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FEASIBILITY STUDY FOR ADDRESSING EXTREME SITE CONSTRAINTS AT BRIDGE ENDS

by

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16. Abstract

The scope of this research study was to investigate extreme site constraints at bridge ends encountered by State DOTs. A categorization methodology is provided for determining proper impact conditions and evaluation criteria for future design concepts. The researchers supplied impact conditions and evaluation criteria for future hardware designs for roadside safety application to be applied at extreme sites at bridge ends. This project does not aim to develop a hardware solution for these site conditions. This study aimed to develop criteria for the development of future hardware solutions. The test matrix presented as a solution will be based on data collected from previous research efforts. The resulting proposed criteria allows for the development of future products that are both crashworthy and that fit within the site-specific conditions.

The research also involved developing a survey to identify critical case scenarios that could be further investigated. The survey aimed to collect data from all the State DOTs to help identify the most common critical case scenarios observed in different states.

A comparison between the evaluation criteria in American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH) and Federal Motor Vehicle Safety Standards (FMVSS) was discussed. This evaluation is to be utilized when site specific conditions make MASH compliance impossible. The study identifies the cases where use of MASH is impossible and instead applies evaluation criteria in alignment with FMVSS.

After analyzing specific extreme site constraint cases indicated by state DOTs, researchers developed criteria for evaluating roadside safety devices placed in areas with extreme site constraints.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units

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CHAPTER 1. INTRODUCTION

A general problem occurs at many bridge locations along highways where there is insufficient right-of-way (ROW) to shield the end of a bridge parapet from errant vehicles. These conflicts occur when existing driveways, roads, or other objects have a short offset distance from the end of the bridge parapet. It is not unusual to have less than a 15-ft length between the end of the bridge parapet and the conflict. Solutions to this problem have included using short radius guardrail, a shortened guardrail section, or a crash attenuator. Typically, these solutions are not practical for the site location, are not cost effective, or crashworthy solutions do not fit within the available space.

The scope of this research study was to investigate extreme site constraints at bridge ends encountered by State Departments of Transportation (DOTs). A categorization methodology will be provided for determining proper impact conditions and evaluation criteria for future design concepts. The researchers will supply impact conditions and evaluation criteria for future hardware designs for roadside safety application to be applied at extreme sites at bridge ends.

1.1 OBJECTIVES

The scope of this research study was to investigate extreme site constraints at bridge ends encountered by State DOTs. A categorization methodology is provided for determining proper impact conditions and evaluation criteria for future design concepts. The researchers supply impact conditions and evaluation criteria for future hardware designs for roadside safety applications to be applied at extreme sites at bridge ends. This project was not aimed at developing a hardware solution for these site conditions. This study's aim was to develop criteria for the development of future hardware solutions. The test matrix presented as a solution was based on data collected from previous research efforts. The resulting proposed criteria allows for the development of future products that are both crashworthy and that fit within the site-specific conditions.

The research also involved developing a survey to identify critical case scenarios that could be further investigated. The survey aimed to collect data from all the State DOTs to help identify the most common critical case scenarios observed in different states.

Finally, a comparison between the evaluation criteria in American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (MASH) and Federal Motor Vehicle Safety Standards (FMVSS) was discussed (*1*, *2*). This evaluation was utilized when site specific conditions make MASH compliance impossible. The study identifies the cases where use of MASH is impossible and instead applies evaluation criteria in alignment with FMVSS.

1.2 BACKGROUND

Typically, a rigid longitudinal barrier is used to contain errant traffic at a highway bridge location. These rigid longitudinal barriers present an obstacle at their terminations for oncoming traffic. There are several methods designers use to alleviate these obstacles. Often a guardrail terminal system is used as an approach rail to the bridge location; however, a general problem occurs at many bridge locations along highways where the required length-of-need (LON) for the bridge approach rail cannot be met. The length of need is defined as the length needed for a traffic barrier typically used to protect and shield fixed features or hazards. A typical equation used to determine the length-of-need is the following:

$$x = \frac{L_H + \frac{b}{a} L_1 - L_2}{\frac{b}{a} + \frac{L_H}{L_R}}$$

where: L_H represents lateral extent of hazard, L_R represents the runout length, L_1 represents the length of tangent section of rail advance of hazard, L_2 represents the distance from edge of pavement to tangent section of guardrail, *b/a* represents the flare rate of guard rail. Alternate solutions to these obstacles include using short radius guardrail, a shortened guardrail section, or a crash attenuator. Historically, short radius guardrails have been used at most locations as crash attenuators might not always represent a feasible or economical solution.

Crash cushions or impact attenuators are devices used to shield and protect fixed features. They are typically employed in areas where use of a long barrier installation is not feasible. When impacted by the errant vehicle, crash cushions absorb the impacting energy by deformation to decelerate the vehicle to a stop, or to redirect the vehicle.

There are two main types of classifications for crash cushions: temporary and permanent. Temporary crash cushions are generally employed in work zone areas. Crash cushions can also be classified as redirective or non-redirective, gating or non-gating, and self-recoverable or non-self-recoverable. Redirective crash cushions absorb the kinetic energy of the impacting vehicle and deflect the vehicle back towards the roadway. On the contrary, non-redirective crash cushions do not have this ability. Instead, non-redirective crash cushions allow the vehicles to penetrate the system while at the same time reducing the vehicle's speed. Gating crash cushions allow the vehicle to penetrate through when outside the LON. In contrast, non-gating crash cushions do not allow penetration and have the capability to redirect an errant vehicle along its entire length. Self-recoverable crash cushions are able to restore themselves with little or no maintenance after an impact. Crash cushions are selected based on these classifications as well as their reusability.

Several studies and tests have been conducted by Southwest Research Institute (SwRI), Midwest Roadside Safety Facility (MwRSF), and Texas A&M Transportation Institute (TTI) on various short radius guardrail systems (*3*). These were evaluated under multiple performance criteria including American Association of State Highway and Transportation Officials (AASHTO) 1989 *Guide Specification for Bridge Railings*, National Cooperative Highway Research Program (*NCHRP) Report 230*, and *NCHRP Report 350* (*4*, *5*, *6*).

Silvestri et al. conducted a research study to identify the best practices used to alleviate problems where length-of-need requirements for bridge approach rails cannot be met (*7*). The guide document was developed through a literature review and survey of State DOTs. The survey addressed data concerning the following: practices or standards for bridge barriers when LON cannot be met, practice variation according to design speed, different types of crash cushions used, and installation of a short radius guardrail in front of a slope.

Some State DOTs prefer to relocate the obstacle/drive access to a point beyond the proposed length of need. When that is not feasible, DOTs have different preferences for how to shield the obstacle, which includes use of short radius guardrail or crash cushions, but Wood Post Controlled Release Terminal (Alaska DOT), T-Intersection or adjustment of the LON equation (Louisiana DOT), and nested thrie beam transition from concrete bridge rail end block, then attachment of short radius rail as necessary (South Dakota) are other options.

From the information collected, it appears that use of short radius guardrail practice at bridge locations where LON cannot be met is generally the option preferred by the DOTs. Although few States indicated that their DOTs make somewhat frequent use of crash cushions at bridge locations where LON cannot be met, their employment is very limited by other States due to their higher installation and maintenance costs. Also, use of crash cushions might be impractical and undesirable on road sections with multiple drives and side roads, considering their size.

Abu-Odeh has conducted a successful research study effort funded by the Texas Department of Transportation which aimed at developing a MASH TL-3 compliant short radius guardrail (*8*). This system was designed to address sites at which the intersecting roadway/driveway is greater than 35 ft from the bridge end and has a ROW distance of 30 ft or greater. This design provides a solution for a common safety problem. However, some sites may have space constraints that are too restrictive for the tested design, or possibly any *MASH* compliant design.

1.3 GENERIC TEST MATRIX ACCORDING TO MASH

MASH categorizes the evaluation criteria for a barrier system into two categories according to the type of system used and its length of need:

1. Longitudinal Barriers.
2. Terminals and Crash Cushions.

According to all the previous research conducted on short radius guardrail systems, the evaluation criteria have been based on Terminal and Redirective Crash Cushions. MASH recommends a total of nine tests to be performed for Terminals and Redirective Crash Cushions, and an additional six tests if the system qualifies as a Non-Redirective type crash cushion. These sets of tests are applicable for a symmetric system for vehicles impacting from a specific direction. If the system is asymmetric, it needs to be tested for vehicles impacting from the opposite direction as well, thus making the test matrix twice as large. Performing a large number of tests for one system would require a substantial amount of time and funds. Hence, it is practical to eliminate the tests that are not critical for the system. The evaluation to determine the usefulness of a test for the chosen system can be done using previous research data, the site constraints data for the specific site case, and engineering judgment.

Table 1 represents the full test matrix recommended in MASH that is applicable for a symmetric short radius guardrail system evaluated at TL-3:

Table 1. Terminal and Crash Cushion MASH Test Matrix.

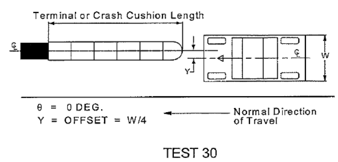
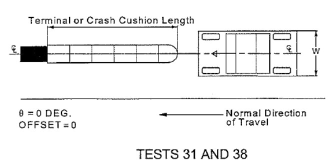
Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-30	1100C	62 (100)	0		Tests 30 and 40 are designed to examine the risk of vehicle instability, particularly for narrow terminal and crash cushion systems. Although Tests 32 and 42 often exhibit higher occupant risk criteria, the risk of vehicle instability is higher for Tests 30 and 40. Hence, Tests 30 and 40 should be conducted even if a system successfully passes Tests 32 or 42.
3-31	2270P	62 (100)	0		For devices intended to decelerate the vehicle to a stop, this test is designed to evaluate the capacity of the feature to absorb sufficient energy to stop the 2270P vehicle in a safe and controlled manner. For gating systems, this test is intended to evaluate occupant risk and vehicle trajectory criteria during high-energy, head-on impacts. This test is conducted with the vehicle approaching parallel to the roadway with the center of the vehicle aligned with the centerline of the terminal or cushion. Again, the centerline of the device is defined as the center of resistance during end-on impacts.

Table 1. Terminal and Crash Cushion MASH Test Matrix (Continued).

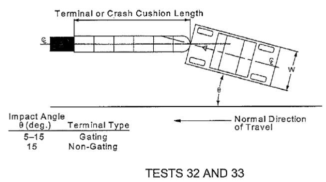
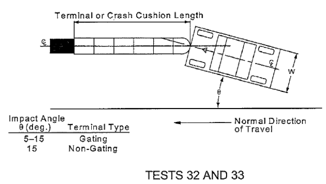
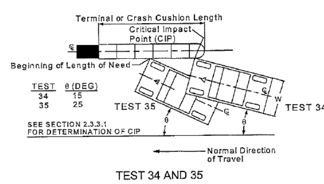
Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-32	1100C	62 (100)	5/15		This test is intended to examine the behavior of terminals and crash cushions during oblique impacts of the end or nose of the system. For most features, occupant risk and vehicle trajectory are the primary concerns. Note that the impact angle for this test should be selected for the range shown.
3-33	2270P	62 (100)	5/15		This test is intended to examine the behavior of terminals and crash cushions during oblique impacts of the end or nose of the system. For most features, occupant risk and vehicle trajectory are the primary concerns. Note that the impact angle for this test should be selected for the range shown.
3-34	1100C	62 (100)	15		Test 34 is intended to evaluate the impact performance of terminals and crash cushions at the critical impact point (CIP) where the behavior of these devices changes from gating or capturing to redirection. Vehicle trajectory and occupant risk are the primary concerns for this test. Criteria for selecting the CIP for post-and-beam terminal or crash cushion systems are presented in Section 2.3.3.1. Whenever practical, finite element analysis should be conducted to identify critical impact points for post-and-beam systems as well as other terminals and redirective crash cushions.

Table 1. Terminal and Crash Cushion MASH Test Matrix (Continued).

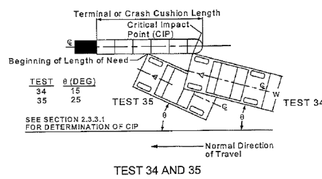
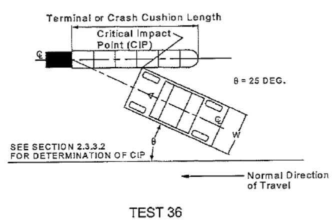
Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-35	2270P	62 (100)	25		Test 35 examines the capacity of a terminal or crash cushion for containing and redirecting heavy passenger vehicles. For this test, a 2270P vehicle is directed into the system at the beginning of the length-of-need at an impact angle of 25 degrees. Note that, for non-gating crash cushions, the beginning of the length-of need should be very near the nose of the crash cushion. In this case, Test 35 should involve a vehicle impacting on the very end of the system where cushion behavior changes from capturing to redirective. Hence, for non-gating systems, the test is essentially a CIP impact with a light truck test vehicle.
3-36	2270P	62 (100)	25		This test is designed to examine the behavior of terminals and redirective crash cushions when attached to rigid barriers of other very stiff features. For this test, the 2270P test vehicle is directed into the terminal of the crash cushion at its CIP with respect to the transition of the backup structure. Note that some terminals, including most W-beam guardrail terminals, are not attached directly to a stiff barrier or backup structure. General guidelines for determining CIP locations for this test are included in section 2.3.3.3. Whenever possible, finite element analysis should be used to determine the CIP for Test 36.

Table 1. Terminal and Crash Cushion MASH Test Matrix (Continued).

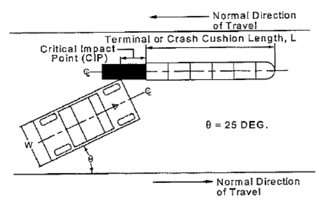
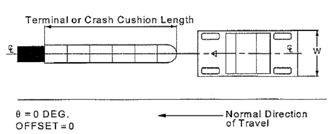
Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-37	2270P	62 (100)	25	 TEST 37 (FOR MEDIAN DEVICE)	Test 37 examines the behavior of crash cushions and terminals during reverse-direction impacts. This test is recommended for any safety feature that will be placed within the clear zone of opposing traffic. This test involves a 2270P or 1100C vehicle striking the critical impact point (CIP) for reverse-direction impacts. CIP locations for reverse direction impacts vary greatly from one system to another, and a generalized system for identifying these locations has yet to be developed. Note that the configuration shown in figure 2.3 for Test 37 is intended for illustration purposes only and do not necessarily reflect the actual test configuration.
3-38	1500A	62 (100)	0	 TESTS 31 AND 38	Tests 38 and 48 are intended to examine the performance of crash cushions and end terminals during impacts by mid-size vehicles. The concern is that attenuator staging can be tuned to meet the testing requirements for the small car and heavy pickup truck without adequately accommodating mid-sized vehicles. For these tests, the centerline of the test vehicle is aligned with the centerline of the test article.

Table 1. Terminal and Crash Cushion MASH Test Matrix (Continued).

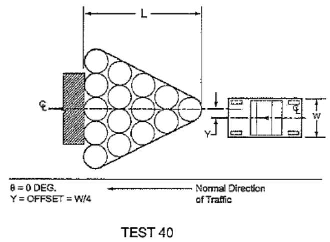
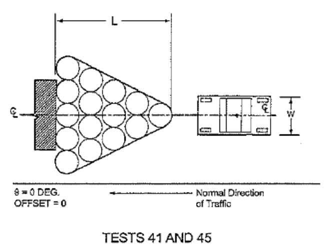
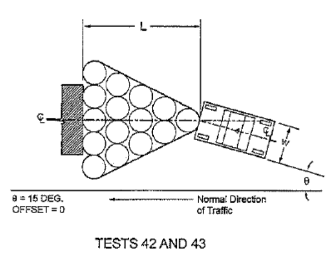
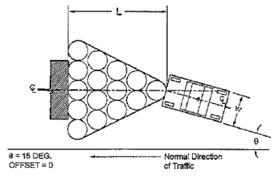
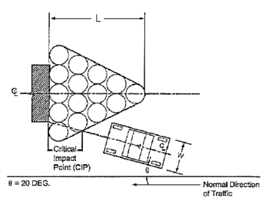
Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-40	1100C	62 (100)	0		Tests 30 and 40 are designed to examine the risk of vehicle instability, particularly for narrow terminal and crash cushion systems. Although Tests 32 and 42 often exhibit higher occupant risk criteria, the risk of vehicle instability is higher for Tests 30 and 40. Hence, Tests 30 and 40 should be conducted even if a system successfully passes Tests 32 or 42.
3-41	2270P	62 (100)	0		For devices intended to decelerate the vehicle to a stop, this test is designed to evaluate the capacity of the feature to absorb sufficient energy to stop the 2270P vehicle in a safe and controlled manner. For gating systems, this test is intended to evaluate occupant risk and vehicle trajectory criteria during high-energy, head-on impacts. This test is conducted with the vehicle approaching parallel to the roadway with the center of the vehicle aligned with the centerline of the terminal or cushion. Again, the centerline of the device is defined as the center of resistance during end-on impacts.
3-42	1100C	62 (100)	5/15		This test is intended to examine the behavior of terminals and crash cushions during oblique impacts of the end or nose of the system. For most features, occupant risk and vehicle trajectory are the primary concerns. Note that the impact angle for these tests should be selected for the range shown.

Table 1. Terminal and Crash Cushion MASH Test Matrix (Continued).

Test Number	Vehicle	Impact Speed mph (km/h)	Impact Angle (deg.)	Impact Conditions	Test Description
3-43	2270P	62 (100)	5/15	 TESTS 42 AND 43	This test is intended to examine the behavior of terminals and crash cushions during oblique impacts of the end or nose of the system. For most features, occupant risk and vehicle trajectory are the primary concerns. Note that the impact angle for these tests should be selected for the range shown.
3-44	2270P	62 (100)	20	 TEST 44	Test 44 is designed to evaluate the ability of a non-directive crash cushion to safely stop a large passenger vehicle in a side impact. For this test, the 2270P test vehicle is directed into the crash cushion at its CIP with respect to the transition to the backup structure. Note that non-redirective crash cushions are not designed to safely attenuate this impact and therefore occupant risk parameters, evaluation criteria H and I, are not among the recommended evaluation criteria. However, these values should be reported as a means for user agencies to estimate the potential risk of using non-redirective crash cushions. The impacting vehicle should remain stable and upright during the test. If a system truly has no redirective capacity, such as a sand inertial cushion, the centerline of the test vehicle should be directed at the corner of the shielded hazard as shown in figure 2-3B. however, if non-redirective crash cushions can be expected to provide some redirective capacity, general guidelines for determining CIP locations presented in section 2.3.3.3 for test 26 should be followed.

1.4 FMVSS

The FMVSS provides standards to ensure minimum safety performance for motor vehicles. FMVSS is a legislative directive by the National Highway Traffic Safety (NHTSA) and has been made mandatory for all the manufacturing companies to follow the standards. The evaluation criteria for FMVSS are based on an instrumented dummy considering a passive restraint system. Figure 1 provides a quick overview of the standards specified in FMVSS:

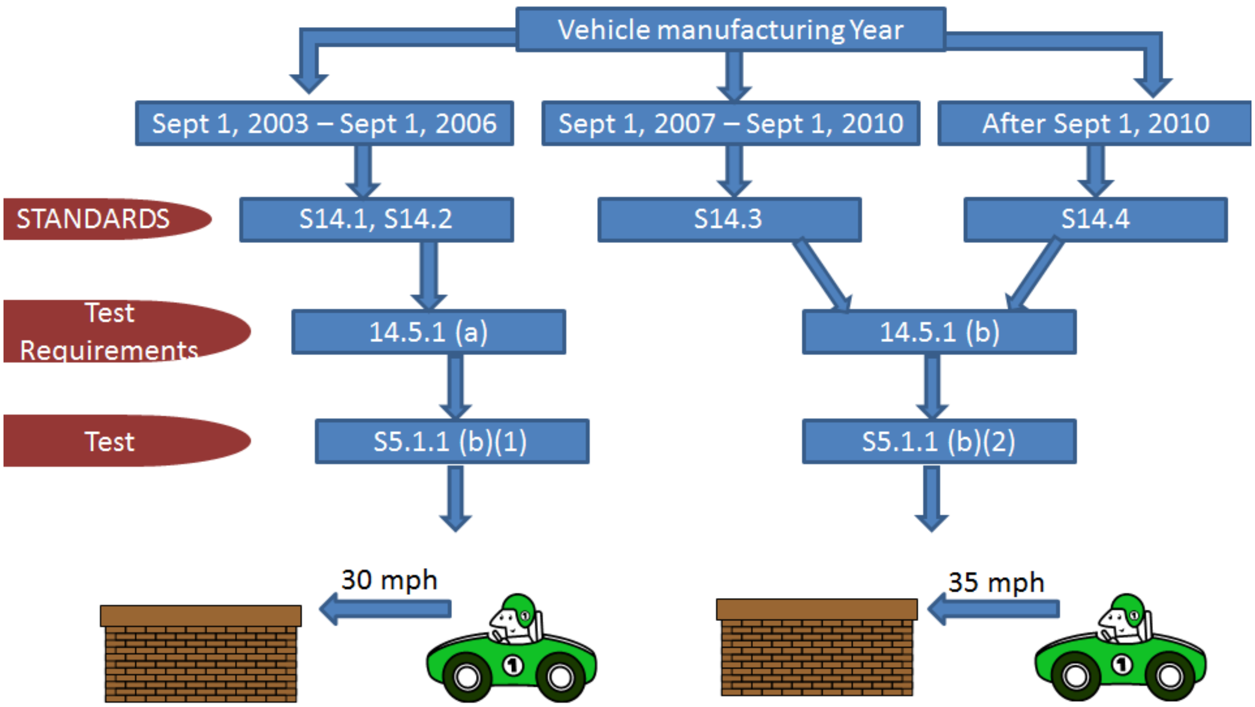


Figure 1. FMVSS Standards Overview

1.5 ALTERNATE TESTING METHODS – NCAP AND IIHS

Both the New Car Assessment Program (NCAP) and Insurance Institute for Highway Safety (IIHS) provide standards to measure the safety level of motor vehicles. Unlike FMVSS, NCAP and IIHS are not mandatory to be followed by the manufacturing companies. NCAP and IIHS rate the results for a particular vehicle rather than providing a pass/fail verdict. The intention here is to make it easier for the consumers to judge the safety of a vehicle. Table 2 summarizes the main differences between FMVSS, NCAP, and IIHS:

Table 2. Summary of FMVS, NCAP, and IIHS Safety Standards.

