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Safety Considerations for All Road Users on Edge Lane Roads

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16. Abstract

Edge lane roads (ELRs), also known as advisory bike lanes or advisory shoulders, are a type of shared street where two-way motor vehicle (MV) traffic shares a single center lane, and edge lanes on either side are preferentially reserved for vulnerable road users (VRUs). This work comprises a literature review, an investigation of ELRs' operational characteristics and potential road user interactions via simulation, and a study of crash data from existing American and Australian ELRs.

The simulation evaluated the impact of various factors (e.g., speed, volume, directional split, etc.) on ELR operation. Results lay the foundation for a siting criterion. Current American siting guidance relies only upon daily traffic volume and speed—an approach that inaccurately models an ELR's safety.

To evaluate the safety of existing ELRs, crash data were collected from ELR installations in the US and Australia. For US installations, Empirical Bayes (EB) analysis resulted in an aggregate CMF of .56 for 11 installations observed over 8 years while serving more than 60 million vehicle trips. The data from the Australian State of Queensland involved rural one-lane, low-volume, higher-speed roads, functionally equivalent to ELRs. As motor vehicle volume grows, these roads are widened to two-lane facilities. While the authors observed low mean crash rates on the one-lane roads, analysis of recently converted (from one-lane to two-lane) facilities showed that several experienced fewer crashes than expected after conversion to two-lane roads.

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Executive Summary

An edge lane road (ELR) belongs to a class of roadways that supports two-way automobile traffic within a single center lane and accommodates vulnerable road users (VRUs), such as bicyclists or pedestrians, in the edge lanes on either side. Automobiles may use the edge lanes to pass approaching vehicles after yielding to any VRUs there. ELRs are alternatively referred to as advisory bike lanes (ABLs), advisory shoulders, or dashed bicycle lanes. An ELR has no centerline. The center lane is separated from the edge lanes with broken lane markings. The broken lane markings indicate a permissive condition allowing motor vehicles to move into the edge lanes after yielding to any VRUs there.

ELRs can inexpensively provide facilities for VRUs on millions of miles of local and collector roads in the US. This can be useful where roads are too narrow or lack the right-of-way for the addition of standard bicycle lanes or sidewalks. ELRs can provide more distance between VRUs and traffic than standard bicycle lanes in some situations and may be an excellent striping treatment for bicycle boulevards. As of July 2020, the authors are aware of approximately 40 installations in the US and Canada. The Federal Highway Administration (FHWA) has approved ELR installations as an experimental treatment in at least eight US cities.

Jurisdictions in the United States have installed ELRs across a wide range of community character types, contexts, and roadway classifications, some of which can be found in a privately published website (www.advisorybikelanes.com) dedicated to the treatment. Yet there is currently no published, peer-reviewed study analyzing and identifying the safety effects of these facilities using the methods prescribed in the Highway Safety Manual (HSM). Hence, the objectives of this study include:

1. Estimate the number of potential conflicts between automobiles and between automobiles and VRUs using a simulation-based approach.
2. Provide a basis and framework for conducting safety analyses on ELRs using the methods outlined in the HSM and other literature.
3. Analyze ELRs that exist in Australia on low-volume high-speed rural roads to determine whether these may be an option in the US.

These results from the simulation analysis lay the foundation for ELR siting criteria, which are based on the number of interactions between MVs and between MVs and VRUs occurring on the facility. A siting criterion may be expressed in terms of the likelihood that any bicyclist or pedestrian will be involved in an interaction involving approaching motor vehicles maneuvering to pass one another, or it may be expressed in terms of an acceptable rate of those same interactions for the entire facility.

Before-and-after analysis using the HSM-recommended Empirical Bayes (EB) approach showed that ELR conversion had an aggregate crash modification factor (CMF) of .56 evaluated over 8 years and across 11 US installations. The one rural American ELR evaluated had a CMF of 0.0 due to the absence of crashes after ELR conversion. Analysis of crash data from Queensland, Australia, for rural higher-speed ELRs did not show consistent patterns in CMF—partly due to the lack of crash data on the low-volume roads. CMF values lower than 1.0 indicate that the treatment resulted in crash reduction and improved safety.

