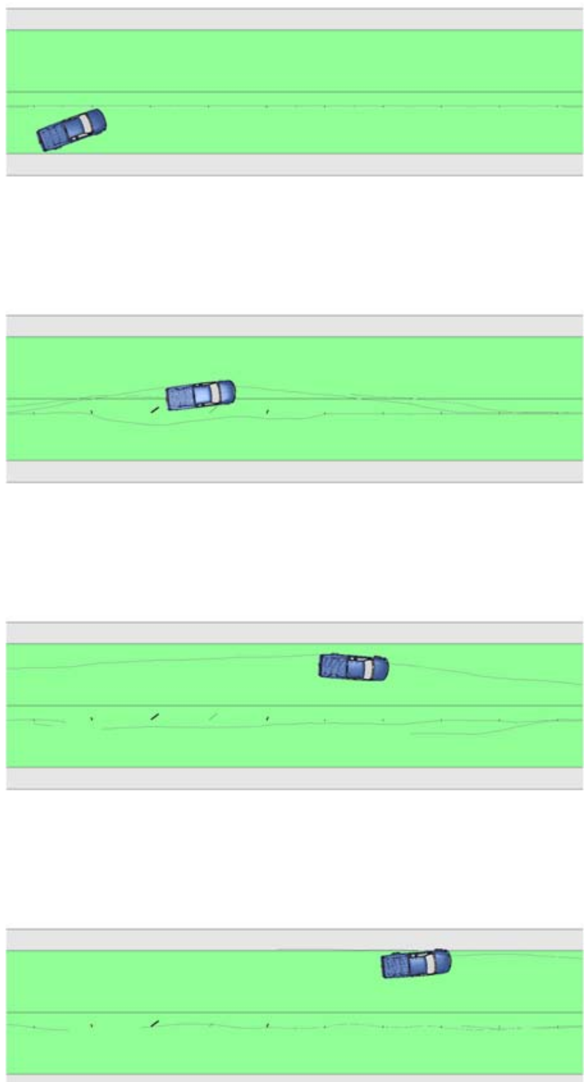


Fig. 3.55: Front-side impact by Ford F250 at 20° and 65 mph for the sixth design of Retrofit Option 1.

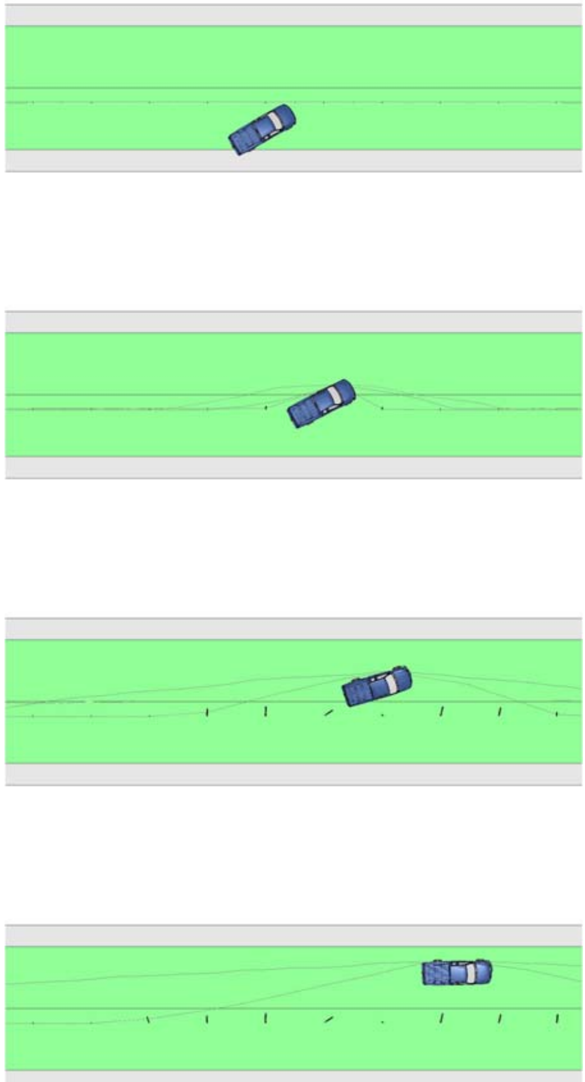
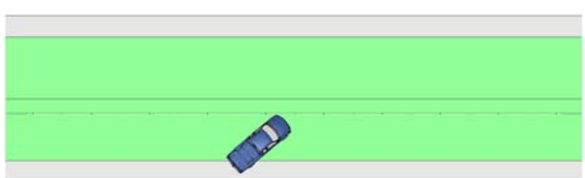


Fig. 3.56: Front-side impact by Ford F250 at 30° and 65 mph for the sixth design of Retrofit Option 1.