CRITERIA	FMVSS	NCAP	IIHS
Overview	Federal regulations specifying design, construction, performance, and durability requirements for motor vehicles and regulated safety-related components, systems, and design features.	Government car safety program tasked with evaluating new automobile designs for performance against various safety threats.	Evaluates two aspects of safety: **Crashworthiness** and **crash avoidance and mitigation technology**
Mandatory?	YES	NO	NO
Evaluation Method	Standards and Regulations	Star Ratings	Ratings
Impact Conditions	• 35 mph – perpendicular to rigid barrier	• 35 mph – perpendicular to rigid barrier	• 35 mph – perpendicular to rigid barrier with **40% of total width impacting**
Evaluation Criteria	• Occupant safety based on accelerations and force transmitted. • Provisions for Motor Vehicle Safety Standards	• Standards Procedures for vehicle measurements pre and post crash test • Vehicle Intrusion, Crush, Velocity • Occupant safety based on accelerations and force transmitted.	• Ratings based on Overlap Front, Side Strength, Roof strength, Head restraints & seats, front crash prevention.
Pass/Fail Criteria	Maximum Limits specified for accelerations and forces, but none found for vehicle for a crash test	Maximum limits specified for accelerations and forces which are used for categorizing based on stars	Maximum limits specified for accelerations, forces which are used for categorizing based on stars.

1.6 MASH VS FMVSS

One of the main objectives of this project was to study the FMVSS evaluation criteria and compare them to the MASH criteria. To optimize the test matrix for implementation of the short radius guardrail, it is imperative to judge what evaluation criteria gives us the most feasible solution. Based on previous research and literature review, it appears that the evaluation criteria in MASH are more conservative as compared to FMVSS. Since the flail space model in MASH is based on an unrestrained occupant, it neglects the effects of the passive and active restraint systems such as seatbelts and air bags that are currently mandatory in all vehicles.

The use of an instrumented dummy while utilizing restraint systems will have a significant impact on the allowable occupant impact velocity (OIV). MASH currently limits the maximum OIV to be 40 ft. /sec, on which the required length of a guardrail is designed. However, if evaluation criteria from FMVSS are implemented, there is a reason to further increase the maximum OIV. This can reduce the minimum length requirements for a guardrail and help develop a solution for cases where the minimum LON requirements cannot be met according to MASH.

CHAPTER 2. SITE CASE SURVEY

2.1 DEVELOPMENT AND DISTRIBUTION OF THE SURVEY

A survey was developed using the LimeSurvey tool to collect data on site constraints from various State DOTs to help identify the critical case scenarios observed in different states. The survey was developed to identify critical case scenarios observed in different states to install a short radius system.

Three generic site cases were identified that were further investigated for specific site cases based on the directions of traffic flow. The survey asked the users to first rank the generic cases, followed by ranking the specific case for each of the generic cases. Based on the directions of traffic flow for the primary and secondary roads, there were a total of nine specific site cases for each of the generic site cases. An additional fourth generic site case was included which was an extension of Case 3 to judge how the inclusion of an addition “left only lane” effects the placement of the short radius system.

The details of the survey have been attached in Appendix B1.

2.2 SURVEY RESULTS

The results of the survey were used to identify the critical site cases according to their rankings. LimeSurvey provides statistics based on the total number of responses which gives the percentage of users opting for a particular case as a particular rank. That is, the statistics may read something like “75 percent of the users chose case 2.3 as rank 1, 66 percent of the users chose case 2.4 as rank 2” and so on. Table 3 provides a summary of the survey rankings.

Table 3. Generic Site Cases Survey Rankings.

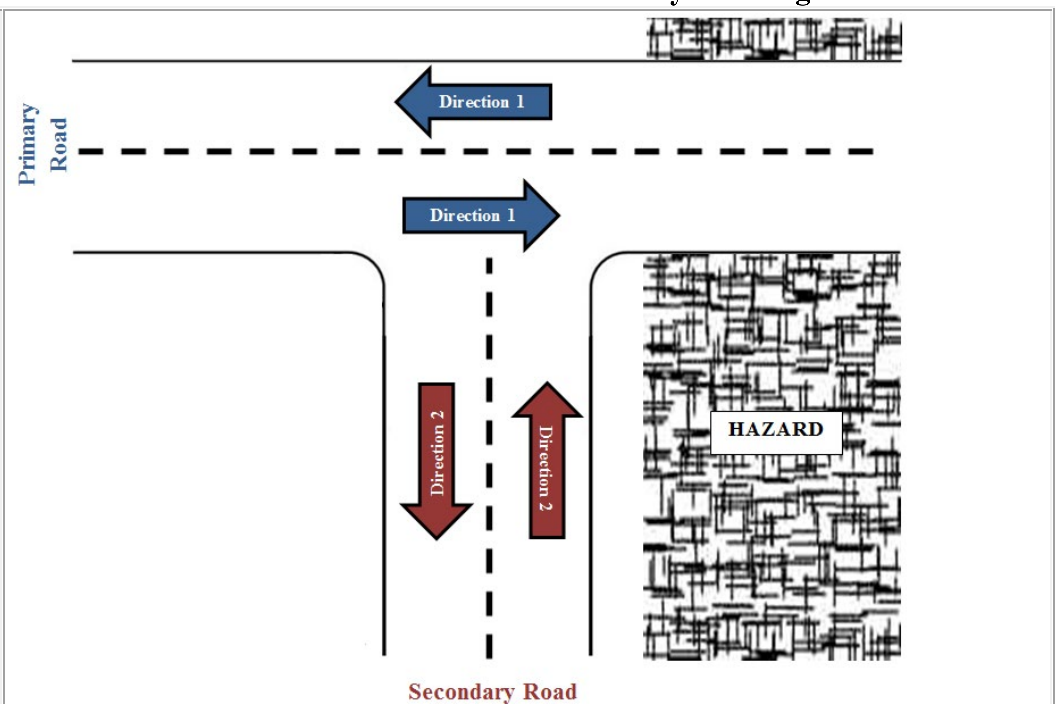
Rank.1 Case3.	

Table 3. Generic Site Cases Survey Rankings (Continued).

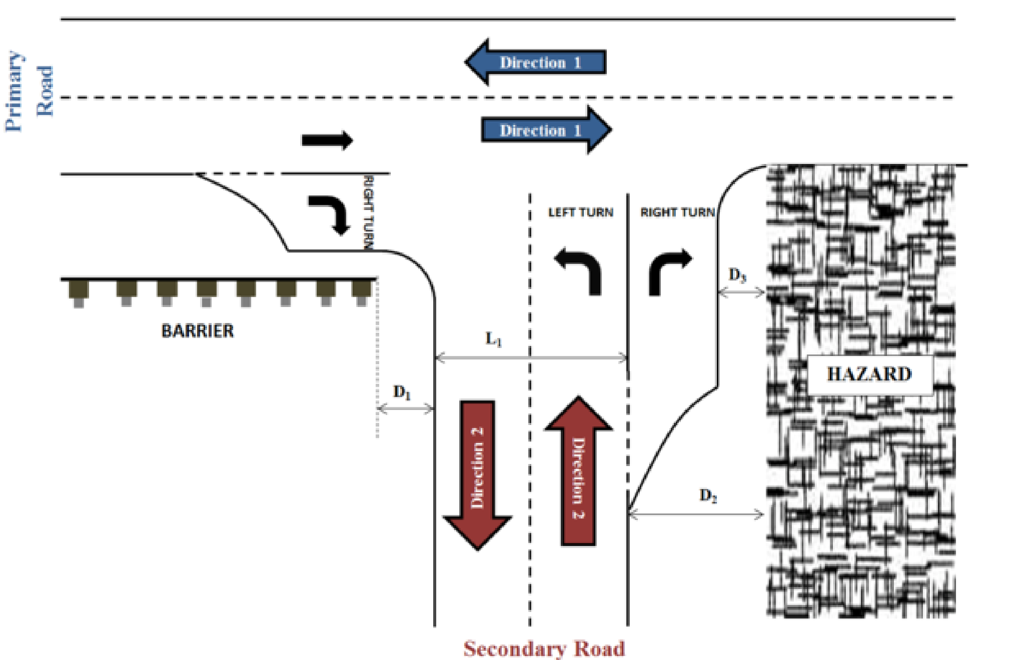
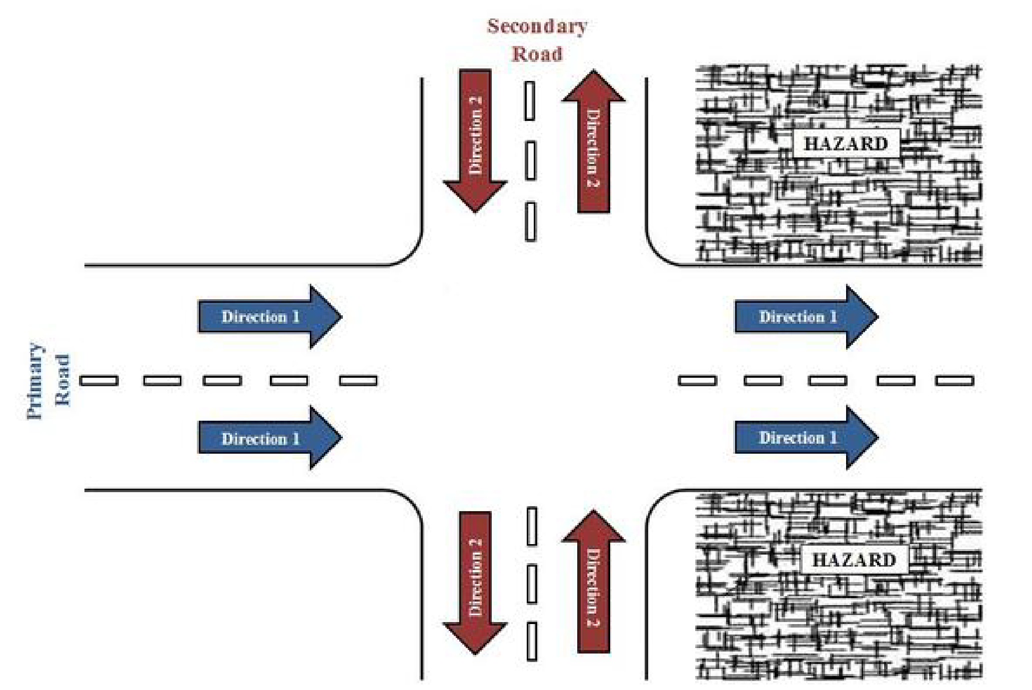
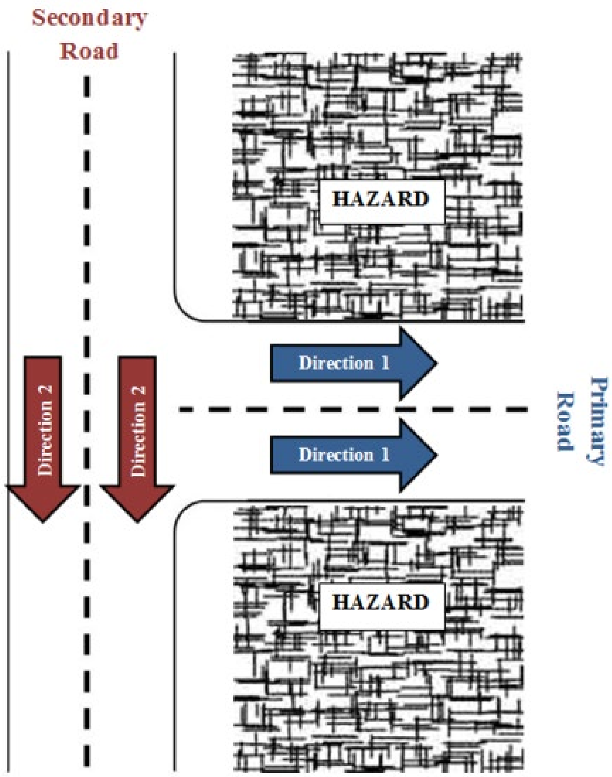
Rank.2 Case4.	
Rank.3 Case1.	

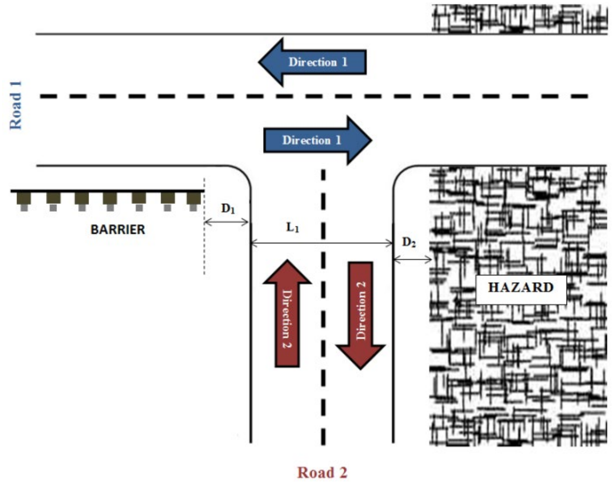
Table 3. Generic Site Cases Survey Rankings (Continued).

Rank.4 Case2.	

The survey recorded a total of 16 complete responses from the various DOTs that were asked to participate. Based on these responses, the top three specific site cases were picked to represent the critical cases for each of the three generic cases. The results of the survey are attached in Appendix B2. Survey participants were also asked to provide specific site cases to identify related site parameters with respect to dimensions of the roadway and short radius guardrail systems currently in place. An example of specific site cases with dimensions is provided in Table 4.

The shaded area in Figure 2 shows the available region to install a short- radius guardrail. The area is predicted based on the potential hazards for a vehicle traveling in the vicinity of the bridge end. In this case, for the primary road, the bridge end itself acts as one of the hazards. Therefore, even though the actual hazard is the water body present, the width of the feasible area is restricted to about 20 ft. in the direction of the primary road. Since there is no notable hazard in the direction of the secondary road, we can assume a width of about 65 ft. for the feasible area based on the length of the existing guardrail.

Table 4. Specific Site Case Example.



Site Parameters Identified:				
State	Speed Limit (mph)	D1 (ft)	D2 (ft)	L1 (ft)
Louisiana	55	20	0	20.22
Link for Google Maps				

Figure 2. Specific Site Case Example.

CHAPTER 3. MINIMUM BARRIER LENGTH

3.1 LENGTH OF CRASH CUSHION

One of the main objectives of this project was to provide minimum lengths of crash cushions required for installation. To get a realistic value, all the crash cushions that are presently being used in the industry were studied. A table was prepared listing all the crash cushions and their corresponding lengths for different Test Levels. The distribution of lengths gave a fair estimate of the minimum lengths that were currently being used in practice. To verify the findings, theoretical calculations for minimum lengths were carried out based on MASH criteria for impact speed and accelerations. These results were further discussed with various researchers from several state DOTs to get their insights on the values.

3.2 THEORETICAL CALCULATIONS FOR MINIMUM BARRIER LENGTH

The theoretical calculations to determine the minimum required barrier length were based on MASH criteria for impact speeds and accelerations. The minimum required length of the barrier was based on the total distance traveled by different types of vehicles during the course of an impact with the barrier. Calculations were carried out for three types of vehicles as specified in MASH: Small Car (1100C), Intermediate Car (1500A) and the Pickup Truck (2270P). An Excel spreadsheet was developed which calculates the distances traveled by all three types of vehicles at a specified test level.

For the small car, the length traveled by the vehicle was calculated at two stages (see Figure 3. The first stage was the initial impact stage assuming the occupant impact velocity to be 40 ft/sec as specified in MASH. At this stage, the occupant's head is allowed to travel a maximum of 2 ft. With this data, the acceleration of the car and the distance traveled while the head travels 2 ft can be determined. The final velocity of the car is calculated at the end of this stage which can be used for calculations at the second stage. The second stage of the crash is the ride-down stage where the car is assumed to travel with a constant acceleration of 20 g's before coming to a complete stop. Thus, with the initial velocity calculated at the first stage, the distance traveled by the car at the second stage can be determined. The total distance traveled by the car is the addition of the distances traveled at both stages.

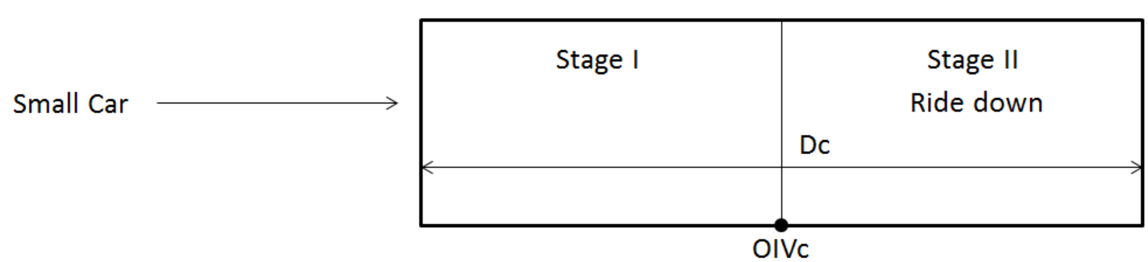


Figure 3. Small Car Theoretical Impact Stages.

For the intermediate car, the calculations were carried out at three main stages. The second stage was further broken into two sub-stages. The first stage assumes that the vehicle travels the same distance as the small car at the stage I. The acceleration depends on the ratio of the masses of the small car to the intermediate car. That means,

$$a = \frac{Mass\ of\ small\ car}{Mass\ of\ intermediate\ car} * ac$$

where, ac = acceleration of small car

With the above data, the distance traveled by the head can be calculated at the first stage. Stage II-a calculates the distance traveled by the car while the head travels the remaining distance of the maximum allowable distance of 2 ft. Stage II-b calculates the remaining distance traveled by the car to match the total distance traveled by the small car at the second stage. Stage III is the ride-down stage where the vehicle is assumed to travel with a constant acceleration of 20 g's until it comes to a complete stop. The total distance traveled by the vehicle is the summation of distances covered at each stage. Figure 4 shows these stages for the car.

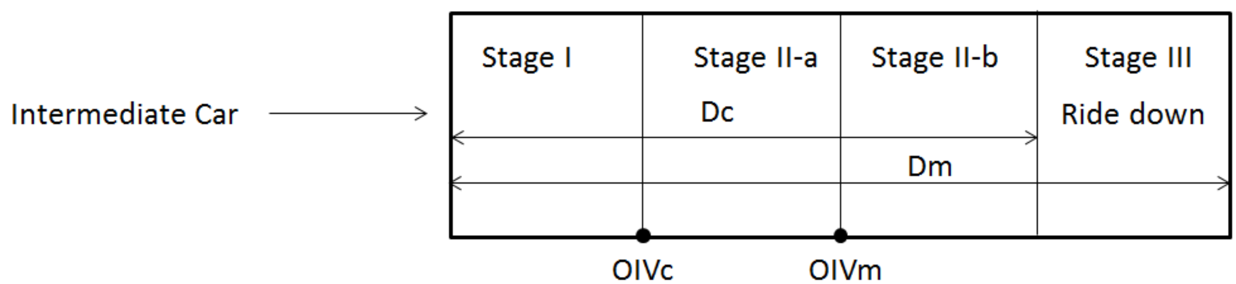


Figure 4. Intermediate Car Theoretical Impact Stages.

Calculations for the pickup truck follow the same procedure as the intermediate car. The calculation is divided into four stages. The third stage is further divided into two sub-stages. The first and second stages calculate the distances traveled by the head while the truck travels the same distance as the small car at stage I and Stage II respectively. The acceleration depends on the ratio of the masses of the small car to the pickup truck. That means,

$$a = \frac{Mass\ of\ small\ car}{Mass\ of\ pickup\ truck} * ac$$

where, ac = acceleration of small car

Stage III-a calculates the additional distance traveled by the truck until the head travels a total distance of 2 ft. Stage III-b calculates the remaining distance traveled by the truck to match the total distance traveled by the intermediate car at the third stage. Stage IV is the ride-down stage where the vehicle is assumed to travel with a constant acceleration of 20 g's until it comes to a complete stop. The total distance traveled by the vehicle is the summation of distances covered at each stage. Figure 5 shows these stages for the pickup truck. Table 5 provides the variables for calculation of the theoretical barrier minim length.

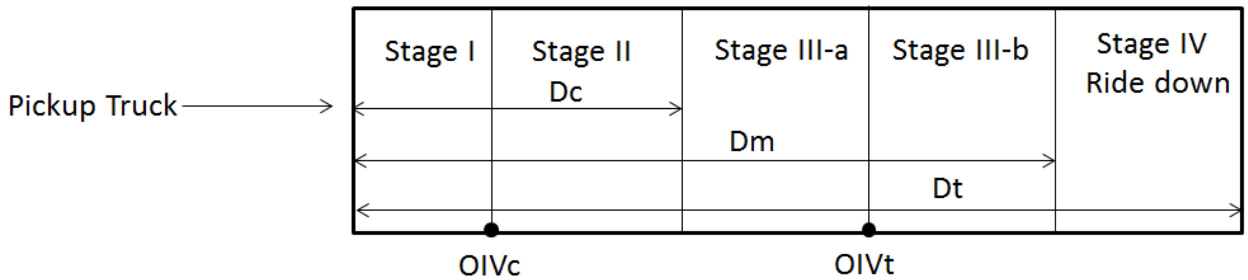


Figure 5. Pickup Truck Theoretical Impact Stages

Table 5. Description of Variables for Theoretical Barrier Minimum Length Calculation.

Designation	Term
Dc	Distance traveled by small car
Dm	Distance traveled by intermediate car
Dt	Distance traveled by pickup truck
OIVc	Occupant Impact velocity of small car
OIVm	Occupant Impact velocity of intermediate car
OIVt	Occupant Impact velocity of pickup truck

3.3 THEORETICAL BARRIER MINIMUM LENGTH

The theoretical minimum barrier length is the maximum of the lengths calculated for the small car, intermediate car, and the pickup truck. The calculated minimum barrier length is **13.01 ft** for TL-3, **6.88** ft for TL-2, and **3.54** ft for TL-1. The summary of minimum barrier length calculations is shown in Table 6.

3.3 LENGTH OF CRASH CUSHIONS CURRENTLY IN USE

A summary of the length of the crash cushions currently being used is presented in Table 7.