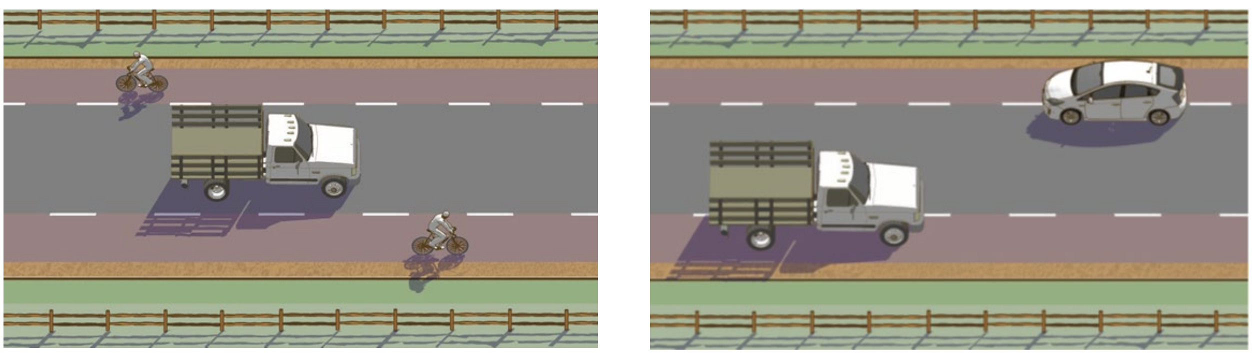
This is the most comprehensive research to date on the safety implication of ELRs. These results provide evidence that these ELRs can provide benefits to California jurisdictions.

I. Introduction

An edge lane road (ELR) is characterized by unconventional roadway striping that provides one central travel lane supporting bidirectional motor vehicle traffic, as opposed to the typical two-lane design. On either side of this central lane is an edge lane: these lanes are preferentially reserved for vulnerable road users (VRUs), primarily bicyclists and pedestrians. No centerline is used with this treatment. When two vehicles approach each other in the center lane, both drivers may maneuver and dip into the edge lanes to safely pass each other after yielding to VRUs. The center lane is separated from the edge lanes with broken line markings. Broken line markings communicate the intention to allow motorists to drive on the edge lane whenever necessary to safely pass an approaching vehicle.

Figure 1 shows two scenarios on an ELR. The left image illustrates proper use when a motorist is alone in the center lane. The right image illustrates proper use when two motorists must pass each other.

Figure 1. Typical ELR Design and Operation



Source: FHWA 2016

This treatment provides multiple benefits. It encourages multimodality by allocating roadway space for non-motorized travelers, which can greatly improve pedestrian and cyclist access and safety. The treatment is cost-effective. It is inexpensive to install and reduces maintenance costs. Moving vehicles to the center of the roadway extends road life by reducing loads on the sensitive asphalt edges, and it reduces rutting by varying the paths taken by motorists.

Some may believe that the use of a single lane for vehicles traveling in two directions is too unconventional or unsuitable for use in the US. The AASHTO Greenbook does not explicitly prohibit the use of ELRs for local streets in urban areas (AASHTO 2013). FHWA does, however, require centerlines dividing the traffic in opposing directions to be placed on all urban collectors and arterials with an Average Daily Traffic (ADT) of 6,000 or greater, thereby precluding the use of ELRs on such facilities (See FHWA 2010 for guidance on Bicycle Facilities and the Manual for Uniform Traffic Control Devices (MUTCD)). Two-way operation on a one-lane road is also explicitly supported by the 2019 AASHTO Guidelines for Geometric Design of Low-Volume Roads for roads with fewer than 2,000 average daily vehicles.

1.1 A Brief History of Edge Lane Roads

Though fairly unknown and not yet heavily used in the United States, ELRs have actually been around for years in countries outside of the United States—even decades in a few of these places. A report from the 2013 International Transport Forum listed ten countries that had been using this roadway design consistently as of 2013, with three of these countries reporting ELR use since before 1970. The Netherlands is credited with being the country that created this treatment. In the Dutch language, ELRs are known as "suggestiestroeken," which translates to "suggestion lanes." Today, the country now has more than 1,000 kilometers of ELRs within its borders, and Dutch road users are accustomed to using these types of facilities on a regular basis, whether they are walking, biking, or driving. Studies conducted on these facilities in the Netherlands found that both motorists and cyclists move away from the edge of the road as a result of ELR installation. This reaction, in turn, may reduce the likelihood of single-lane roadway departure crashes along with crashes involving cyclists and/or pedestrians, ultimately enhancing the safety effects that all road users will experience. While other countries have been using these facilities for a long time, they are fairly new in the United States and are not widespread or well-known among general American road users.