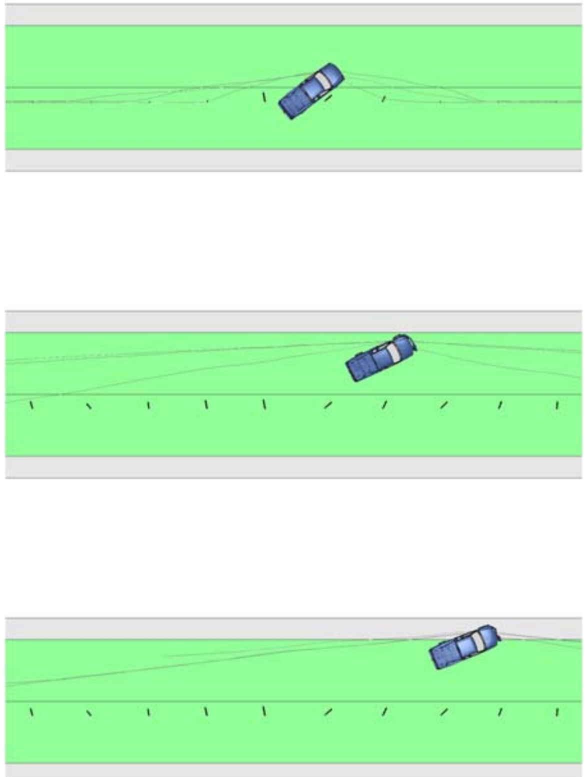
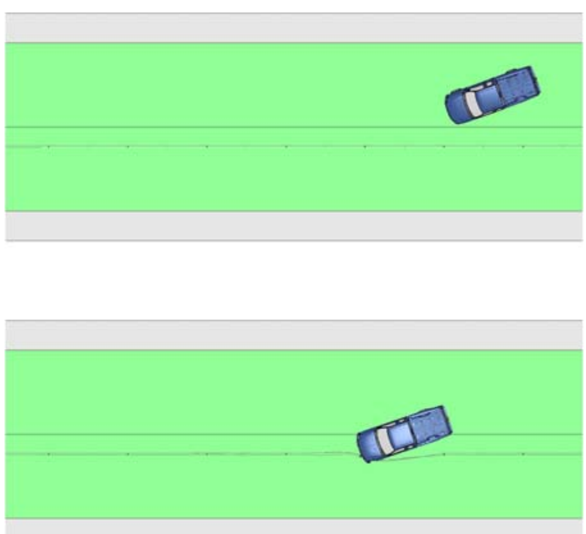


Fig. 3.57: Front-side impact by Ford F250 at 40° and 65 mph for the sixth design of Retrofit Option 1.



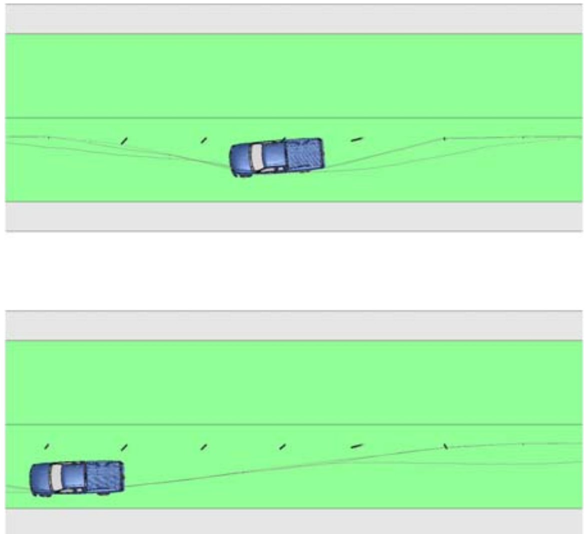
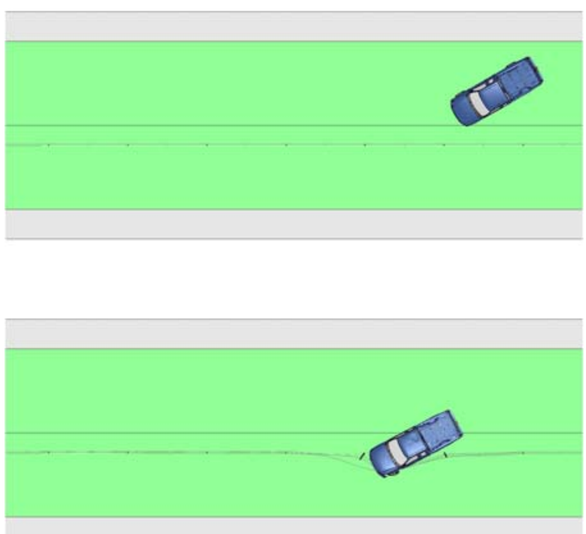


Fig. 3.58: Back-side impact by Ford F250 at 20° and 65 mph for the sixth design of Retrofit Option 1.