A comparison of the calculated theoretical minimum barrier length and the lengths of existing barriers revealed that the calculated TL-3 barrier length of 13.01 ft. was less than the shortest TL-3 system length of 19.42 ft., and that the calculated minimum TL-2 barrier length of 6.88 ft. was less than the shortest TL-2 system length of 8.5 ft. This shows that all currently developed systems could be used in these site cases, physical space permitting, and be within MASH occupant impact criteria. However, based on the theoretical nature of the minimum length calculation, real world efficiency losses, and insights from researchers representing various DOT’s, lengths of 19 ft for TL-3 systems and 8 ft for TL-2 systems were selected as practical estimates for minimum required barrier lengths.

Table 6. Summary of Theoretical Barrier Minimum Length Calculations

Vehicle	Stage	TL-3		TL-2		TL-1	
		Distance traveled (ft.)	OIV (ft./sec)	Distance traveled (ft.)	OIV (ft./sec)	Distance traveled (ft.)	OIV (ft./sec)
Small Car	I	7.095	40	4.454	40	2.54	40
	II	2.017		0.468		0.023	
	Total	**9.112**		**4.92**		**2.57**	
Intermediate Car	I	7.0954	38.06	4.454	38.76	2.54	40
	II-a	1.39		0.941		0.57	
	II-b	0.626		0		0	
	III	1.714		0.863		0.428	
	Total	**10.826**		**6.259**		**3.55**	
Pickup Truck	I	7.095	35.09	4.454	37.27	2.54	38.847
	II	2.017		0.468		0.023	
	III-a	1.344		1.650		1.20	
	III-b	0.369		0		0	
	IV	2.18		1.09		0.545	
	Total	**13.007**		**7.67**		**4.31**	

Table 7. Comparison of Existing Barrier Lengths and Calculated Theoretical Minimum Barrier Lengths

Summary Of Length Calculations

TL - 3	
System	**Length (ft)**
REACT 350 (36)	19.42
WIDETRACC	21.00
TRACC	21.25
SCI100GM	21.50
QUADGUARD CZ SYSTEM	22.11
QUADGUARD SYSTEM (69 OR 90)	22.12
QUADGUARD CZ SYSTEM ON A PLATE	22.13
UNIVERSAL TAU-II	24.00
X-TENUATOR	24.75
FASTRACC	26.00
HEART	26.19
QUADGUARD CEN	26.75
QUADGUARD HIGH SPEED	29.50
REACT 350 WIDE	30.58
QUADGUARD SYSTEM	31.00
BREAKMASTER 350 SYSTEM (Terminal End Treatment)	31.50
ABSORB 350	32.00
QUADGUARD LMC SYSTEM	32.80
QUADGUARD ELITE SYSTEM	33.62

TL - 2	
System	**Length (ft)**
EASI-Cell	8.50
N-E-A-T System	9.71
SCT01a-b	12.75
SHORTRACC	14.25
ABSORB 350	19.33

Calcluated Minimum Length (ft)		
TL - 3	**TL - 2**	**TL - 1**
13.01	6.88	3.54

CHAPTER 4. DEVELOPMENT OF TEST MATRIX

4.1 SPECIFIC SITE CASES

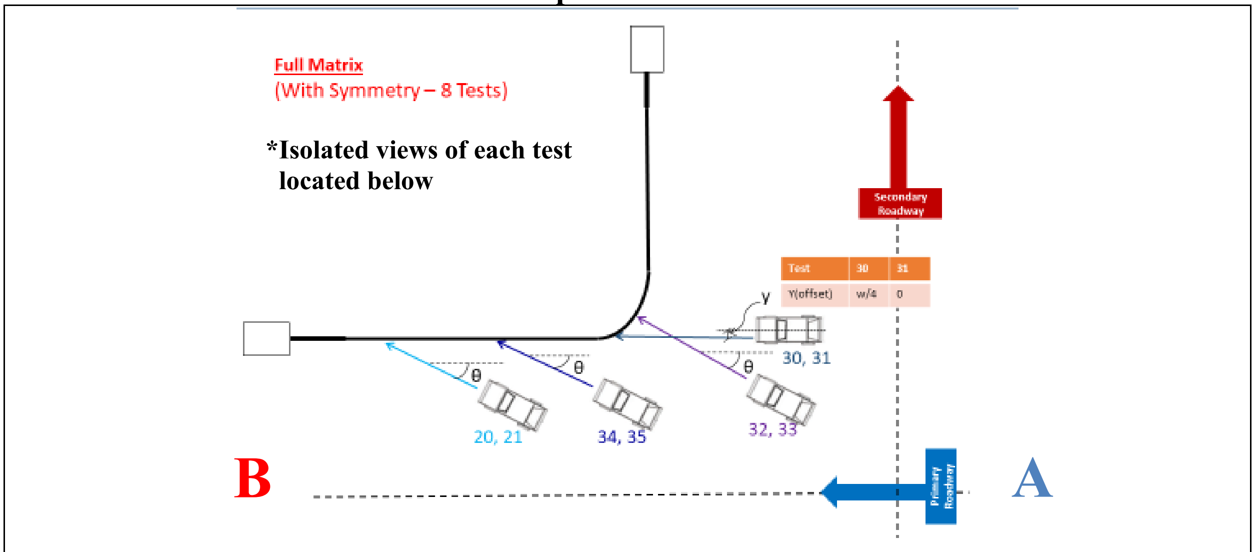
In addition to the survey, participants were requested to provide data of any practical case scenarios that they might have come across in their respective states. The data collected mainly included photographs of the cases showing the associated site constraints and site parameters where short radius guardrail systems were used and were considered to be critical with respect to the site constraints present. The site parameters included details such as the total number of lanes for primary and secondary roads, speed categories for primary and secondary roads, offset distance of the hazard from the face of the road etc.

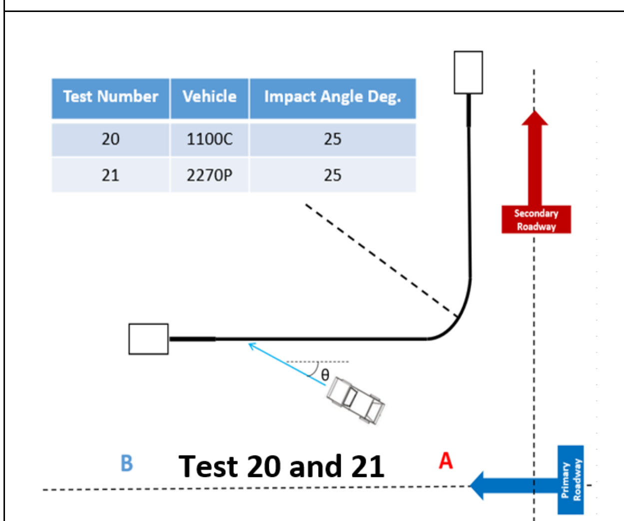
Photographs and documents representing specific site cases have been attached in Appendix C.

4.2 PROPOSED TEST MATRIX

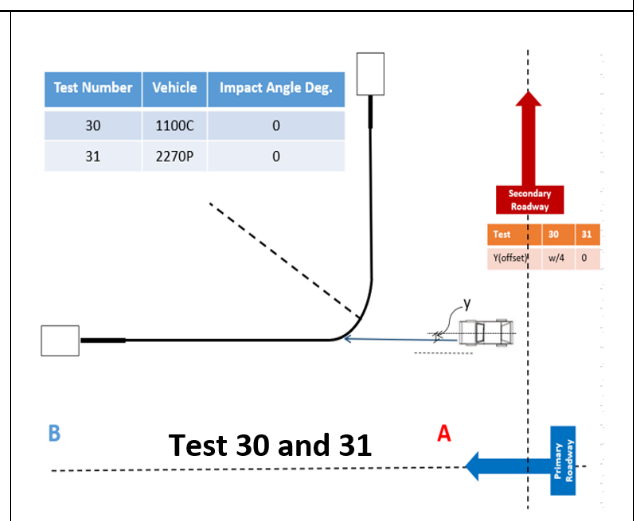
After reviewing the results of the survey and specific site cases researchers developed a new test matrix made up of the MASH tests deemed critical. The proposed test matrix is comprised of 8 tests, 2 transition section tests (20 and 21) and 6 terminal/crash cushion tests (30-35). As with the original MASH test matrix, the number of tests required to perform is based on the symmetry of the system. Asymmetric systems require testing of the test matrix on both approaches to the system, bringing the total number of tests to 16. Symmetric systems only require testing for one approach. The full test matrix is shown in Table 8.

Table 8. Proposed Full Test Matrix

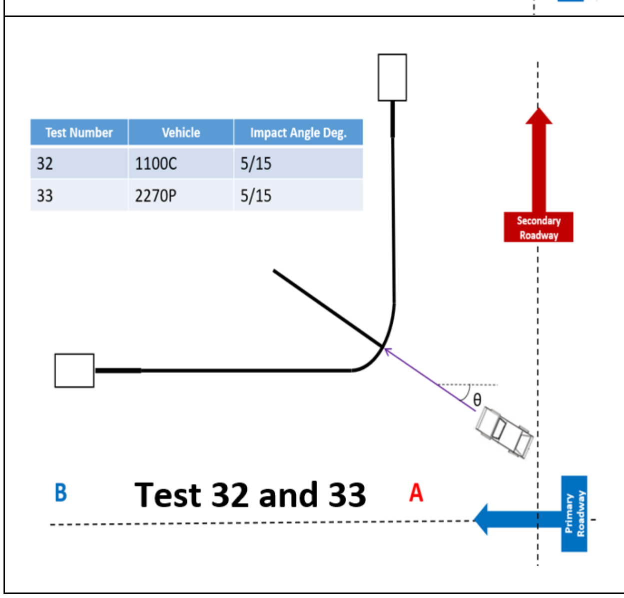




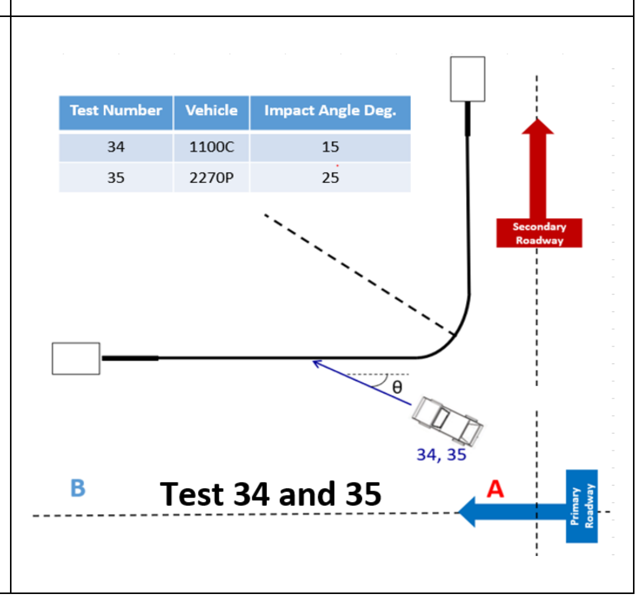
Test Number	Vehicle	Impact Angle Deg.
20	1100C	25
21	2270P	25



Test Number	Vehicle	Impact Angle Deg.
30	1100C	0
31	2270P	0



Test Number	Vehicle	Impact Angle Deg.
32	1100C	5/15
33	2270P	5/15



Test Number	Vehicle	Impact Angle Deg.
34	1100C	15
35	2270P	25

In addition to the symmetry of the system, the direction of travel of the vehicle determines what tests are critical. For systems that are adjacent to roadways with bidirectional traffic, and unidirectional traffic in the same direction as the system, in the direction from A to B, the full test matrix is required with respect to the symmetry of the system. For systems placed on roadways with unidirectional traffic in the opposite direction of the system, in the direction from B to A, only 2 tests are deemed critical, test 34 and 35. The proposed required testing for roadways with unidirectional traffic in the opposite direction as the system is shown in Figure 6.

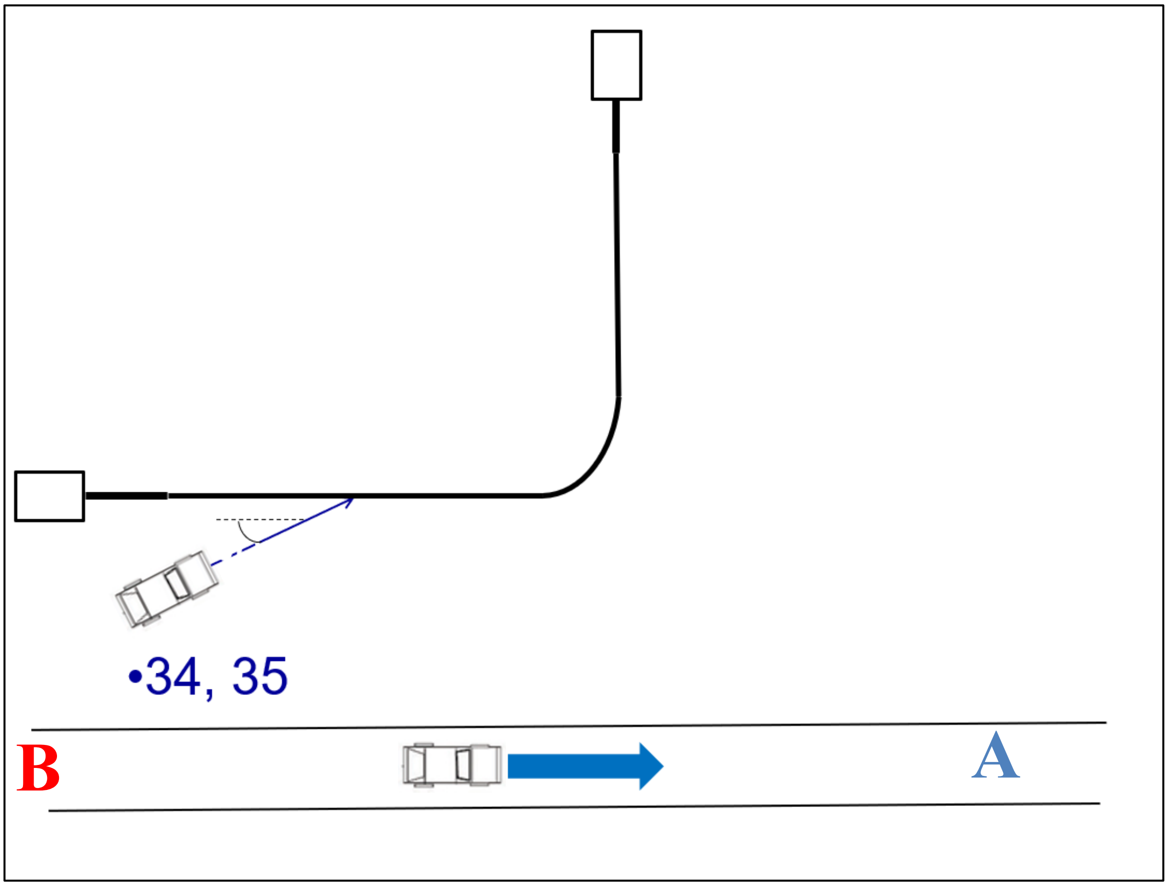


Figure 6. Proposed Test Matrix for Unidirectional Traffic in Opposite Direction as System.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 RECOMMENDED TEST MATRIX

After analyzing specific extreme site constraint cases indicated by state DOTs, researchers developed criteria for evaluating roadside safety devices placed in areas with extreme site constraints. The developed evaluation criteria are based on the symmetry of the system utilized and on the direction of traffic flow adjacent to the system. To help identify which evaluation criteria is recommended for a given system, a flow chart was developed. (Figure 7).

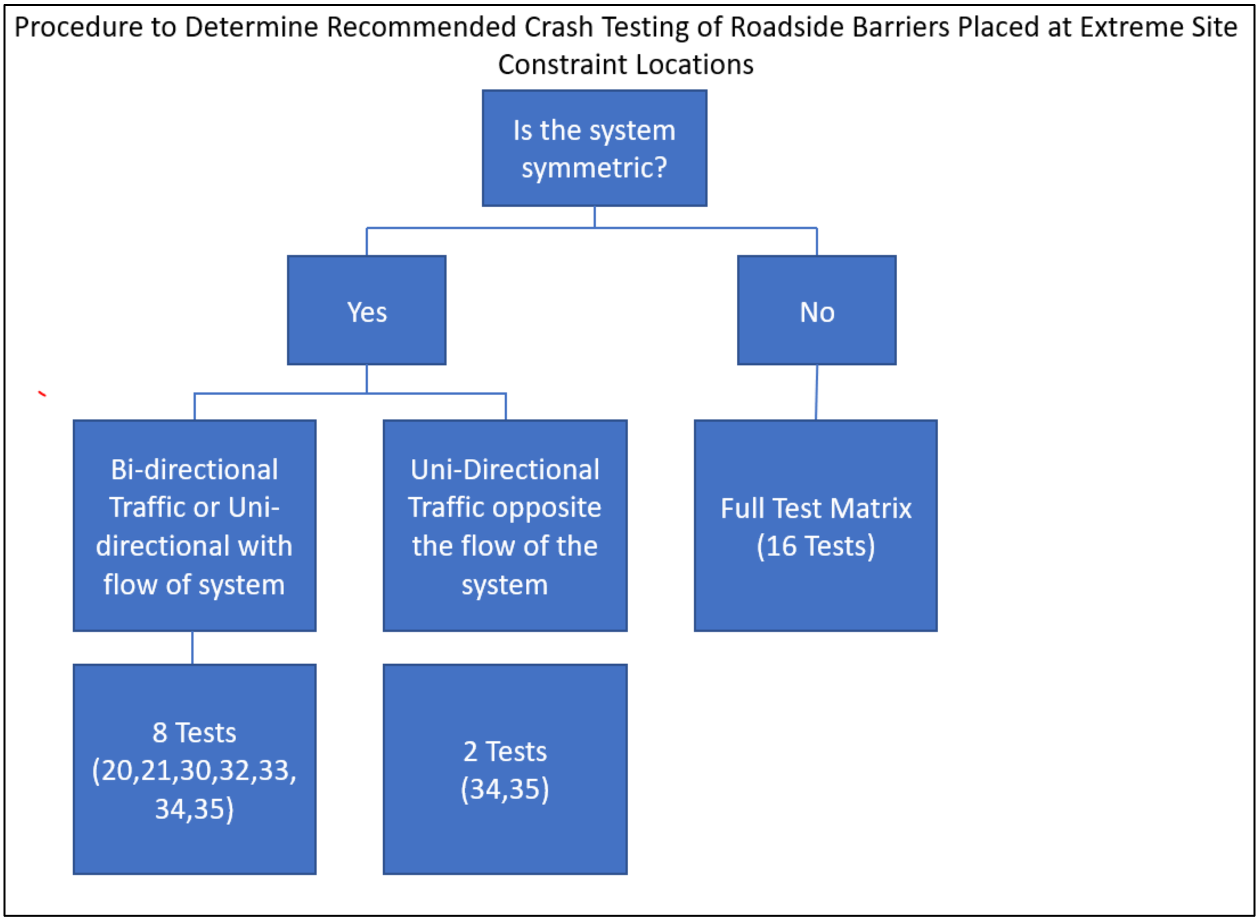


Figure 7. Proposed Flow Chart to Determine Required Testing

5.2 RECOMMENDED MINIMUM BARRIER LENGTH

Based on the theoretical minimum barrier length calculations, studying the lengths of the crash cushions currently being used, and insights from the researchers representing various DOTs, the lengths in Table 9 were selected as practical estimates for the minimum barrier lengths.

Table 9. Recommended Minimum Barrier Lengths.

TEST LEVEL	LENGTH (ft)
TL – 3	19
TL – 2	8

5.3 RECOMMENDATION FOR FUTUR RESEARCH

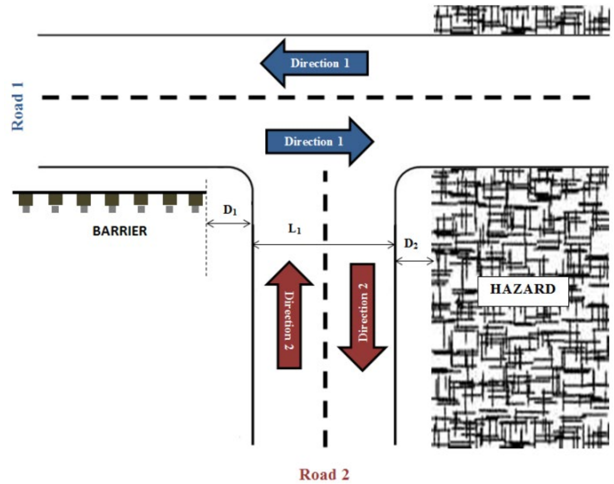
This report presents preliminary views of the research team to develop a template for evaluating a short radius design for an extreme site constraints placement. Further research is needed to refine the template using more representative crash data for encroachment (speed and angle) for such geometric constraints. Additionally, an investigative study is needed to address a realistic implementation process of such template.

REFERENCES

1. AASHTO. *Manual for Assessing Roadside Safety Hardware, Second Edition.* American Association of State Highway and Transportation Officials: Washington, DC, 2016.
2 FMVSS. Federal Motor Vehicle Safety Standards and Regulations, U. S. Department of Transportation, National Highway Traffic Safety Administration, Washington, DC, March 1999.
3. Abu-Odeh A.Y., Kim K.-M., Alberson D.C., *Evaluation of Existing T-Intersection Guardrail Systems for Equivalency with NCHRP Report 350 TL-2 Test Conditions*, Texas Transportation Institute, Project No. 405160-10, College Station, Texas, August 2010.
4. AASHTO, *1989 Guide Specification for Bridge Railings*, American Association of State Highway and Transportation Officials, Washington D.C., 1989.
5. Michie J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, NCHRP 230, Transportation Research Board, Washington D.C., March 1981.
6. Ross, H. E., Sicking, D. L., et al., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, NCHRP Report 350, Washington D.C., 1993.
7. Silvestri Dobrovolny, C., Brackin M.S., and Betancourt, P., *Best Practices for Barrier Protection of Bridge Ends*, Pooled Fund Project, Washington State Department of Transportation, Report No. 405160-38, Texas A&M Transportation Institute, 2013.
8. Abu-Odeh, A.Y., McCaskey, K.M., Bligh, R.P., Menges, W.L., and Kuhn, D. L. Crash Test and MASH TL-3 Evaluation of the TxDOT Short Radius Guardrail, Report No. 0-6711-1, Texas A&M Transportation Institute, College Station, TX, March 2015.