1.2 Edge Lane Roads in the United States

The first official mention of ELRs in the US came from the City of Portland in its 2010 bikeway facility design guidance (City of Portland 2010). After that, two official sources emerged to provide guidance for designing and implementing ELRs in the US. Both sources were compiled and published by the Federal Highway Administration (FHWA). The first source is *Small Town and Rural Multimodal Networks* (FHWA 2016), and the second is the FHWA webpage addressing experimentation with "dashed bicycle lanes" (FHWA 2010). While these resources provide a good framework to implement ELRs in the US, ELRs are not as widespread as they are in other countries. The reason is that they are a fairly new roadway design in the US, and as such, ELRs are currently classified as "experimental treatments" by the FHWA in advance of a determination whether they are safe and effective to implement throughout the US. As of August 2020, there are approximately 40 ELR installations located in the US and Canada.

While a moderate amount of guidance that informs ELR design and implementation has been published, the same cannot be said for safety analyses of ELRs. Prior to this work, safety analyses of ELRs in the US have been limited to before-and-after studies of single installations for short periods of time, with the exception of one study of six installations by one of the co-authors (Williams 2019). The study was based on a simple comparison of crash frequency during the pre- and post-installation period. There has also been research on the safety effects of related bicycle facilities like exclusive bike lanes, shared-lane markings (sharrows), and dashed bike lanes at intersections, which are all components of ELRs. The studies on these specific treatments have helped inform the transportation research community of how safe and effective ELRs can be for cyclists and pedestrians. Several studies have also found that wide, paved shoulders reduce the incidence and severity of run-off-road conditions, which show the safety potential ELRs provide for motorists, though there has been no work published focusing explicitly on ELRs in the US. Thus, this research aims to provide a basis and framework for the safety analysis of ELRs using the methods prescribed in the 2010 Highway Safety Manual (See Dixon et al. 2012 for details of the methods).

1.3 Motivation & Objectives

While unconventional in design, ELRs are valuable because they inexpensively provide facilities for vulnerable road users (VRUs) on miles and miles of local and collector roads. They are effective solutions for providing bike and pedestrian access along roads that are too narrow or do not provide planners enough space on either side to expand the facilities and add standard bike lanes or sidewalks. Another way ELRs can be used is to reduce the rate of single-vehicle, roadway departure crashes on low-volume, high-speed two-lane rural roads. A reduction in such crashes may be attributed to cars driving on the center of the roadway rather than closer to the edge. ELRs' many benefits and advantages can change the way people view and implement multimodality measures in this country.

However, as mentioned above, the literature is lacking statistically robust estimations of the safety effects of ELRs. Hence, the purpose of this study is:

1. To estimate the number of potential conflicts between automobiles and between automobiles and VRUs using a simulation-based approach.
2. To provide a basis and framework for conducting safety analyses of ELRs using the methods outlined in the HSM and other literature.
3. To analyze ELRs that exist in Australia on low-volume high-speed rural roads to learn from experiences in that jurisdiction and determine whether these may be an option in the US.

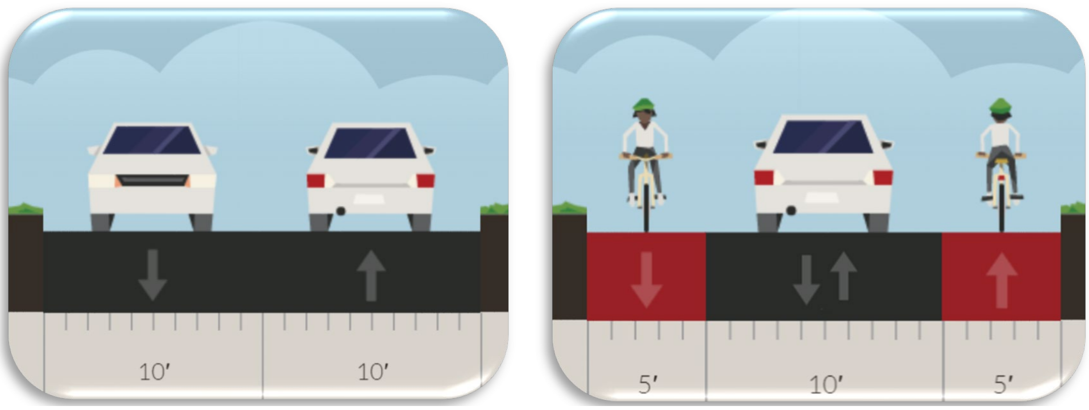
The research report is organized as follows. A detailed literature review on ELRs and safety evaluation is provided in Chapter II. Chapter III presents detailed results from the simulation-based analysis. Chapters IV and V provide details of crash data analysis from the US and Australia, respectively. Chapter VI provides conclusions from this research and suggests directions for future investigations of ELRs.