The simulation results indicated that the sixth design was potentially better than the current design for small vehicles (e.g., the Dodge Neon), and that it also performed well for large vehicles (e.g., the Ford F250). The new design should be considered for performance evaluation by physical crash testing before using it to retrofit current CMBs.



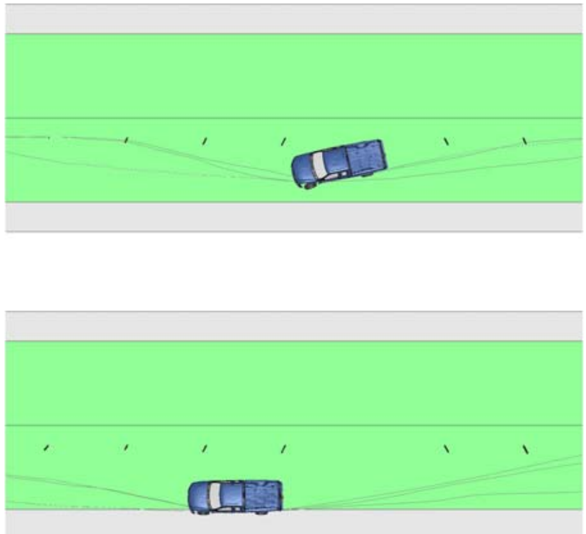
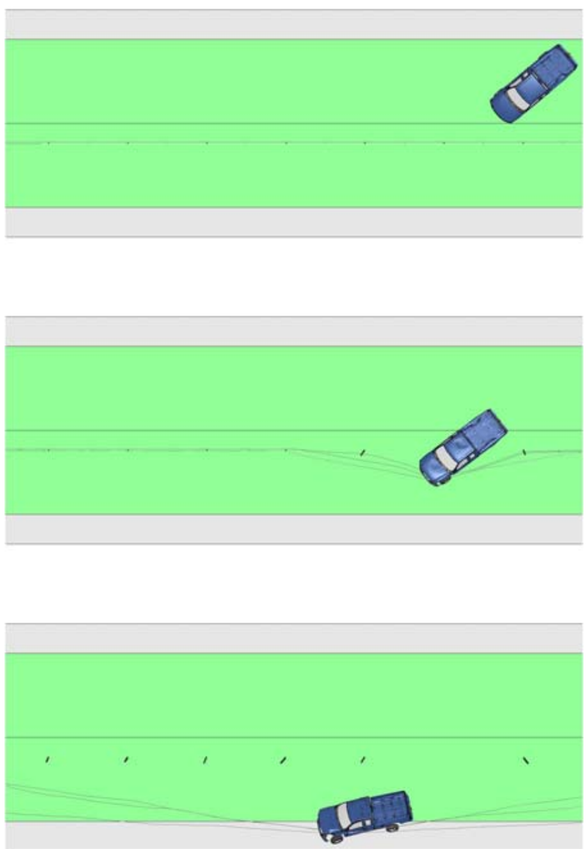


Fig. 3.59: Back-side impact by Ford F250 at 30° and 65 mph for the sixth design of Retrofit Option 1.



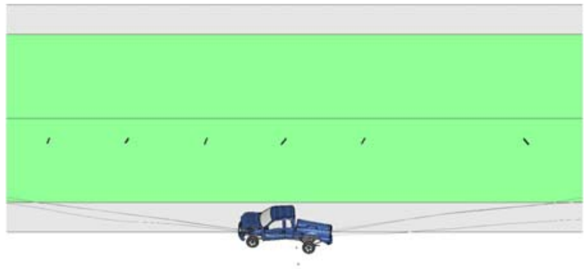


Fig. 3.60: Back-side impact by Ford F250 at 40° and 65 mph for the sixth design of Retrofit Option 1.

3.6 Simulation Results of Retrofit Option 2

In Retrofit Option 2, a fourth cable was added to the current design on the same side of the post as the middle cable. Based on the cable height analysis described in Section 3.5.6, the fourth cable was placed at 17 in. (432 mm) above grade for the first design. A second design, where the fourth cable was placed at 16 in. above grade, was also used to determine if further lowering the fourth cable would improve the CMB's performance. The cable heights of the two designs of Retrofit Option 2 are given in Table 3.12.