APPENDIX A. SPECIFIC SITE CASES – FEASIBLE AREA FOR SHORT RADIUS GUARDRAIL

SITE CASE - 1

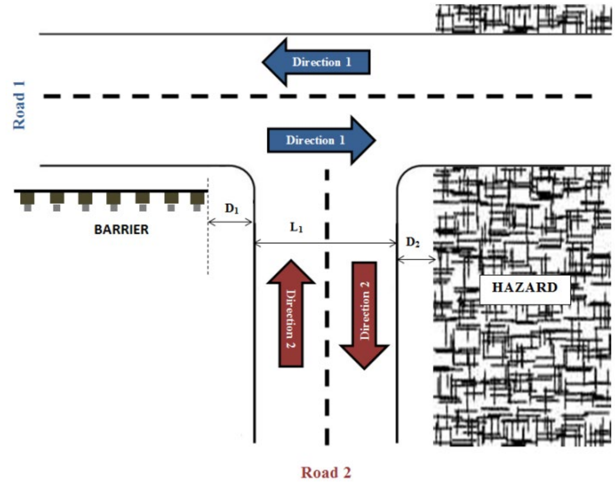


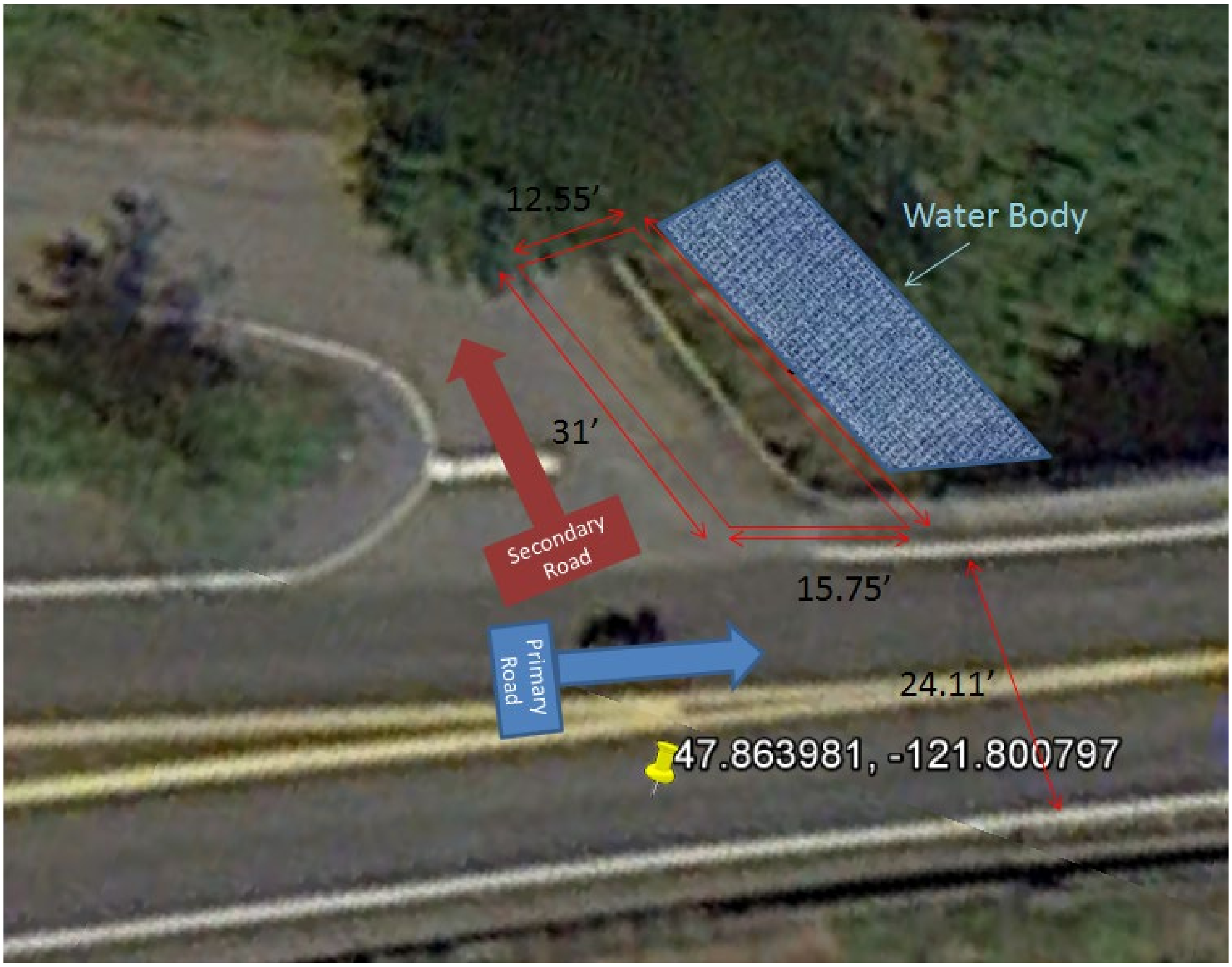
Site Parameters Identified:				
State	Speed Limit (mph)	D1 (feet)	D2 (feet)	L1 (feet)
Louisiana	55	20	0	20.22
Link for Google Maps				


WEIGHT LIMIT
RIVER
LAKE

The shaded area shows the Available region to install a short- radius guardrail. The area is predicted based on the potential hazards for a vehicle traveling in the vicinity of the bridge end. In this case, for the primary road, the bridge end itself acts as one of the hazards. Therefore, even though the actual hazard is the water body present, the width of the feasible area is restricted to about 20 ft. in the direction of the primary road. Since there is no notable hazard in the direction of the secondary road, we can assume a width of about 65 ft. for the feasible area based on the length of the existing guardrail.

SITE CASE - 2

				
State	Speed Limit (mph)	D1 (feet)	D2 (feet)	L1 (feet)
Washington	35	2.5	15.75	24.11
Link for Google Maps				



The marked area in the above figure shows the feasible region to install a short- radius guardrail. The area is predicted based on the potential hazards for a vehicle traveling in the vicinity of the bridge end. In this case, both the bridge end and the water body are potential hazards for vehicles traveling on the primary road. This restricts the width of the feasible area in the direction of the primary road to about 16 ft. For vehicle traveling in the direction of the secondary road, the terrain on the right side of the road restricts the width of the feasible area to about 31 ft. from the end of the road.

APPENDIX B. THE SURVEY

2.1 SCOPE OF THE SURVEY

Texas A&M Transportation Institute (TTI) is conducting a study for the Roadside Safety Research Program Pooled Fund Study entitled "Feasibility study for addressing extreme site constraints at bridge ends".

As first step of this study, a survey was designed with the intent to gain information regarding generic site cases and their rank with respect to frequency of occurrence, according to DOTs experience.

The results of this survey will be used to develop a categorization methodology for determining proper impact conditions and evaluation criteria for future design concepts.

Your participation in the survey is very important to have your DOT's needs accurately represented in this study.

Thank you very much in advance for your time and dedication in helping with this research effort.

Contact Information

Please enter your contact information:

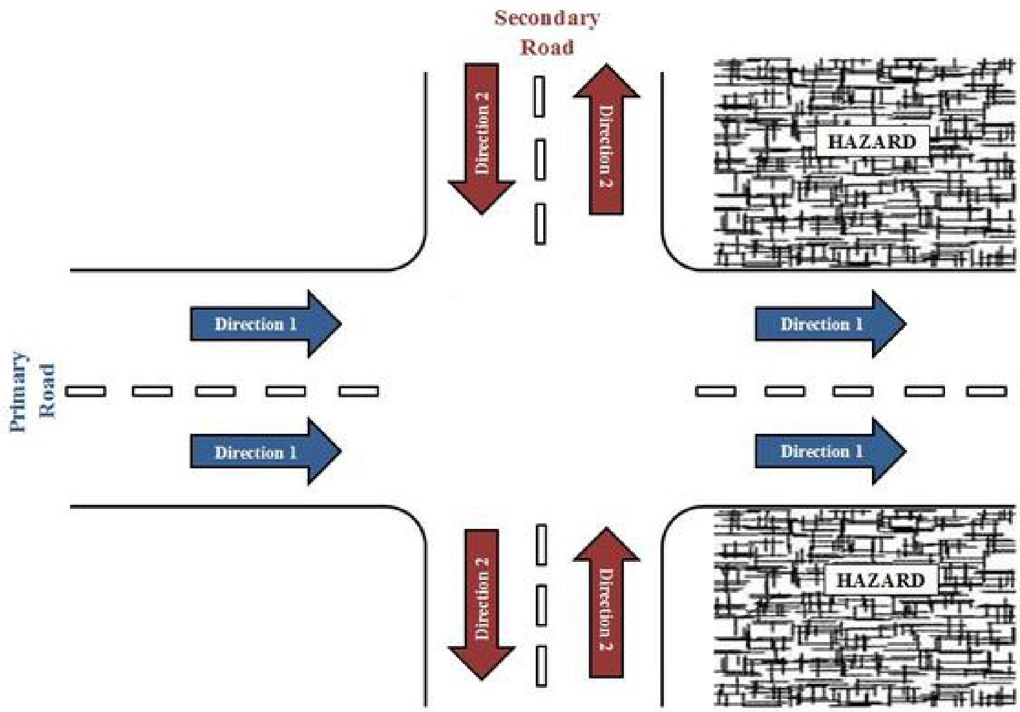
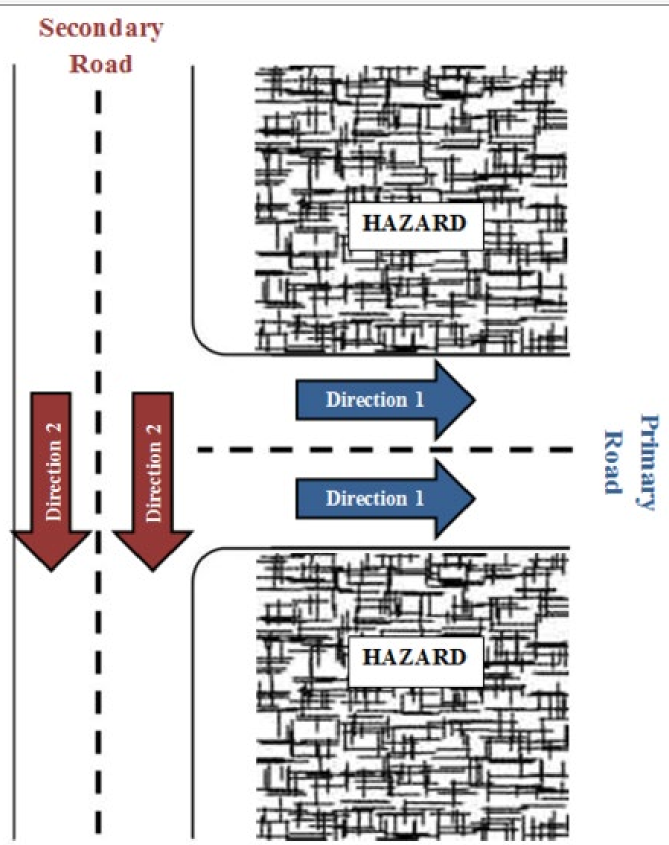
- Name:
- Title:
- Agency:
- Address:
- City/Town:
- State:
- ZIP:
- Email Address:
- Phone Number:

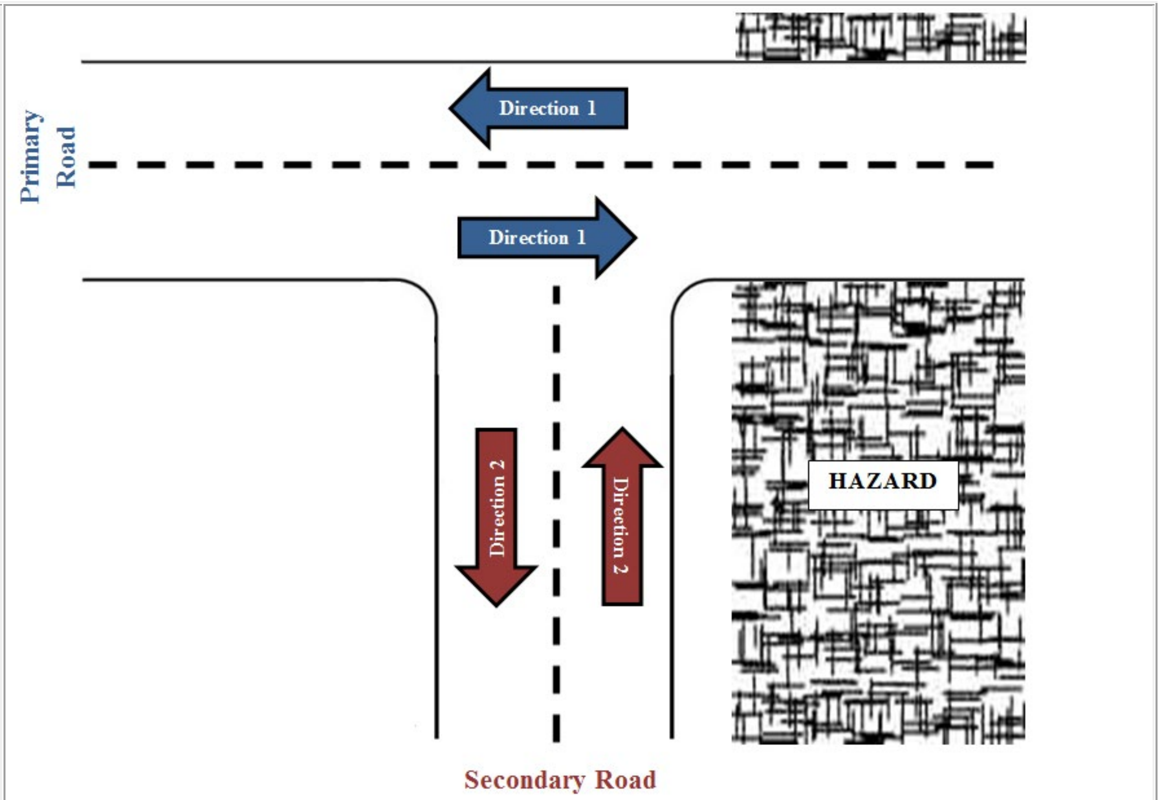
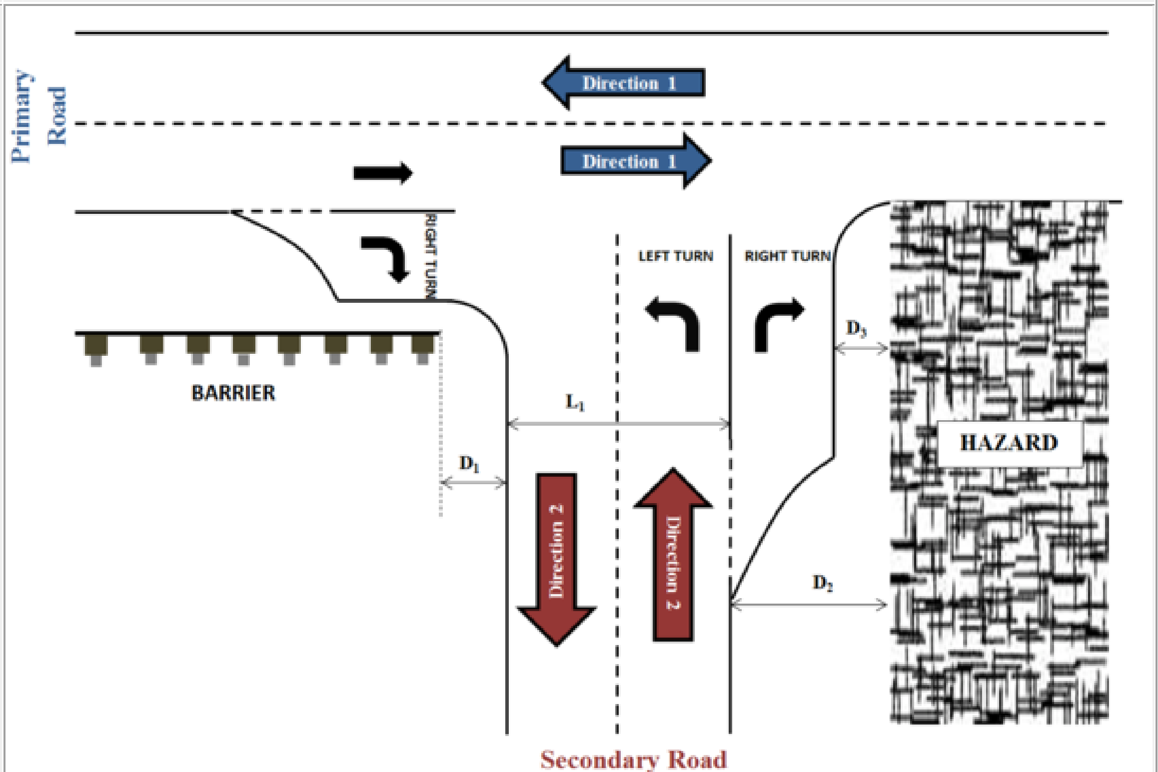
May we contact you for more information?

- Yes
- No

Please Contact:

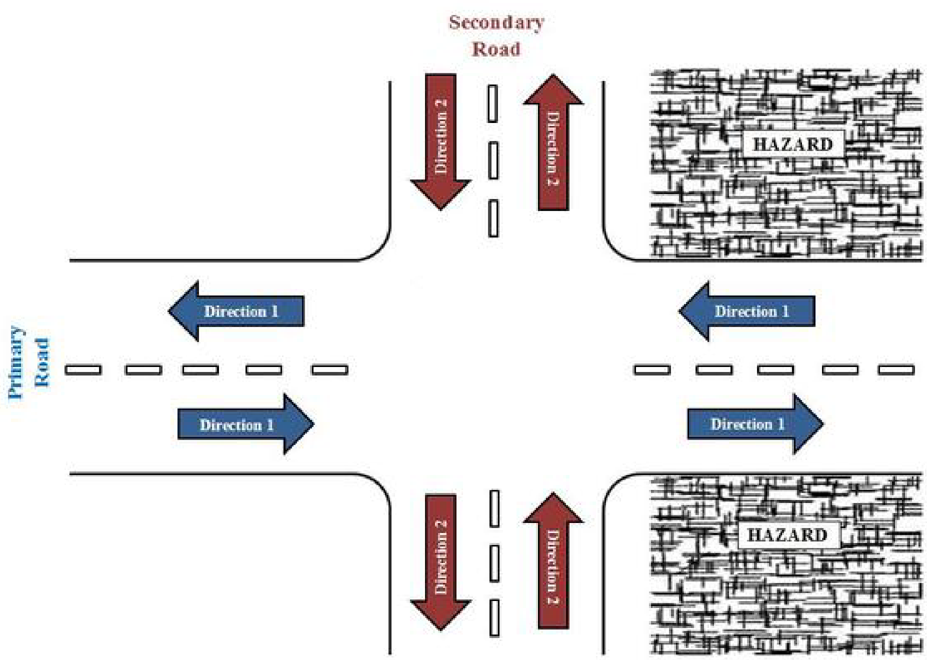
Please rank the following generic site cases according to their frequency of occurrence:

Case1.	
Case2.	