II. Literature Review

2.1 What Is an Edge Lane Road?

An edge lane road (ELR)[1] is a road configuration composed of one center lane supporting two-way motor vehicle traffic and an edge lane on either side (Figure 2). Normally, the edge lanes are preferentially reserved spaces for vulnerable road users (VRUs). Vulnerable road users include pedestrians and micromobility users such as users of bicycles, electric scooters, wheelchairs, and electric skateboards. Edge lane roads provide VRU facilities without the need for expensive improvements.

Figure 2. Traditional Roadway Cross-Section (left) and Edge Lane Road (right)



Source: Created by the authors at Streetmix.net.

ELRs, which include both advisory bike lanes and advisory shoulders, are characterized by the absence of a centerline and the presence of broken lines to delineate the edge lanes. Motor vehicles travel in the middle lane until they encounter a vehicle traveling in the opposite direction. Both drivers merge into the edge lanes after yielding to any users already there. After completing the passing movement, the drivers return to the center lane, as shown in Figure 1 (Chapter I).

Edge Lane Roads in the United States

The first mention of edge lane roads in the United States was in 2010 in Portland's bikeway design guidance (City of Portland 2010). ELRs are currently classified as an experimental treatment by the Federal Highway Administration (FHWA). The FHWA interchangeably uses the terms "advisory bike lanes," "advisory shoulder," and "dashed bicycle lane."

[1] Also known as *advisory shoulders* in the United States and Canada, *2-1 veje* and *2-minus-1 roads* in Denmark, *suggestiestrooken* in the Netherlands, *advisory cycle lanes* in the UK, *bymiljöväg* in Sweden, *Schutzstreifen* in Germany, and *2-minus-1 roads* in New Zealand.

At the federal level, the facility was first introduced as "advisory shoulders" in 2016 in a publication titled FHWA Small Town and Rural Multimodal Networks(FHWA 2016). This guide includes design guidelines and implementation recommendations, and it emphasizes the need for continued experimentation and data collection. The guide presents the following conditions needed for the implementation of an ELR.

- The preferred motor vehicle volume is less than 3,000 ADT, while the maximum is 6,000 ADT.
- The preferred width of the central lane is 13.5–16 ft, although widths of 10–18 ft are possible.
- The preferred motor vehicle operating speed is up to 25 mph, while the maximum speed is 35 mph.
- The preferred width of the edge lane is 6 ft, with the absolute minimum being 4 ft when no curb or gutter is present.
- The sections where the ELR is implemented should not have frequent stops or intersections that require vehicles to stop (FHWA 2016).

The maximum of 6,000 ADT is based on FHWA guidance on centerlines. The FHWA Manual on Uniform Traffic Control Devices (MUTCD) recommends placing centerline markings on urban collectors and arterials with motor vehicle traffic volumes above 4,000 ADT and on rural arterials and collectors with volumes above 3,000 ADT. Centerline markings are required on all urban collectors and arterials with traffic volumes above 6,000 ADT. ELRs cannot be installed on these roads since they must have centerline markings.

Jurisdictions in the United States have installed ELRs across a wide range of community character types, contexts, and roadway classifications, most of which can be found in "Lessons Learned: Advisory Bike Lanes in North America" published by Portland's Alta Planning + Design (2017) as well as Williams' "Advisory Bicycle Lane Design Guide" (2017). The list of existing edge lane roads in the United States is presented in Table 1.