Table 3.12: Cable heights of Retrofit Option 2

Design	Top Cable (in)	Middle Cable (in)	Bottom Cable (in)	Fourth Cable (in)
Option 2 – Design 1	30	25.25	20.5	17.0
Option 2 – Design 2	30	25.25	20.5	16.0

The two retrofit designs were expected to have at least the same performance as the current design for front-side impacts and to improve the CMB performance for back-side impacts. Since the performance of the current design in front-side impacts was satisfactory, the evaluation of these two retrofit designs was focused on back-side impacts.

3.6.1 First Retrofit Design

Table 3.13 summarizes the simulation results for the first design of Retrofit Option 2, predominantly for back-side impacts. Compared to the current design, this design improved the CMB performance for back-side impacts due to the added fourth cable. Front-side impacts simulations were performed for the cases of 75 mph (120.7 km/hr) at 20°, 30°, and 40°. The results confirmed that the new design had the same performance as the current design for front-side impacts. Figures 3.61 to 3.63 show the results of 65 mph (104.6 km/hr) back-side impacts. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.

Table 3.13: FE simulation results of the first design of Retrofit Option 2 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Front	20				RD (E, E, O, O)
	30				RD (E, E, O, O)
	40				RD (E, E, O, O)

Back	20	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)
	30	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)
	40	RD (E, E, O, O)	RD (E, E, O, O)	RD_S (E, E, O, O)	RD_S (E, E, O, O)

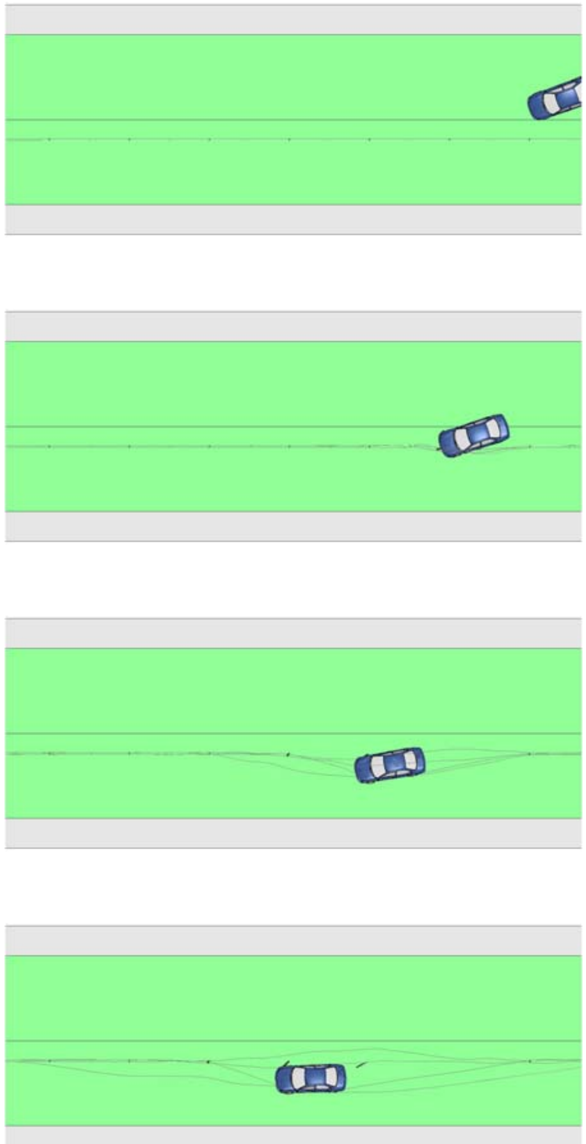
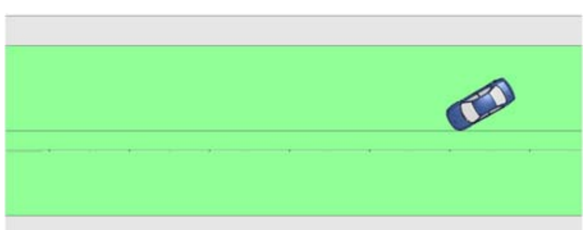


Fig. 3.61: Back-side impact by Dodge Neon at 20° and 65 mph for the first design of Retrofit Option 2.