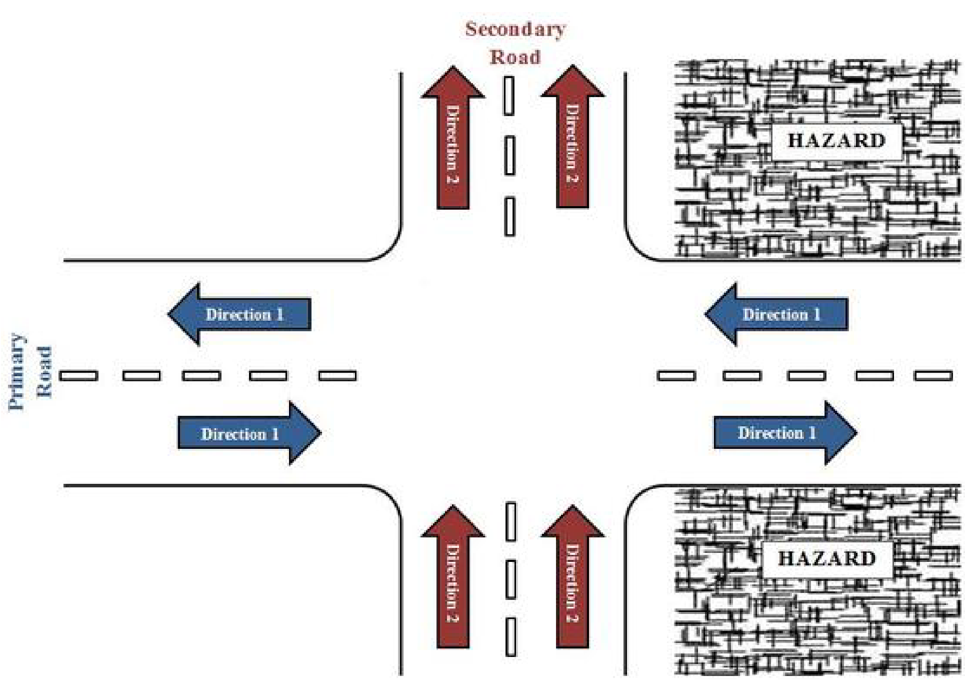
Case3.	Primary Road Direction 1 Direction 1 Direction 2 Direction 2 HAZARD Secondary Road
Case4.	Primary Road Direction 1 Direction 1 RIGHT TURN LEFT TURN RIGHT TURN BARRIER D3 L1 D1 HAZARD Direction 2 Direction 2 D2 Secondary Road

Please rank the following specific site cases according to their frequency of occurrence:

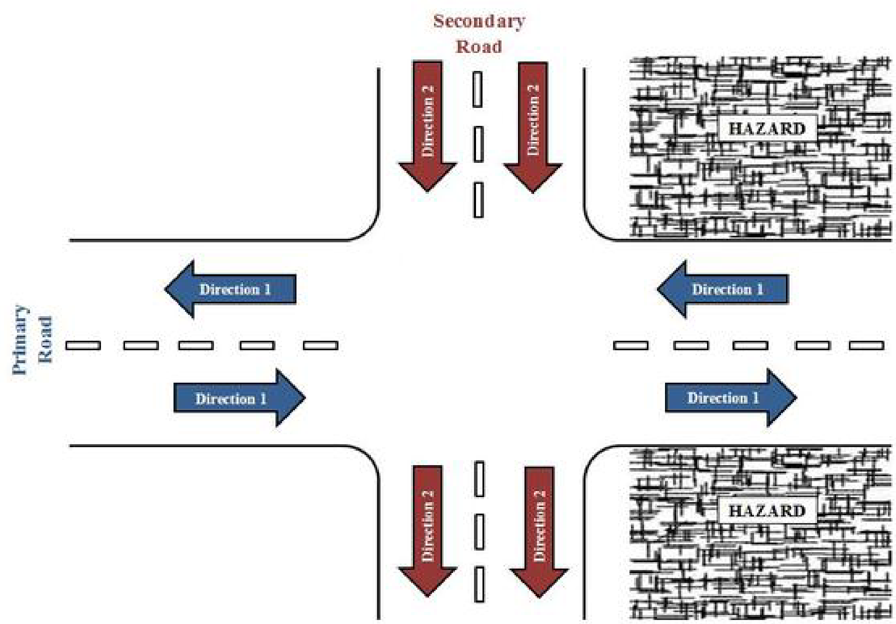
Case - 1.1



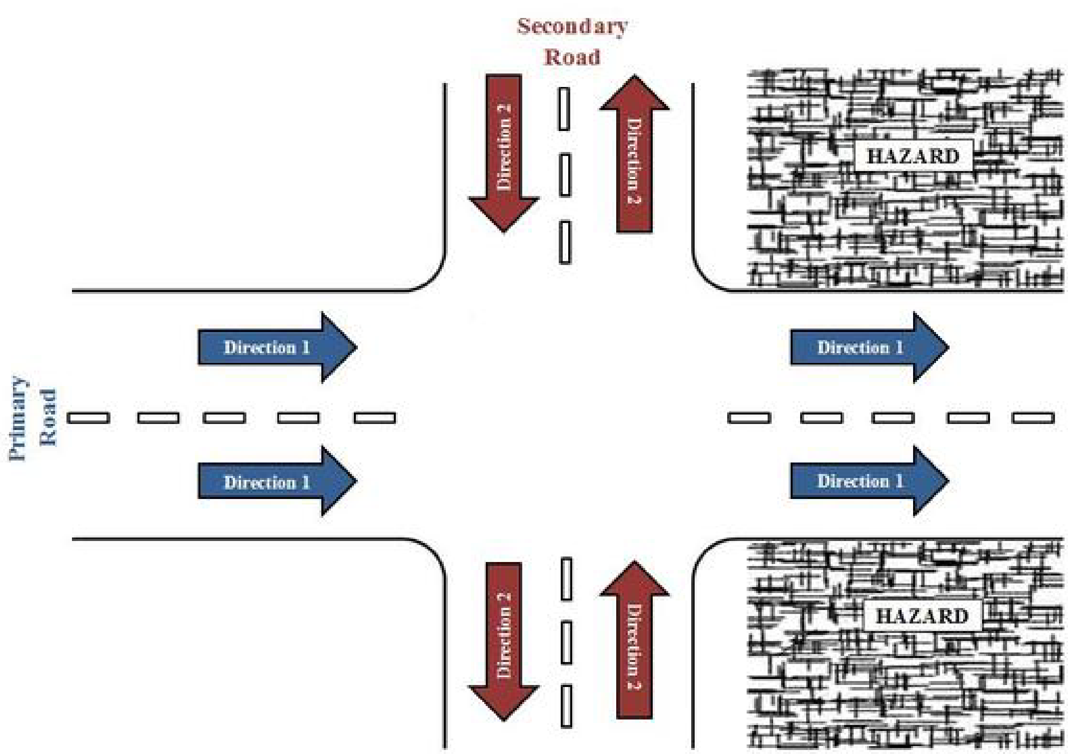
Case - 1.2



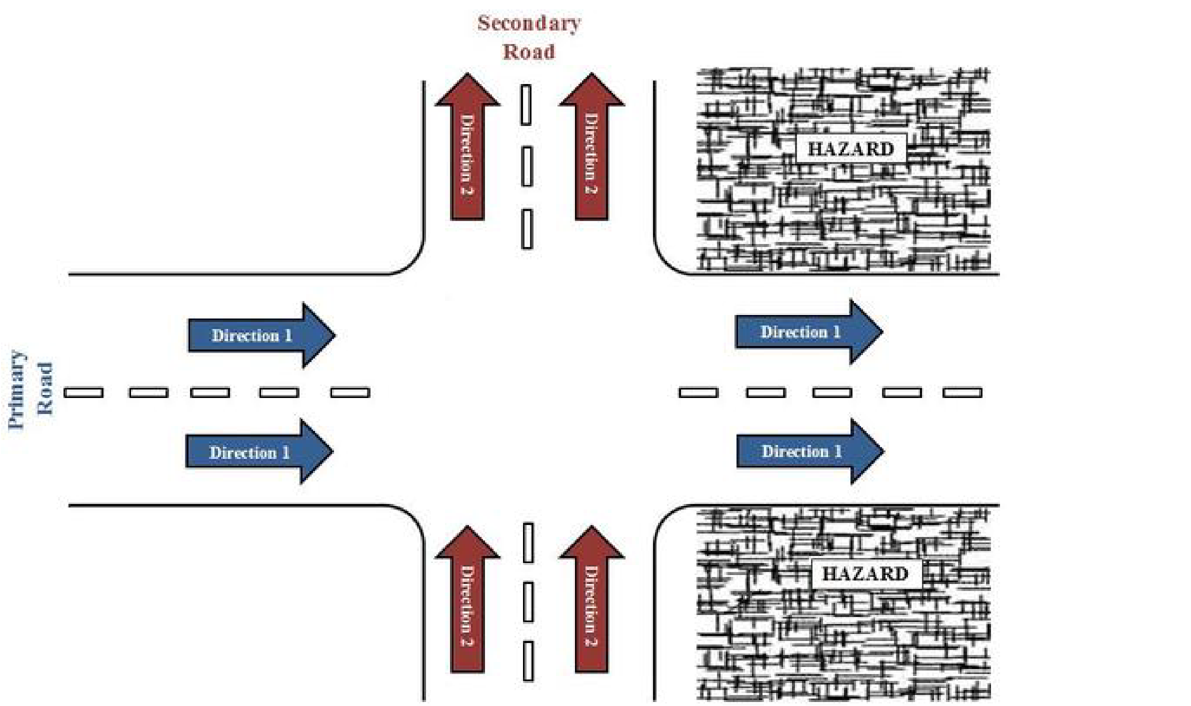
Case - 1.3



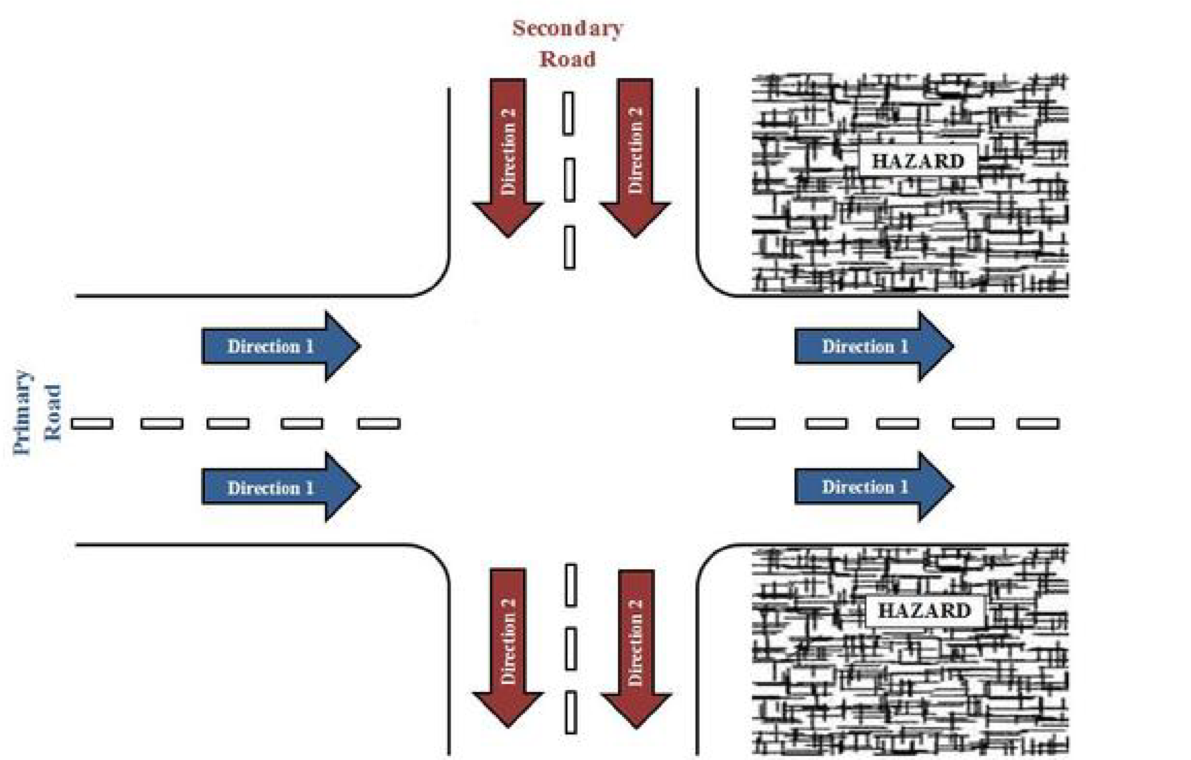
Case - 1.4



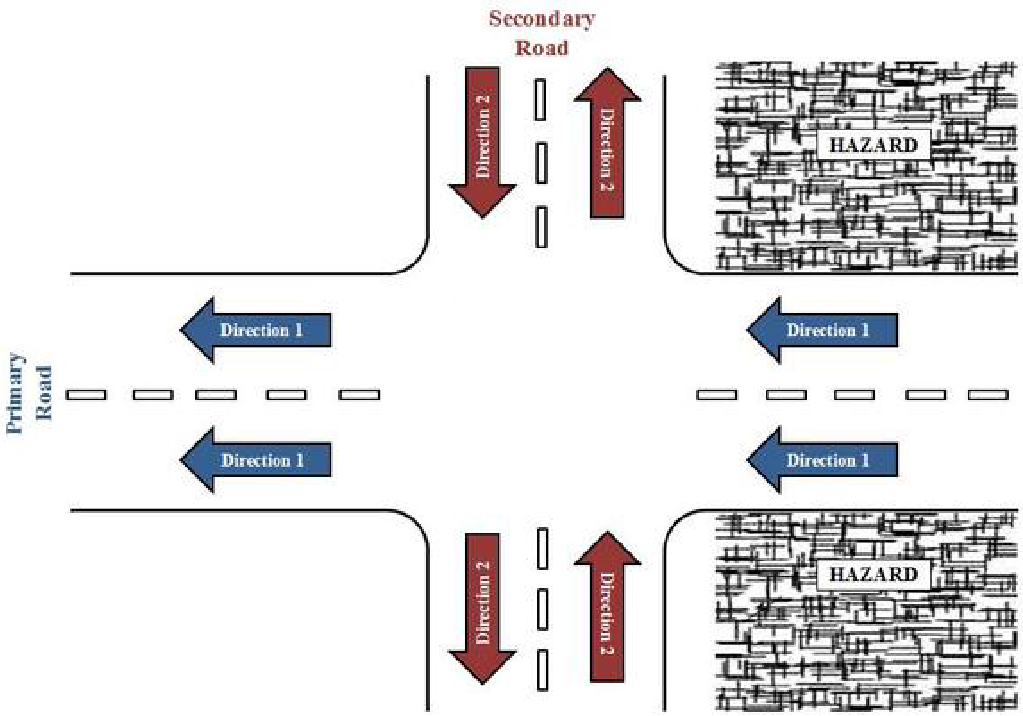
Case - 1.5



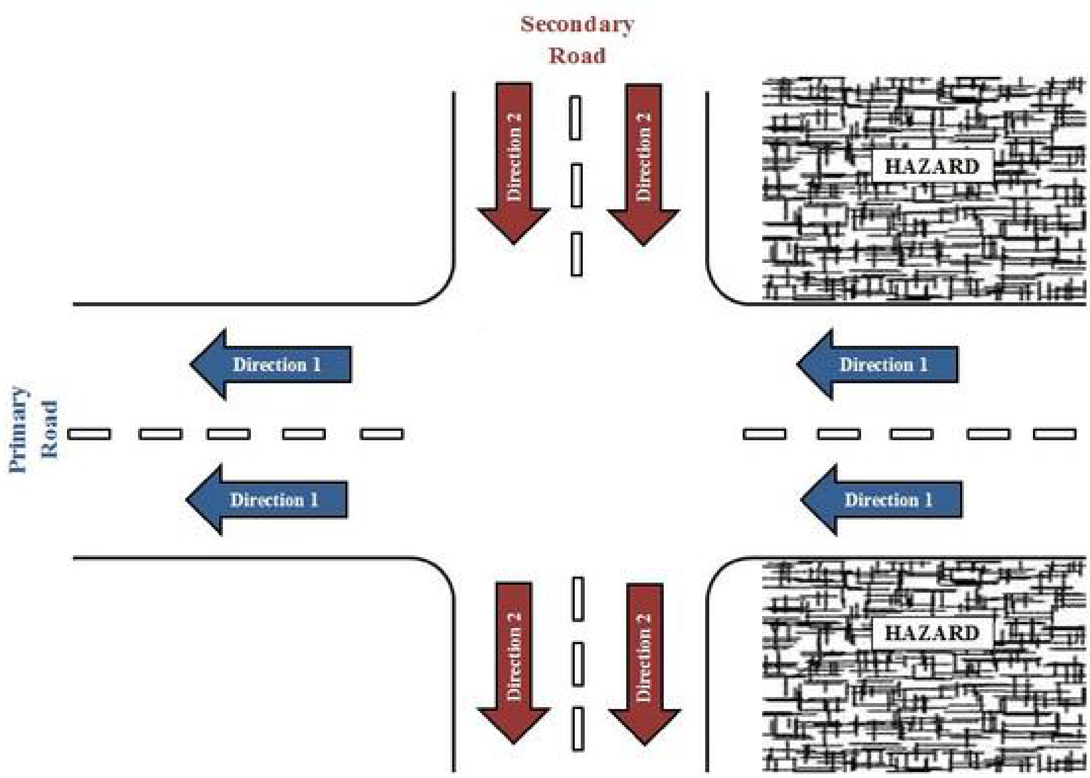
Case - 1.6



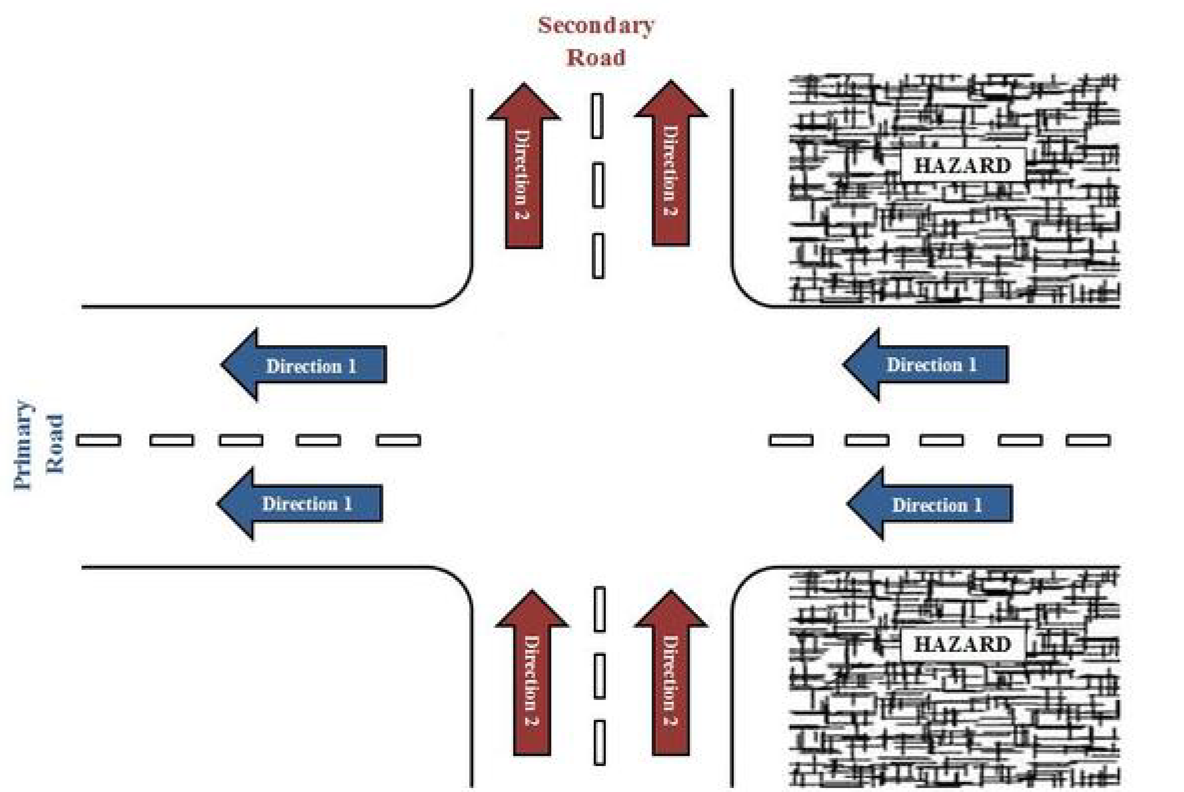
Case - 1.7



Case - 1.8

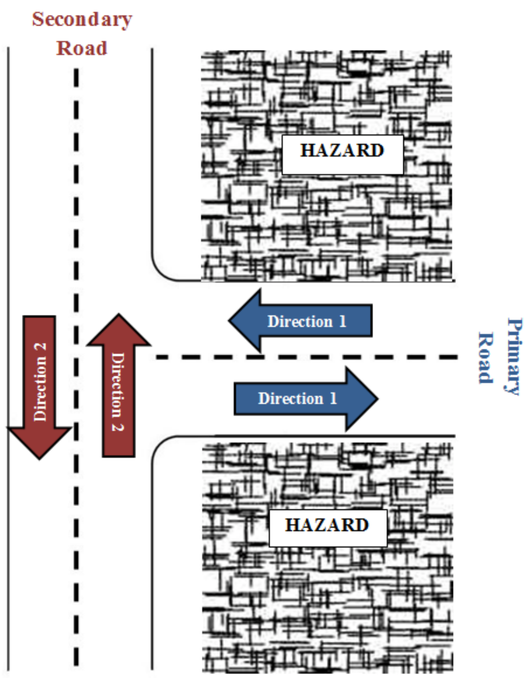


Case - 1.9

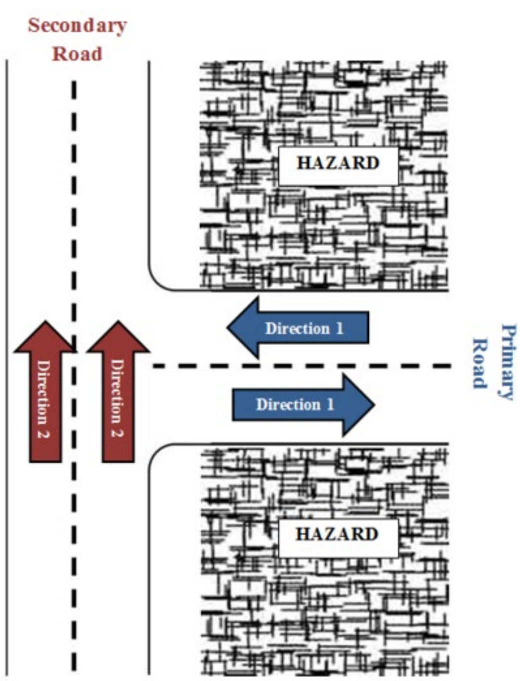

Secondary Road
Direction 2
Direction 2
HAZARD
Direction 1
Direction 1
Primary Road
Direction 1
Direction 1
Direction 2
Direction 2
HAZARD

Please rank the following specific site cases according to their frequency of occurrence:

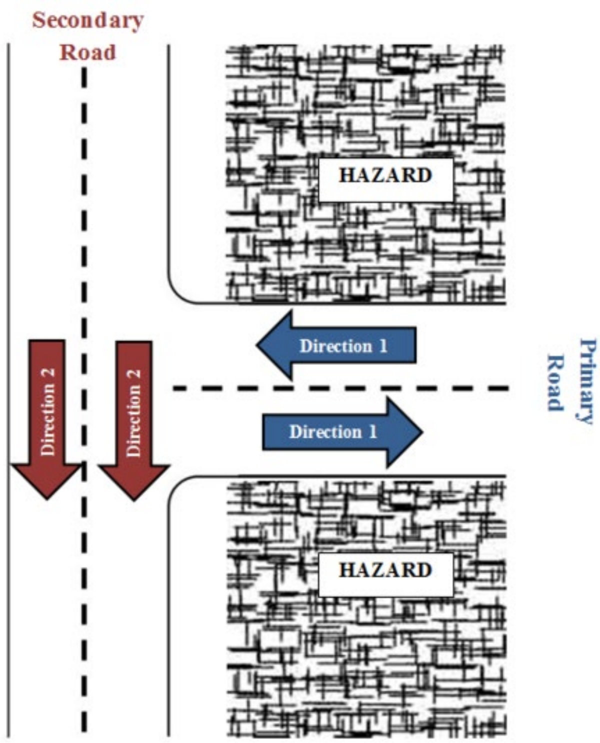
Case - 2.1



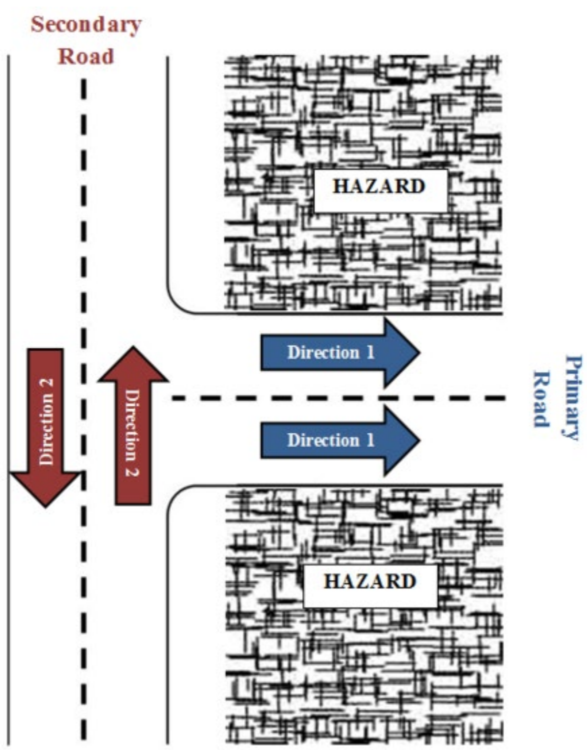
Case - 2.2



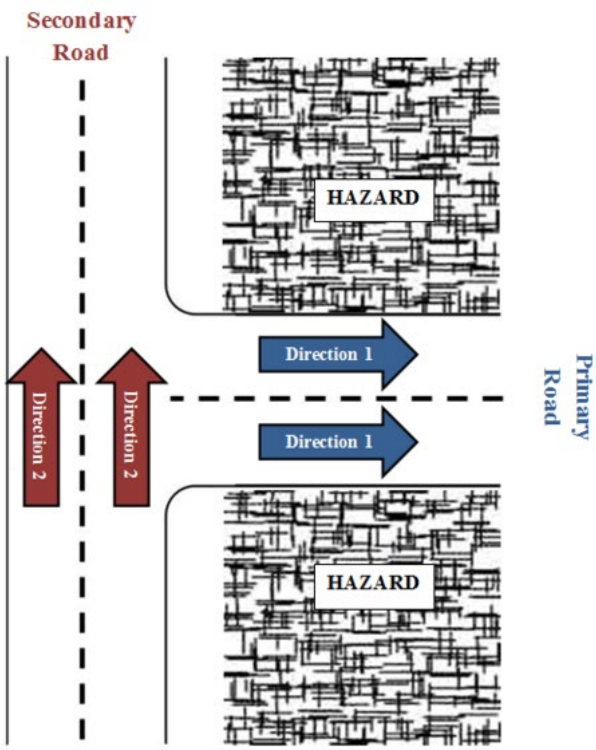
Case - 2.3



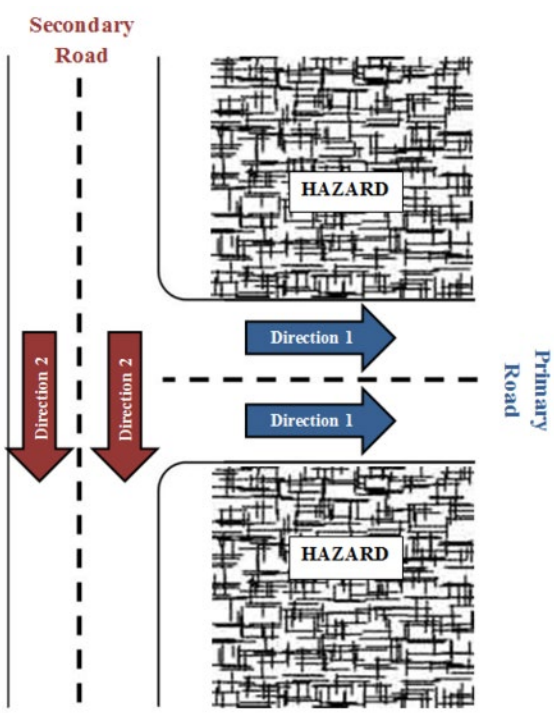
Case - 2.4



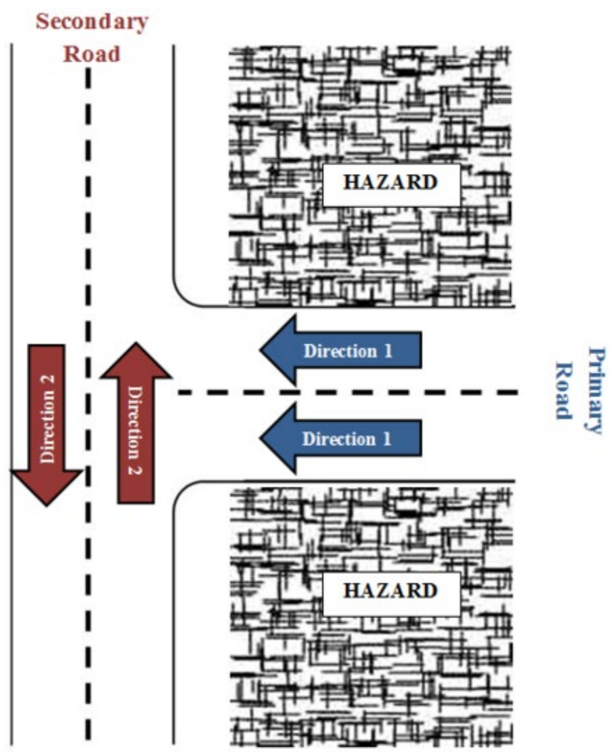
Case - 2.5



Case - 2.6



Case - 2.7



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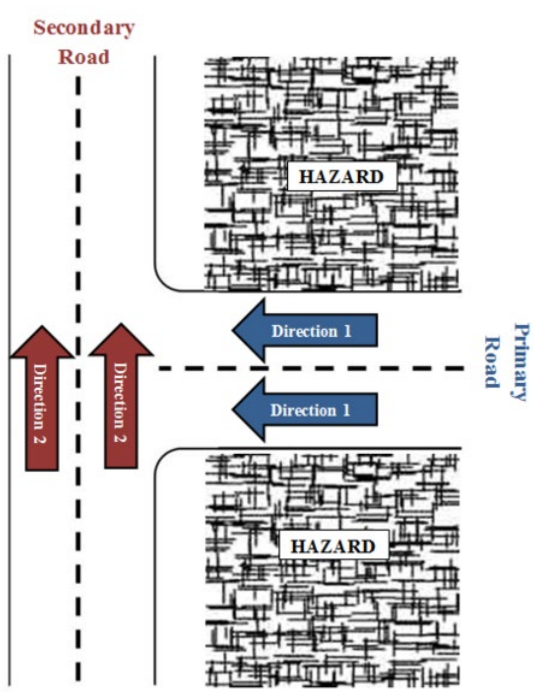
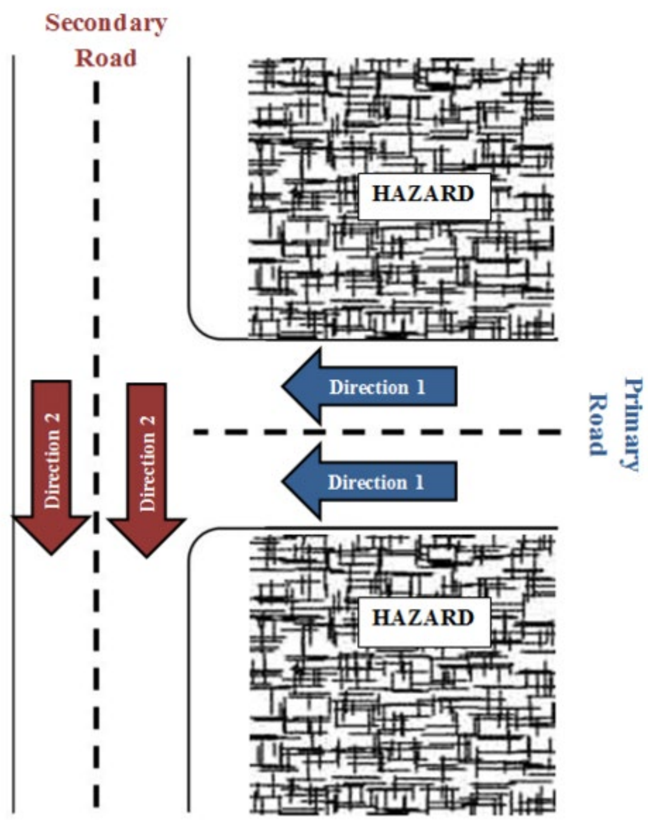
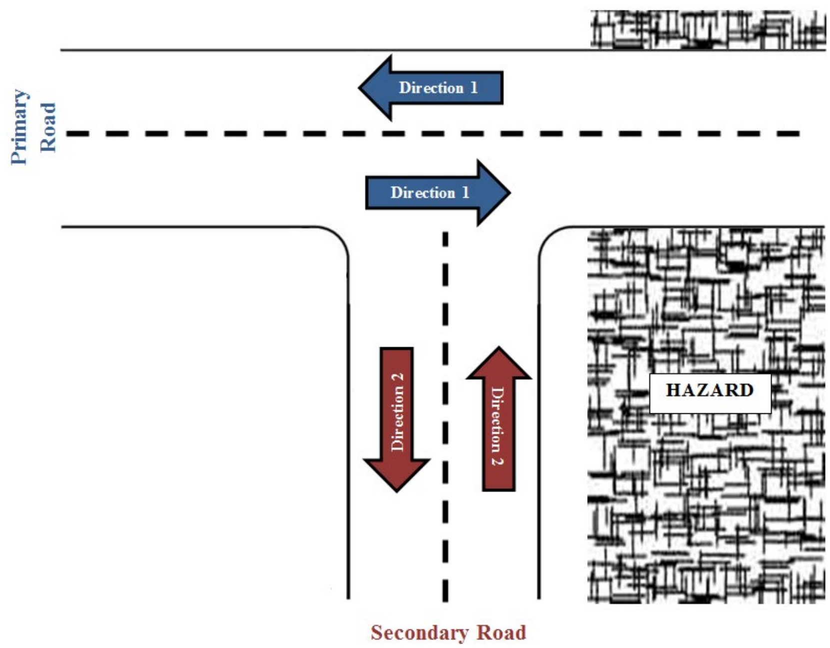


Case - 2.9

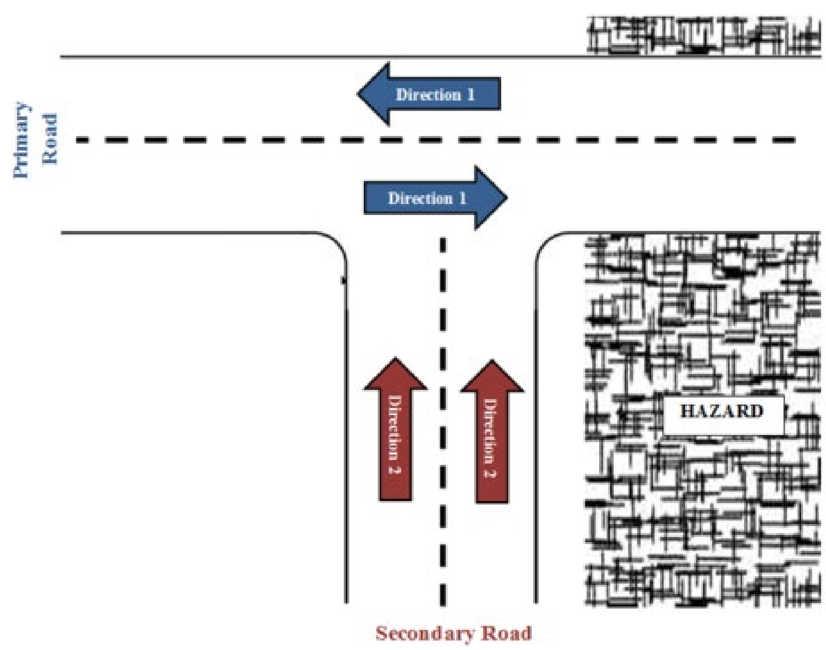

Secondary
Road
HAZARD
Direction 1
Direction 2
Direction 2
Direction 1
Primary
Road
HAZARD

Please rank the following specific site cases according to their frequency of occurrence:

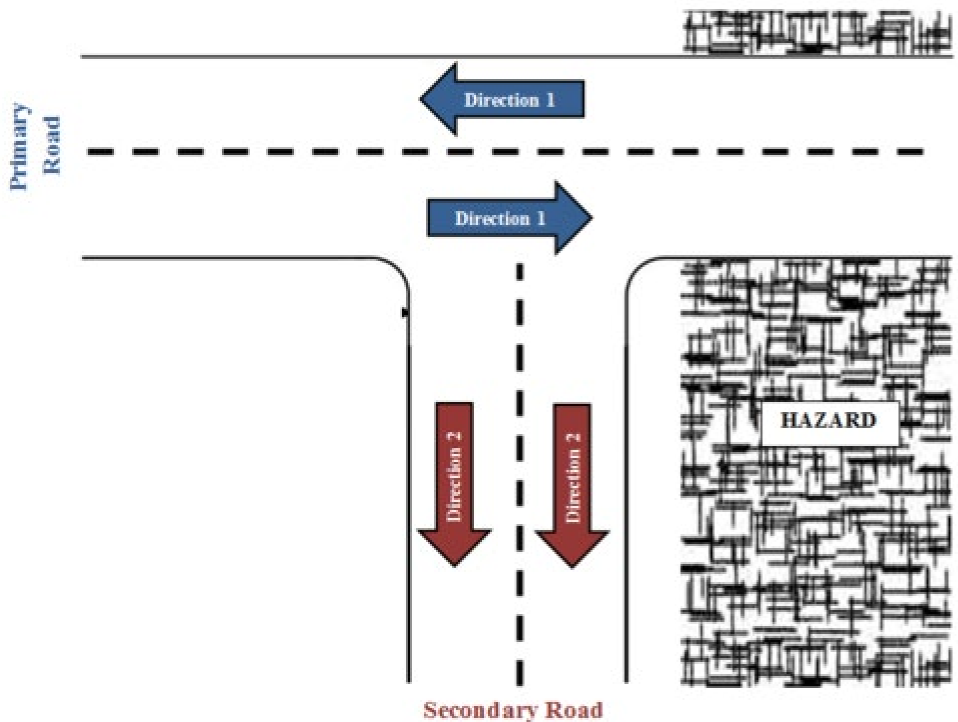
Case - 3.1



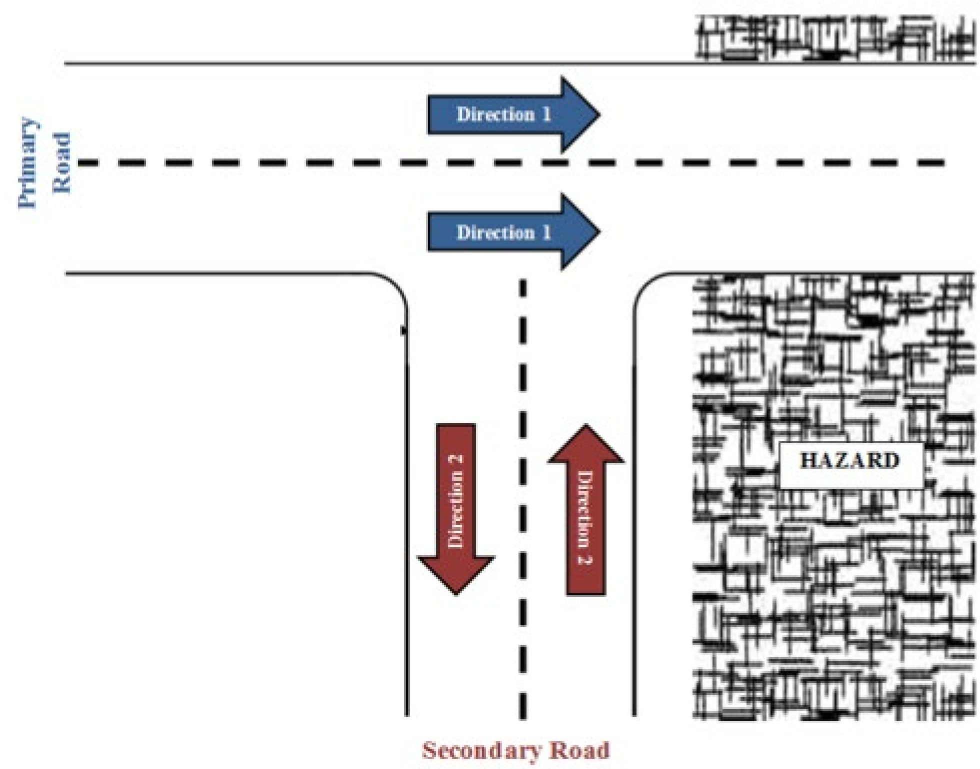
Case - 3.2



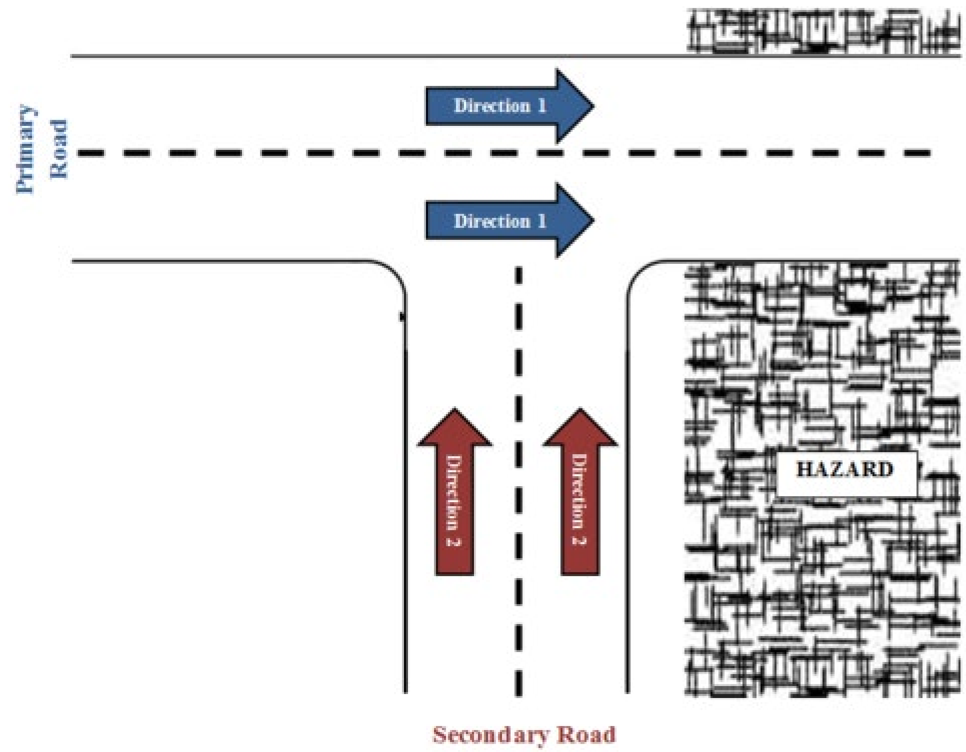
Case - 3.3



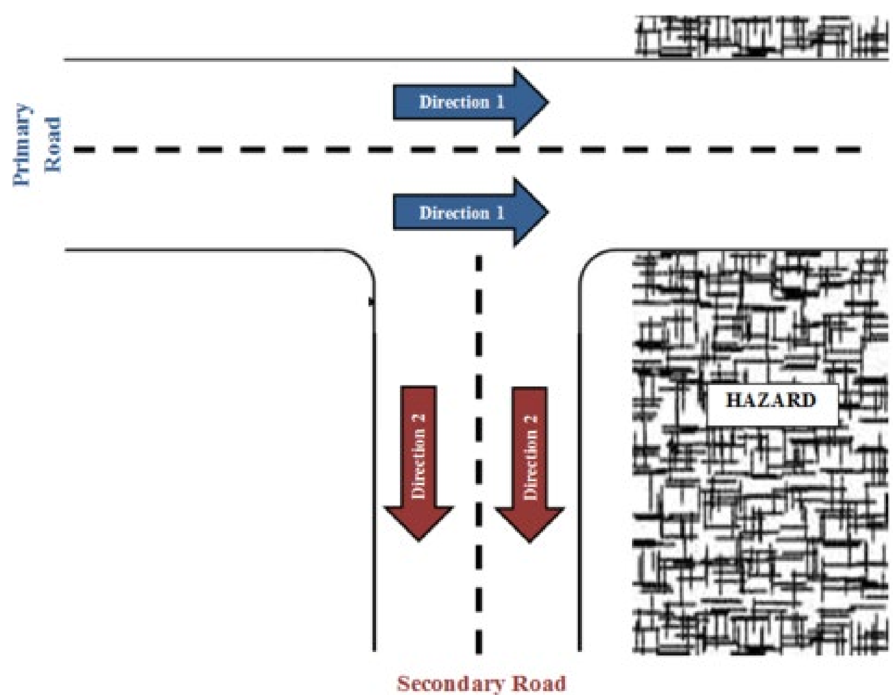
Case - 3.4



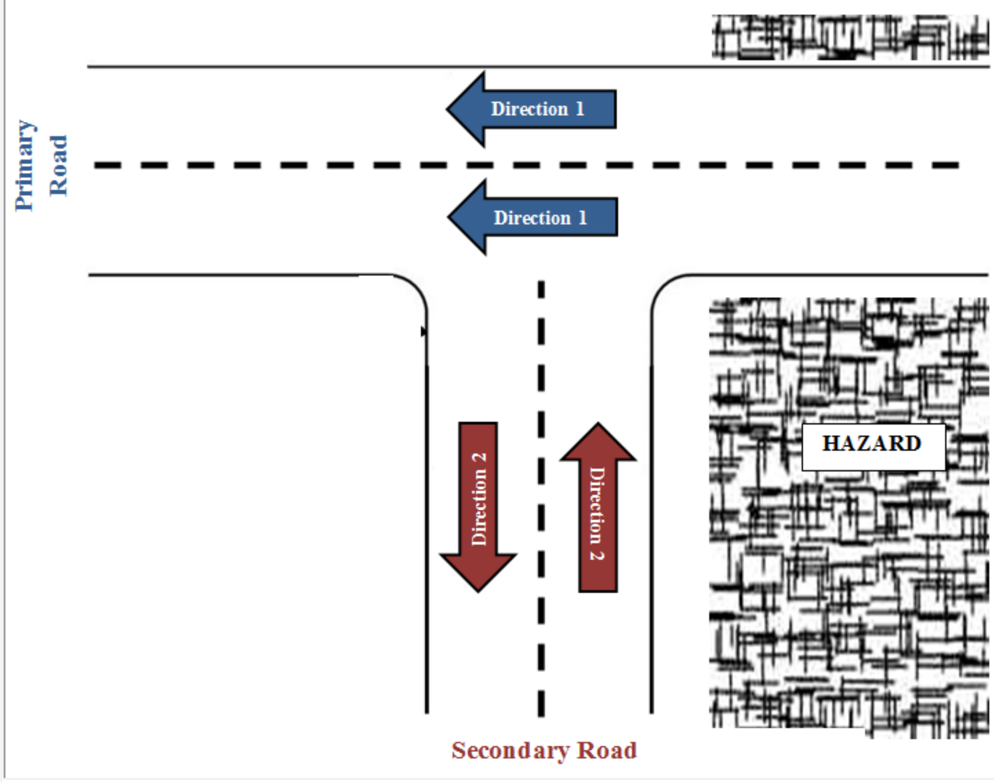
Case - 3.5



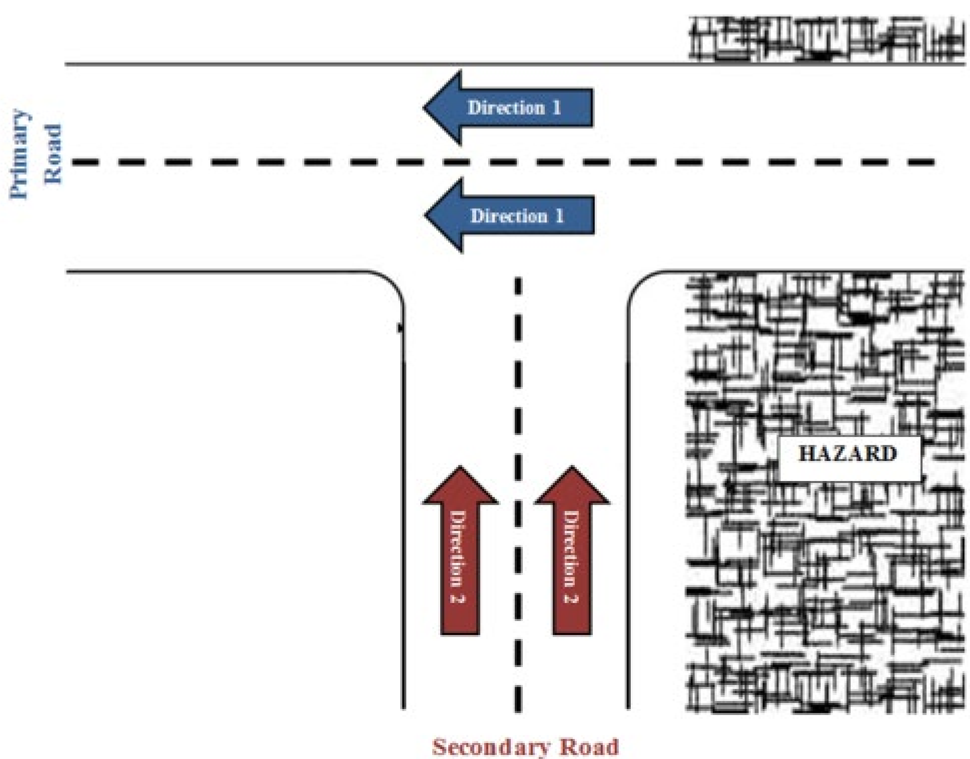
Case - 3.6



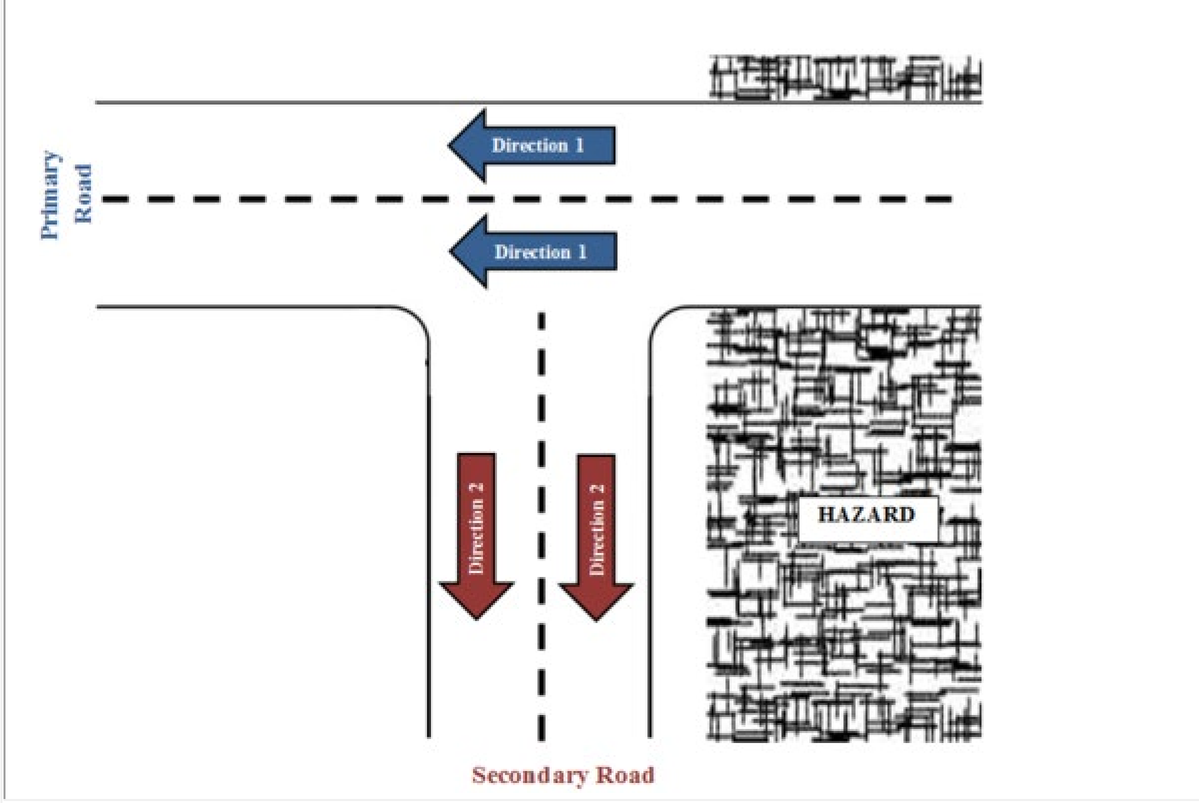
Case - 3.7



Case - 3.8



Case - 3.9


Direction 1
Direction 1
Primary Road
Direction 2
Direction 2
HAZARD
Secondary Road

If you would like to provide us with any further details or investigate any additional case, please email us at:

d-arrington@tti.tamu.edu

c-silvestri@ttimail.tamu.edu

r-rao@tti.tamu.edu

2.2 RESULTS FROM THE SURVEY

1. GENERIC CASES:

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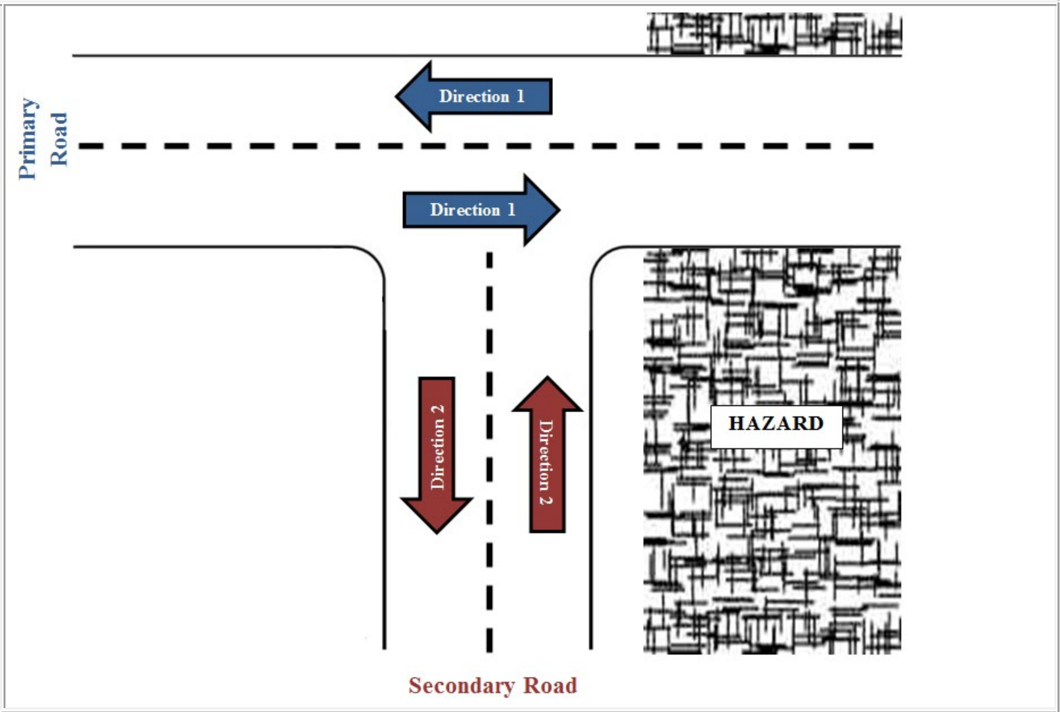
Case3.</td><td>
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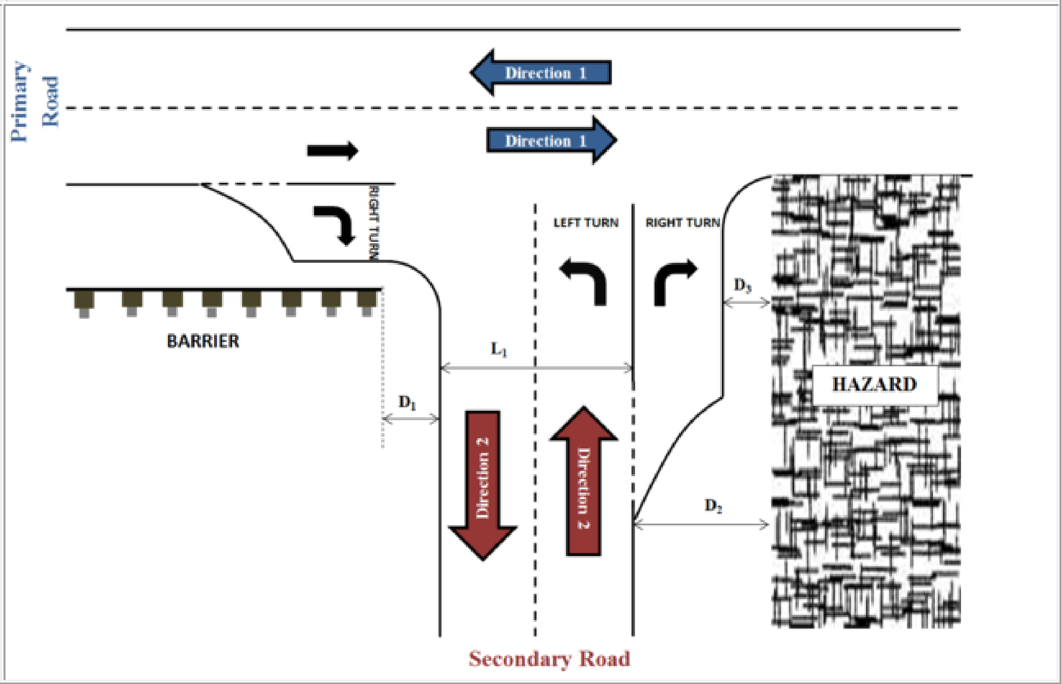
Case4.</td><td>
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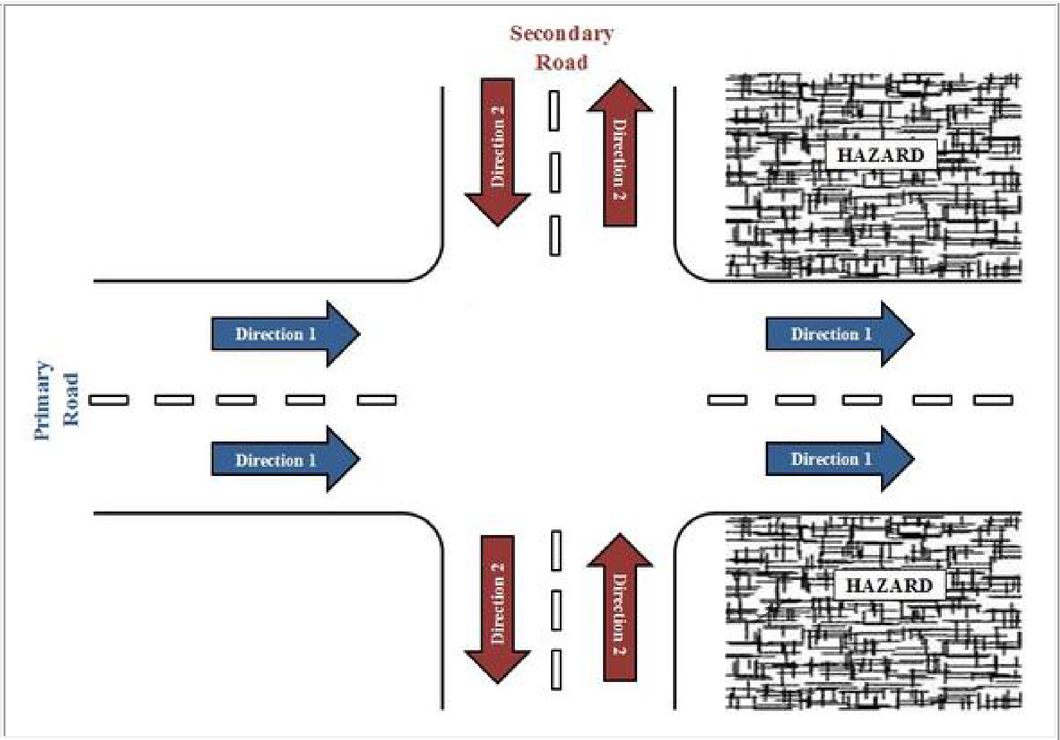
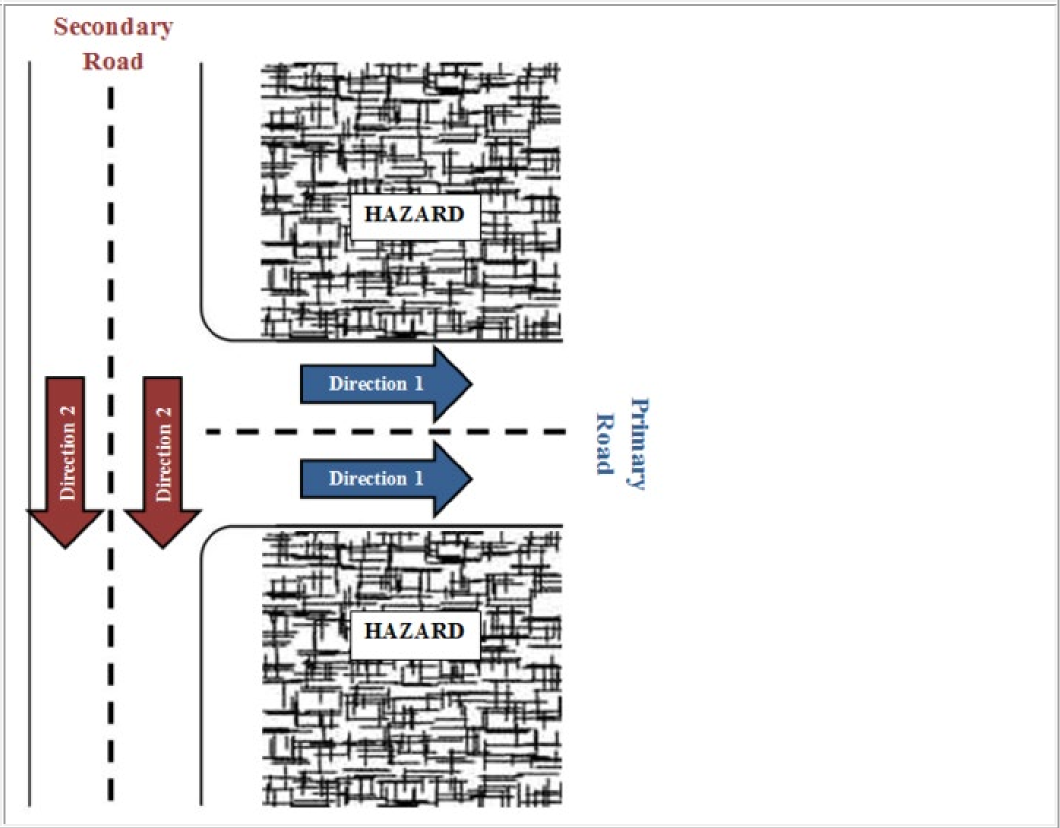
Case1.



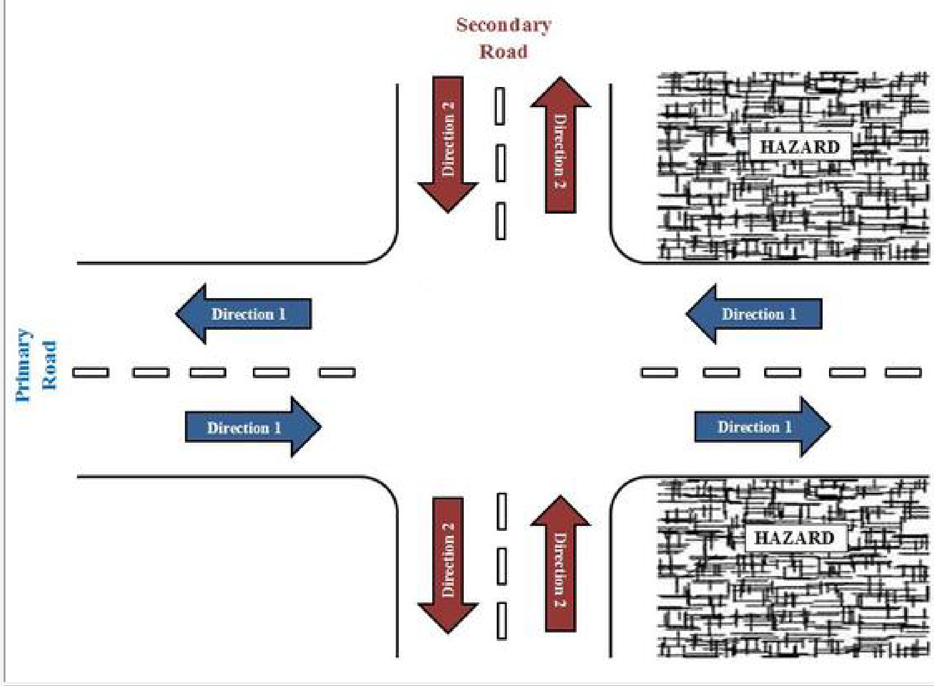
Rank.4
Case2.