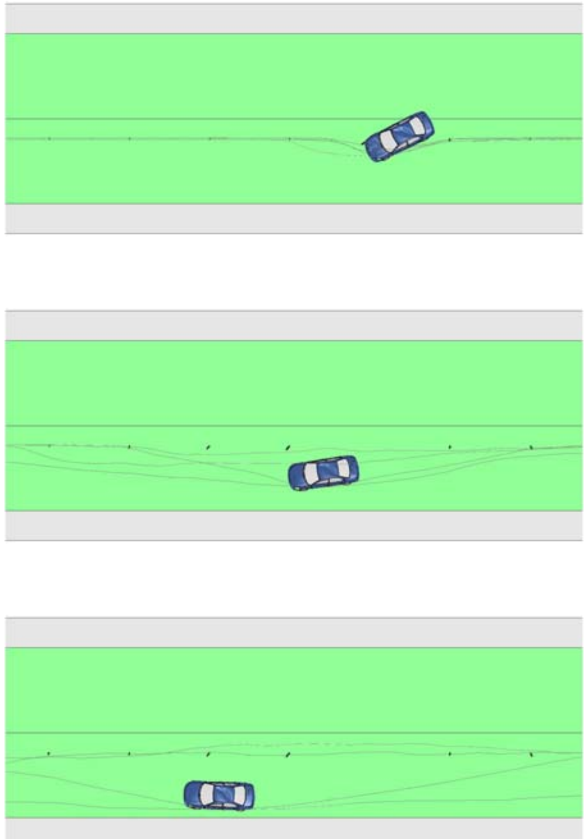
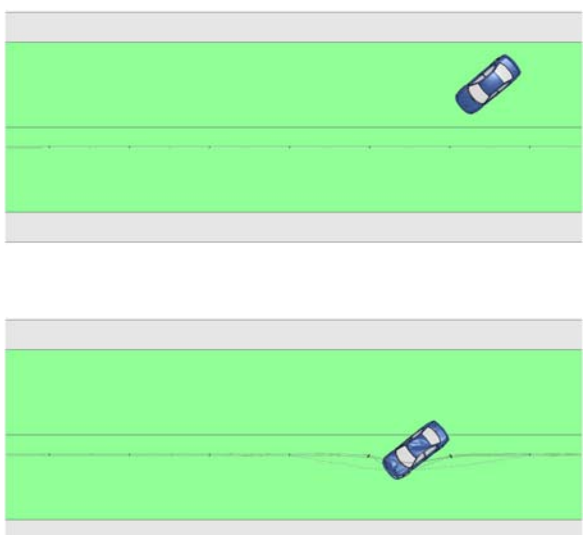
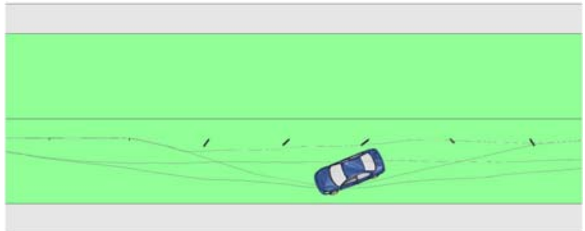


Fig. 3.62: Back-side impact by Dodge Neon at 30° and 65 mph for the first design of Retrofit Option 2.





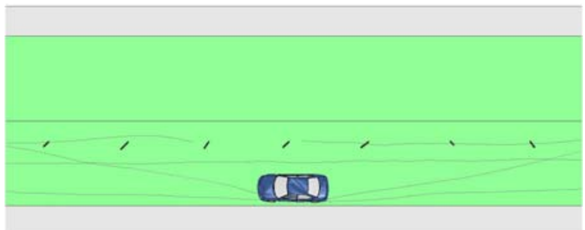


Fig. 3.63: Back-side impact by Dodge Neon at 40° and 65 mph for the first design of Retrofit Option 2.

This design was also evaluated for back-side impacts using the Ford F250 model. The results of cable-vehicle engagement are given in Table 3.14. The performance of this four-cable design was similar to that of the sixth design of Retrofit Option 1. The CMB was able to redirect the vehicle within the median for low-speed, small-angle impacts, but failed on high-speed, large-angle impacts. Compared to the results in Table 3.11, it was observed that the first design of Retrofit Option 2 performed slightly worse for back-side impacts than the sixth design of Retrofit Option 1. For back-side impact, the two strong cables of the sixth design of Retrofit Option 1 were at 30 in. (762 mm) and 17 in. (432 mm), while they were at 25.25 in. (641 mm) and 17 in. (432 mm) for the first design of Retrofit Option 2. The higher position of the top strong cable in the sixth design contributed to the slightly better performance for large vehicle impacts.