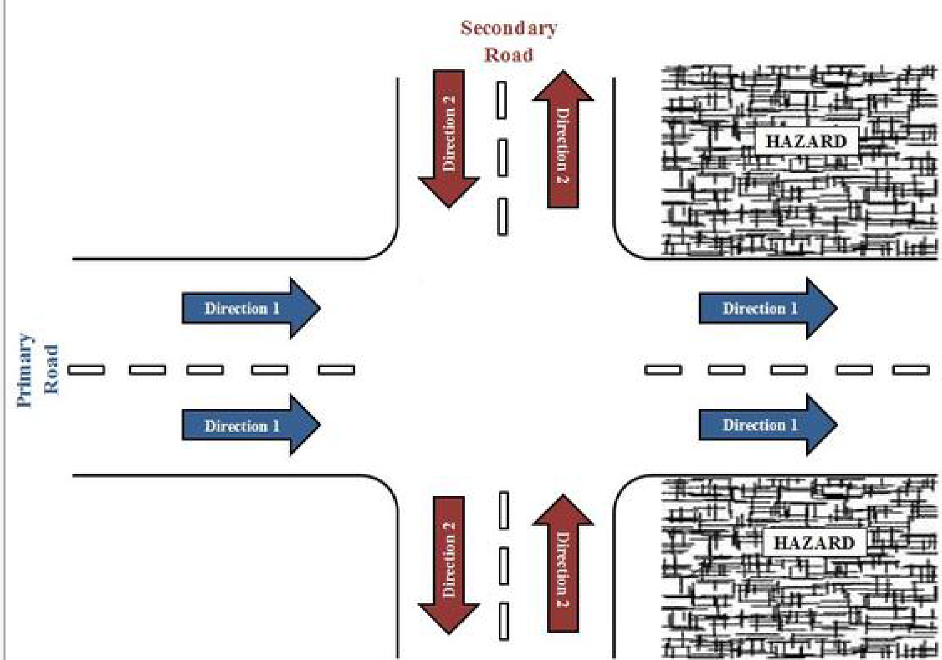
2. SPECIFIC SITE CASES:

I. CASE - 1

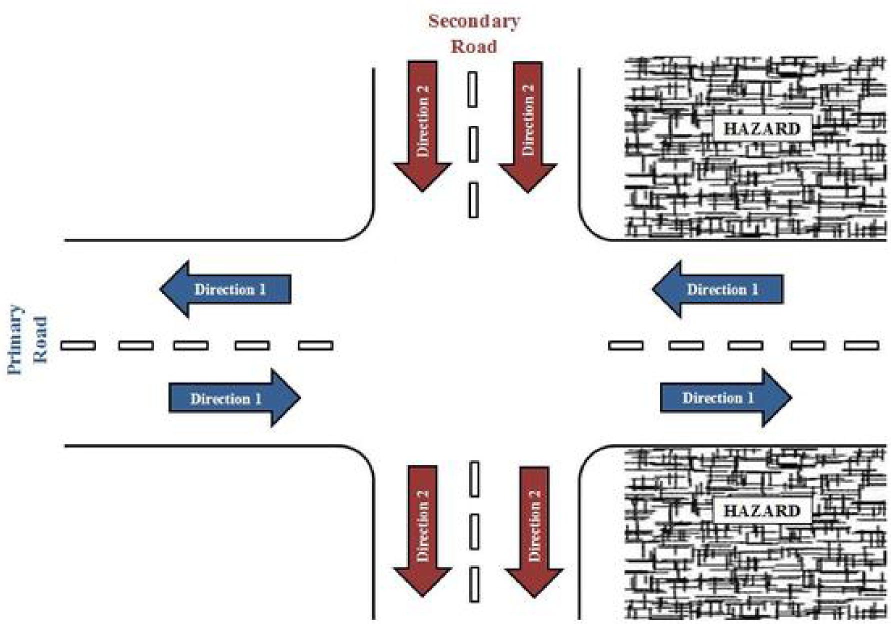
Rank.1: Case - 1.1



Rank.2: Case - 1.4

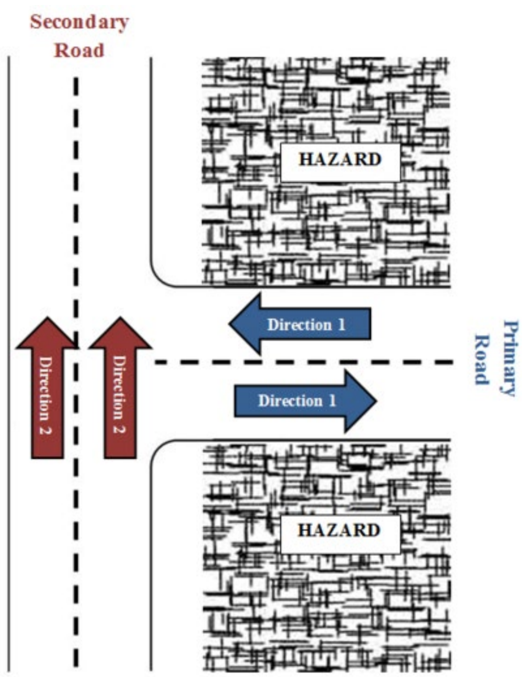


Rank.3: Case - 1.3

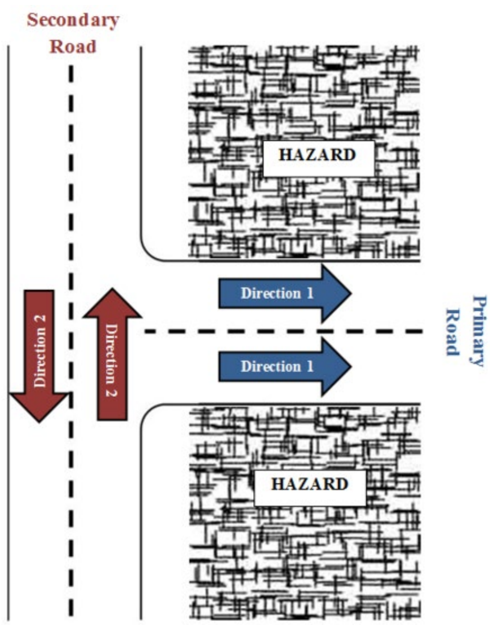


II. CASE – 2

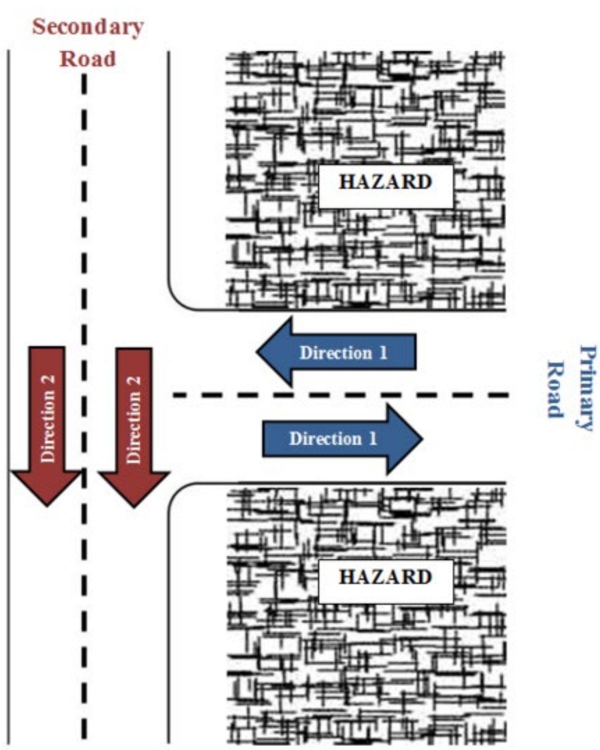
Rank.1: Case - 2.2



Rank.2: Case - 2.4

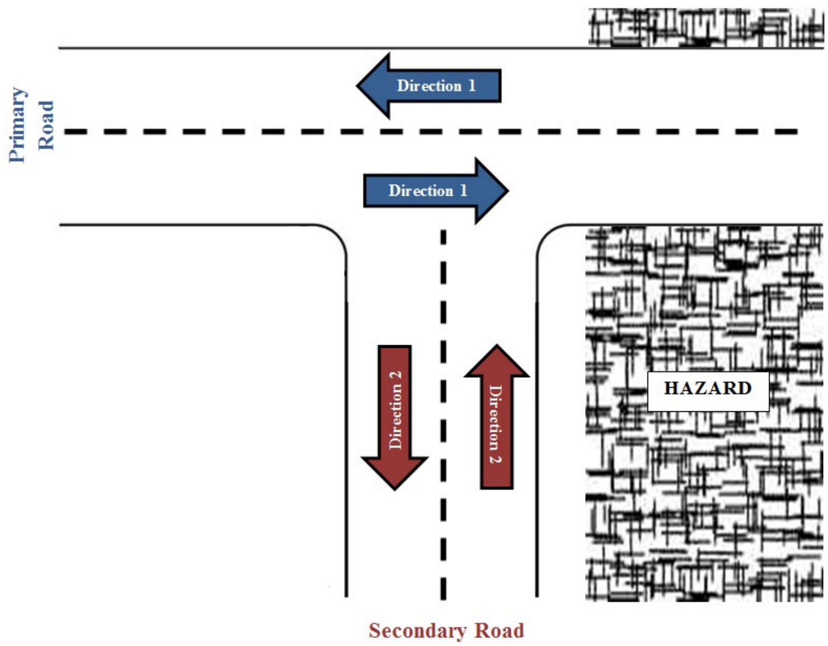


Rank.3: Case - 2.3

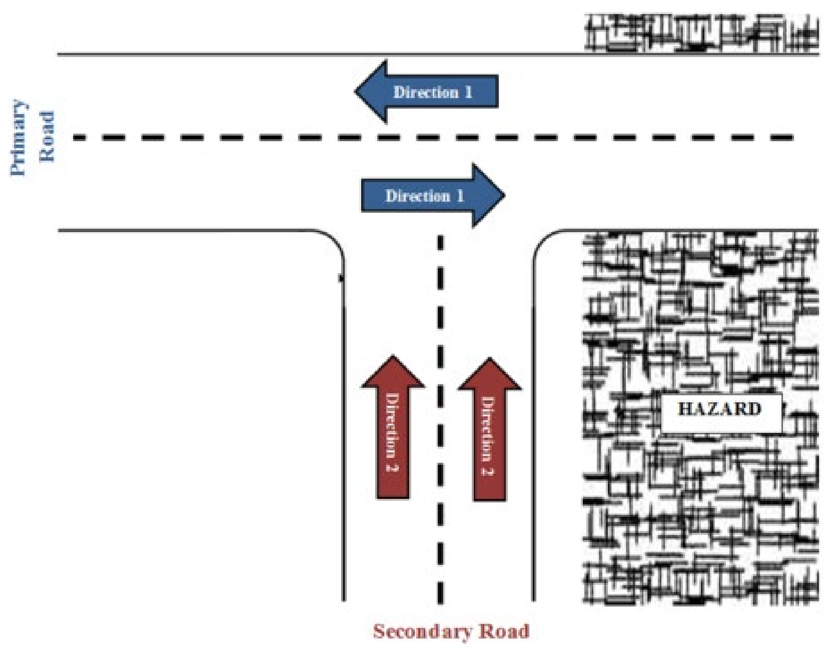


III. CASE – 3

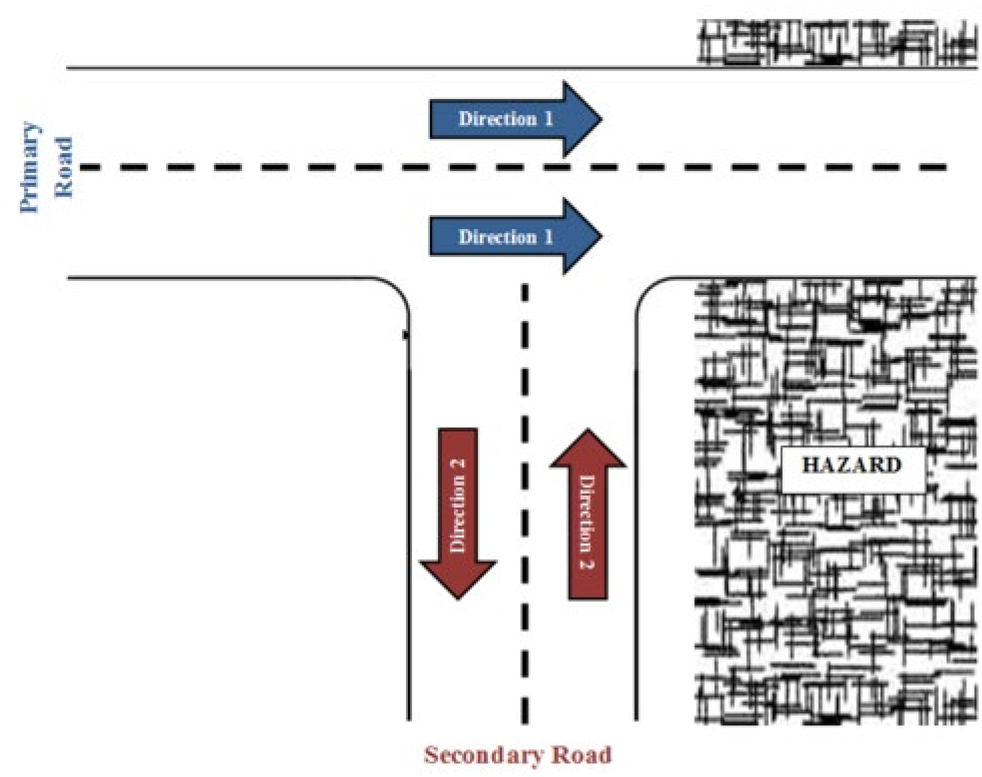
Rank.1: Case - 3.1



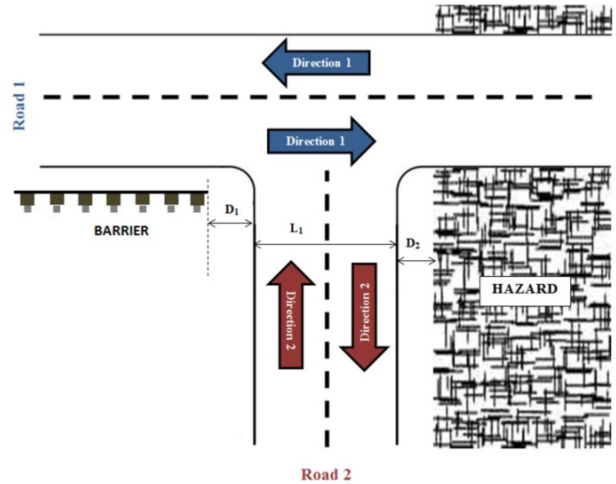
Rank.2: Case - 3.2



Rank.3: Case - 3.4



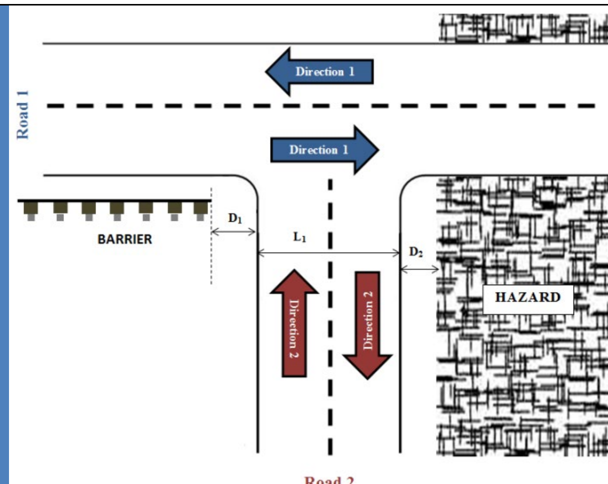
APPENDIX C. SPECIFIC SITE CASES

Practical Case	**Site Case Classification**
	 **Figure 1: Case - 3.1**

Site Parameters Identified:

State	Speed Limit (mph)	D1	D2	L1 (feet)
Louisiana	55	0’	NA	18.5

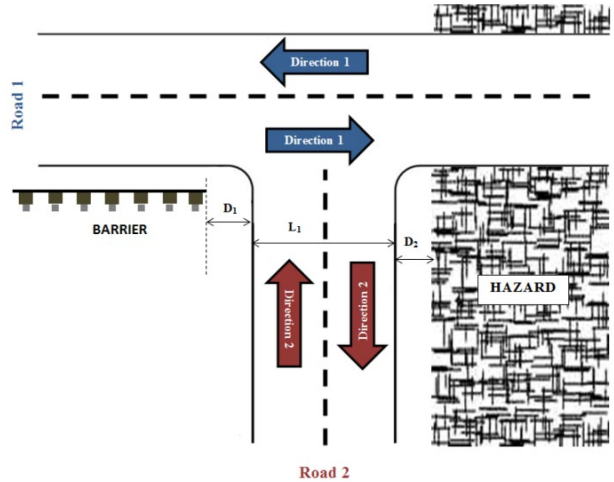
https://maps.google.com/maps?q=Abbeville,+LA&hl=en&ll=30.021014,-92.141508&spn=0.000019,0.016512&sll=30.441474,-91.111418&sspn=0.580147,1.056747&oq=abbevi&t=m&hnear=Abbeville,+Vermilion+Parish,+Louisiana&z=17&layer=c&cbll=30.021018,-92.143674&panoid=Nd_Z6H4TrNmeK_NhJPj8dw&cbp=12,29.81,,0,12.68

Site Parameters Identified:

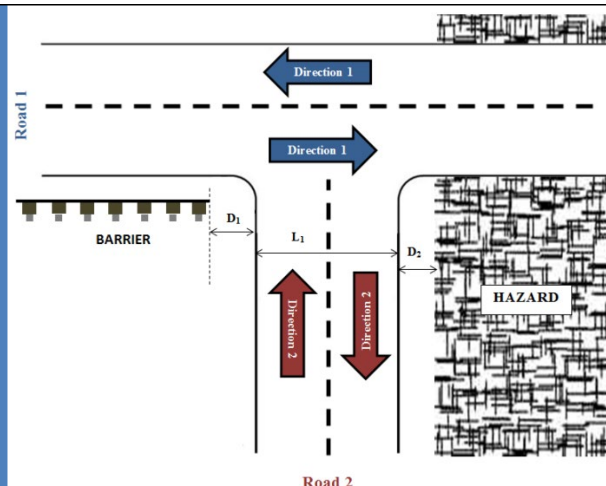
State	Speed Limit (mph)	D1	D2	L1 (feet)
Louisiana	55	20’	N.A	20.22

https://www.google.com/maps/@31.595327,-92.974397,3a,75y,104.36h,65.14t/data=!3m4!1e1!3m2!1s42eVS9JDeJj2w6yuSMUZiQ!2e0?hl=en



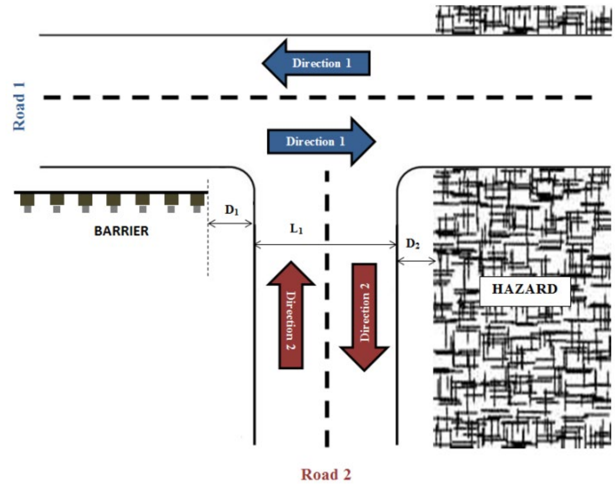
State	Speed Limit (mph)	D1	D2 (feet)	L1 (feet)
Washington	35	N.A	10	21.61

https://www.google.com/maps/@47.863989,-121.800751,3a,75y,296.46h,59.54t/data=!3m4!1e1!3m2!1sfnoht9SjrOSXHtGy2u95_w!2e0?hl=en



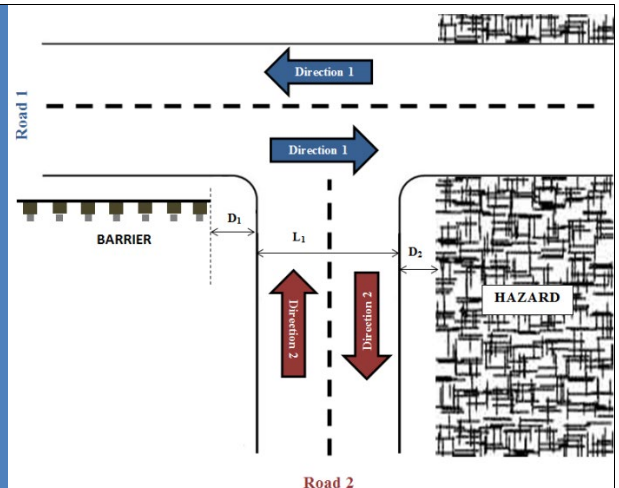
State	Speed Limit (mph)	D1	D2 (feet)	L1(feet)
Washington	40	N.A	30	22

https://www.google.com/maps/@47.265863,-123.004737,3a,75y,340.3h,70.56t/data=!3m4!1e1!3m2!1ssjUQqjbCmt6Ns4b_sLChag!2e0!6m1!1e1?hl=en



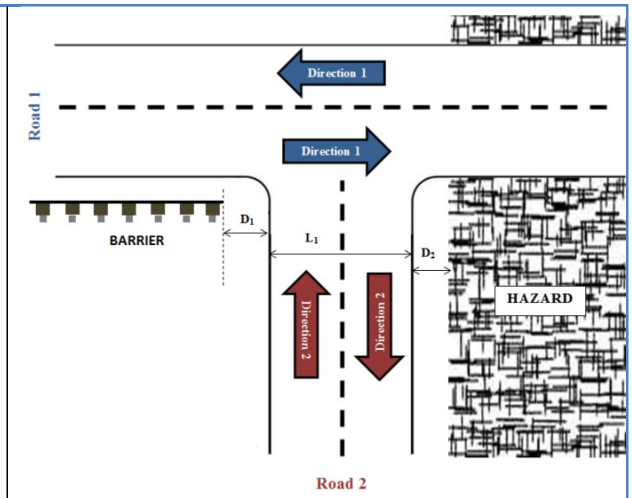
State	Speed Limit (mph)	D1(feet)	D2 (feet)	L1(feet)
Washington	55	15	NA	19.33

https://www.google.com/maps/@46.830303,-123.186166,3a,75y,330.31h,80.16t/data=!3m4!1e1!3m2!1soapV-2rfTgmbAJ04S-XLVQ!2e0!6m1!1e1?hl=en

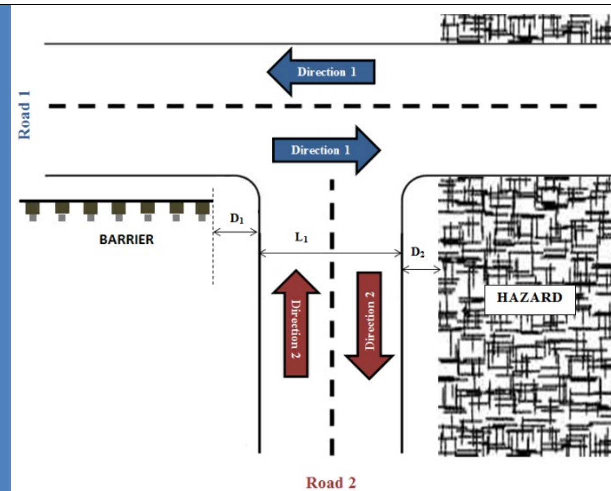


State	Speed Limit (mph)	D1(feet)	D2 (feet)	L1(feet)
Washington	55	33	113	21.76

https://www.google.com/maps/@45.613077,-122.055341,3a,75y,108.76h,84.33t/data=!3m4!1e1!3m2!1spVkYvshJHaVO4YnzYNWAbg!2e0



State	Speed Limit (mph)	D1	D2 (feet)	L1
Washington	50		15	
Not enough information on the exact location of the site				



State	Speed Limit (mph)	D1 (feet)	D2	L1(feet)
Washington	50	15	N.A	19.88
https://www.google.com/maps/@48.601657,-122.2328,3a,75y,62.97h,76.61t/data=!3m4!1e1!3m2!1sAylAVbDFsB-Ich_WnJhsSA!2e0!6m1!1e1?hl=en				

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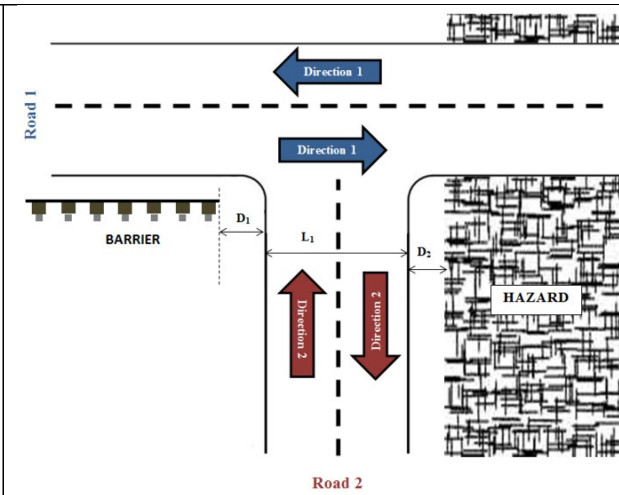
<tr><td colspan="3"></td><td colspan="2"></td></tr>
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