Table 3.14: FE simulation results of the first design of Retrofit Option 2 impacted by Ford F250

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Back	20	RD (E, E, E, E)	RD (E, E, E, E)	RD (E, E, E, E)	RD_S (E, E, E, E)
	30	RD_S (E, E, E, E)	RD_S (E, E, E, E)	RD_O (E, E, E, E)	RD_O (E, E, E, E)
	40	RD_O (E, E, E, E)	RD_O(E, E, E, E)	RD_O(E, E, E, E)	RD_O(E, E, E, E)

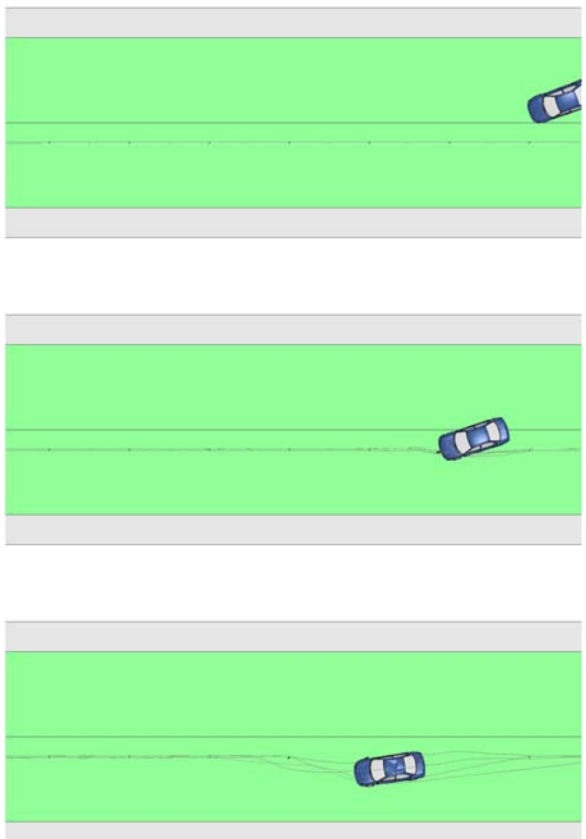
3.6.2 Second Retrofit Design

The results of the second retrofit design for back-side impacts are summarized in Table 3.15. Similar to the first design of Retrofit Option 2 (Table 3.13), the CMB successfully redirected the vehicle for all back-side impacts. The first design of Retrofit Option 2, however, was found to perform slightly better than the second design in the case of 40° and 65 mph (104.6 km/hr) impact.

Figures 3.64 to 3.66 show the results of back-side impacts at an initial vehicle speed of 65 mph (104.6 km/hr) with impact angles of 20°, 30°, and 40°, respectively. The plan-view snapshots, traversal displacements and velocities of the vehicle, and traces of frontal nodes of the vehicle are included for all impact scenarios in Appendices A, B, and C, respectively.

Table 3.15: FE simulation results of the second design of Retrofit Option 2 impacted by Dodge Neon

Impact Side	Impact Angle (°)	Impact Speed (mph)			
		55	65	70	75
Back	20	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)
	30	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)	RD (E, E, O, O)
	40	RD (E, O, O, O)	RD_S (E, O, O, O)	RD_S (E, E, O, O)	RD_S (E, E, O, O)



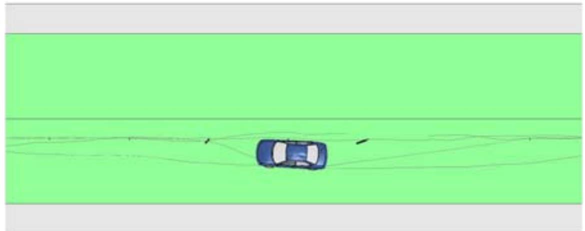


Fig. 3.64: Back-side impact by Dodge Neon at 20° and 65 mph for the second design of Retrofit Option 2.

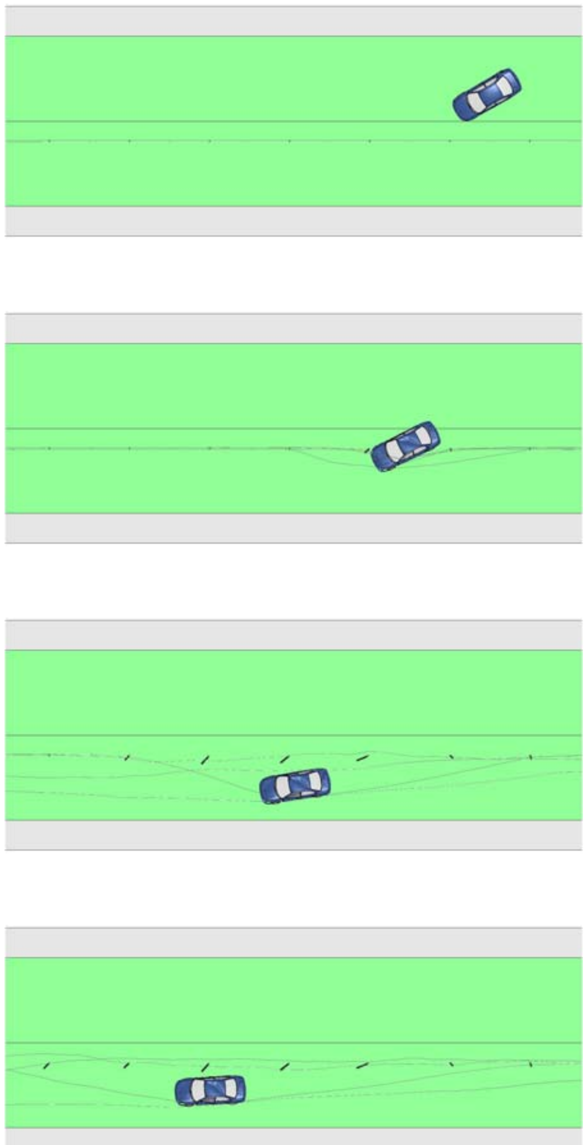


Fig. 3.65: Back-side impact by Dodge Neon at 30° and 65 mph for the second design of Retrofit Option 2.

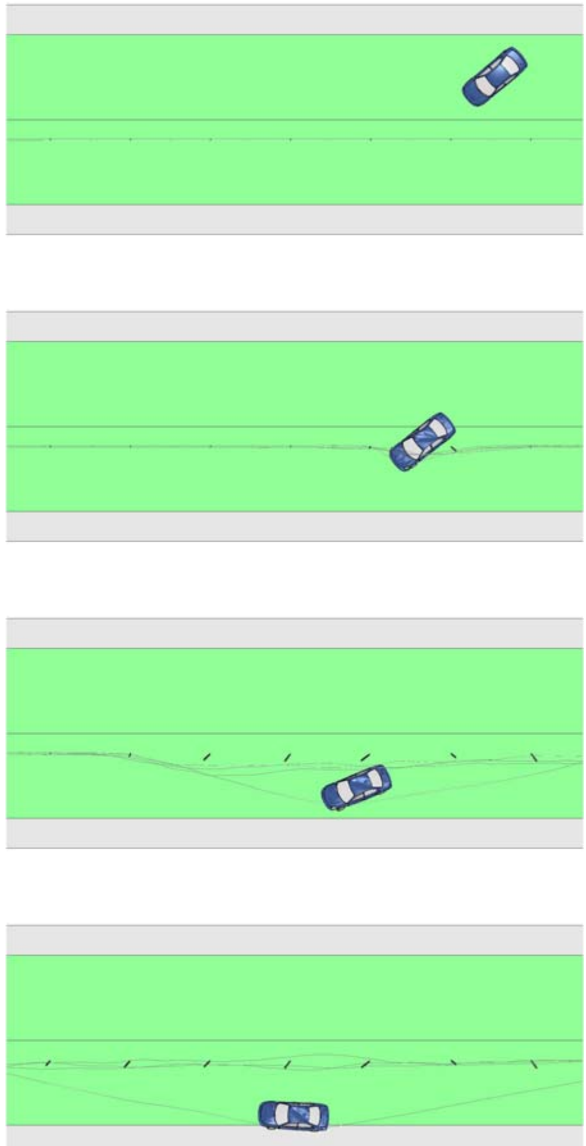


Fig. 3.66: Back-side impact by Dodge Neon at 40° and 65 mph for the second design of Retrofit Option 2.

4. FINDINGS AND CONCLUSIONS

The FE simulations performed in this project give significant insight into the crash mechanisms of vehicle impacts with CMBs. Some of the major research findings are summarized as follows.

- Cable heights affect the cable-vehicle interactions and engagements. Lower cables typically engage better with smaller vehicles (i.e., vehicles with lower profiles). The top cable is effective for large vehicles but ineffective for small vehicles.
- Upon impacting the CMB placed four feet from the bottom of the ditch, the vehicle's front-end is significantly lower in back-side impacts than in front-side impacts due to compression of the suspension upon crossing the ditch.
- The resistance of a cable from bearing against posts plays an important role in the cable's ability to redirect a vehicle. Cables on the sides of the posts facing the impacting vehicle have larger resistance than cables on the opposite sides of the posts.
- Cable-vehicle engagement depends upon the impact locations between two adjacent posts. For example, the cable-vehicle engagement can be totally different when a vehicle impacts the CMB midway between two posts than when it impacts a post first.

In addition to the above major findings, it was also observed that cable-vehicle engagements could be affected by impact speeds and impact angles. Under the same impact speed, the larger the impact angle, the higher the likelihood of engaging with the cables. Under the same impact angles, it was observed from several cases that a cable that was not engaged in a low-speed impact might be engaged in a high-speed impact. Although large impact angles and high impact speeds increased the likelihood of cable-vehicle engagement, they also increased the impact severity and required larger travel distance to redirect the vehicle, as observed from the simulations.

The results of the FE simulations showed that the current NCDOT CMBs could prevent small vehicle under-riding in front-side impacts, even at high speeds (e.g., 75 mph or 120.7 km/hr) and large angles (e.g., 40°). For back-side impacts, the current design could safely redirect the vehicle for impact angles less than 30° and impact speeds lower than 65 mph (104.6 km/hr). For back-side impacts with larger impact angles and higher impact speeds, the current design could not redirect the vehicle within the median due to the short traversal distance for cable deflections.

The five designs of Retrofit Option 1, which were initially proposed by NCDOT officials and researchers at UNC Charlotte, did not improve on the current design for both front- and back-side impacts. While some designs improved the performance for back-side impacts, they performed worse in front-side impacts than the current design. Other designs performed worse than the current design in back-side impacts. A new design, which was referred to as <u>the sixth design of Retrofit Option 1</u>, was proposed based on an aggregated analysis of cable-vehicle engagements in the current design and the five designs of Retrofit Option 1. In the sixth retrofit design, the bottom and middle cables were located at 17 in. (432 mm) and 20.5 in. (521 mm), respectively, above grade. A major difference of the sixth design from all other designs was that the three cables were on the opposite sides of the posts to effectively utilize bearing from the posts. The sixth design showed the same performance as the current design for all front-side impacts. For back-side impacts, the vehicle was redirected within the grassy median for most cases and within the shoulder (i.e., within the 46-ft or 14-m median) for the remaining three cases, 40° impacts at 65, 70, and 75 mph (104.6, 112.6, and 120.7 km/hr). The evaluation of the sixth design using a large vehicle, a Ford F250, showed that this new design performed well in both front- and back-side impacts under conditions well beyond the TL-3 requirements of the NCHRP Report 350.

In Retrofit Option 2, a fourth cable was added to the current design on the same side of the post as the middle cable. The fourth cable was placed at 17 in. (432 mm) above grade; this cable height was determined based on the aggregated analysis that was used for the sixth design of Retrofit Option 1. Evaluation of this four-cable design showed that it had the same performance as the current design for front-side impacts and improved performance for back-side impacts. Compared to the sixth design of Retrofit Option 1, this four-cable design was shown to have similar performance for both small and large vehicle impacts.

The simulation results showed that the potential of vehicle under-ridings for back-side impacts was higher than that for front-side impacts, because the vehicle's suspension was compressed and there was less median traversal space available to redirect the vehicle. The evaluation of different retrofit options indicated that lowering the middle and bottom cables and changing the sides of each cable's attachment to the posts could increase the likelihood of redirecting small vehicles for back-side impacts without sacrificing the CMB's performance for front-side impacts. This was clearly shown by the sixth design of Retrofit Option 1. Furthermore, the sixth design was shown to perform well for large vehicle impacts, which is beyond the requirements of NCHRP Report 350.

The simulation results of this project should be used to investigate performance trends for evaluating CMBs. They should not be used to draw definitive conclusions about CMB performance for a specific crash event, because many factors that affect CMB performance were not considered in the simulations of this project. These factors included, but were not limited to, impact locations along the longitudinal axis of the CMB, soil conditions, driver behavior, etc. Nevertheless, FEA was demonstrated to be a useful tool in crash analysis and could be used in future research to investigate these remaining issues.

5. RECOMMENDATIONS

The results of the finite element simulations in this project showed that the current NCDOT CMB met the requirements of the NCHRP Report 350 for both front- and back-side impacts by small vehicles on a 6:1 sloped median. It was also shown that cable heights can strongly affect the cable-vehicle engagement and therefore the redirection of the impacting vehicle.

The two retrofit designs, the sixth design of Retrofit Option 1 (with cable heights of 30 in., 20.5 in., and 17 in. above grade) and the first design of Retrofit Option 2 (with cable heights of 30 in., 25.25 in., 20.5 in., and 17 in. above grade), can potentially reduce under-ridings of small vehicles. However, these designs must first be crash tested before being considered for use to ensure that they satisfy the requirements of the NCHRP Report 350 and that they perform well under both large and small vehicle impacts.

6. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

In this project, the current NCDOT CMB design and several retrofit designs are evaluated using FE simulations. Two retrofit designs, one with three cables and the other with four cables, are identified to have potentially better performance in preventing vehicle under-rides.

The research results of this project will be distributed to the public through this report, which will be available on the NCDOT official website. The modeling and simulation work along with research findings will be presented at national and international conferences such as the Transportation Research Board Annual Meetings, the U.S. National Congress on Computational Mechanics, and the World Congress on Computational Mechanics. The results of this research will also be submitted for publication in technical journals such as the Transportation Research Records and Finite Elements in Analysis and Design.

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