Table 1. Installed Edge Lane Roads in the United States

City	Street Name	Length (ft)	Center Lane Width (ft)	Edge Lane Width (ft)	Speed limit (mph)	AADT
Alexandria, VA	Potomac Greens Drive	1,600	17	5	25	2,000
Bloomington, IN	East 7th Street	2,200	17	5	25	500
Boulder, CO	Harvard Lane	1,600	15	5	25	380
Burlington, VT	Flynn Avenue	1,600	18	5	25 (15)	5,000
Cambridge, MA	Lakeview Avenue	1,600	9	2.75	30	1,000
Chicago, IL	West Argyle Street	1,080	16	5	20	3,500
Chicago, IL	West Leland Avenue	1,050	16	5	20	3,500
Grand Rapids, MI	Jefferson Ave SE	4,680	18	5	25	3,250
Edina, MN	54th Street	1,100	14.5	5	30	2,450
Hailey, ID	2nd Avenue	3,580	13	6	20	700
Hanover, NH	Valley Road	1,255	10	5	25	470
Lincoln, VT	Quaker Street	960	14	4	30	550
Lorain, OH	Washington Ave #1	2,160	16	5	25	2,100
Lorain, OH	Washington Ave #2	3,440	20	4.5	25	2,850
Lorain, OH	West 26th Street	950	16	5	25	400
Mankato, MN	Poplar Street	860	15	5.5	30	2,500
Minneapolis, MN	East 14th/Grant St	2,400	20	6	30	4,700
Minneapolis, MN	West 46th Street	1,300	18	6	30	4,100
Minneapolis, MN	East 54th Street	4,250	18	6	30	4,300
Minneapolis, MN	5th Street NE	940	14	6	30	500
Minneapolis, MN	40th Street W	650	14	6	30	2,000
Minneapolis, MN	Bloomington Ave S	2,600	16	6	30	3,350
Port Townsend, WA	Water Street	2,120	19.5	4.5	20	7,116
Sandpoint, ID	Oak Street	1,365	21	5	25	810
Scarborough, ME	Eastern Rd	4,800	14.5	5	25	1,020
Yarmouth, ME	Morton Rd	2,900	20	4	25	400
Yarmouth, ME	Bridge Street	250	12	5	25	920

An average ELR in the US is about 2,000 ft long and 21 ft wide, with average daily traffic of about 2,000 vehicles.

Edge Lane Roads Abroad

In Canada, the implementation of edge lane roads lags behind the US and especially European countries. The government of British Columbia recommends ELR installation on narrow, low-volume streets to provide dedicated space for vulnerable users on roads where sharing the space is neither safe nor comfortable (Ministry of Transportation and Infrastructure [British Columbia] 2019). The same source suggests that a comprehensive data collection and monitoring program is needed to assess the effectiveness of ELRs, along with a public education program to inform all road users about how to use these facilities.

In the United Kingdom, "advisory cycle lane" design guidelines recommend the implementation of the facility on narrow roads (Sustrans 2006). Advisory cycle lanes can be installed on roads with ADT between 1,000 and 4,000 and where the speed (85th percentile) does not exceed 40 mph. On roads with lower speeds or lower traffic volumes, special measures are not recommended. According to the standards for cycling in London (Transport for London 2014), advisory cycle lanes can be installed on roads with a speed limit of up to 40 mph. The goal of advisory cycle lanes is not necessarily to separate motorized and active traffic but rather to suggest to motorists how much space cyclists need when they are overtaken (CTC 2008). Some local agencies allow the installation of advisory cycle lanes on roads with traffic volumes up to 10,000 ADT (Cardiff Council 2011).

In the Netherlands, edge lane roads are known as "suggestiestrook." The Dutch design guide differentiates between urban and rural conditions for the implementation of ELRs (CROW 2017). An ELR can be placed on rural roads with a speed limit of up to 60 km/h and traffic between 2,000 to 3,000 ADT. In the urban environment, ELRs can be implemented on streets with speed limits of 30 km/h and traffic volumes between 2,000 and 5,000 ADT.

In Denmark, "2 minus 1 vej" (2-minus-1 roads) were introduced in the early 2000s as a new type of road design. The design recommendations are presented in the rules of road signage use issued by the Danish Road Directorate (Vejdirektoratet 2017):

- The speed limit is 60 km/h in rural areas and 50 km/h in urban areas.
- The center lane width is between 3.0 and 3.5 m.
- The edge lane width is between 0.9 and 1.5 m (Vejdirektoratet 2017).

Additional recommendations include a traffic volume of a maximum of 300 vehicles per hour (3,000–3,750 ADT). The preferred central lane width is 3.5 m so that the lane can accommodate agricultural vehicles. However, Helsingør Municipality recommends a lane width between 3 and 3.25 m instead (Helsingør Kommune 2006). The effective width of the edge lane is, in some places, reduced due to poor road maintenance and pavement edge damage. Thus, reducing the driving lane leaves more effective space for VRUs. Finally, it is recommended that an ELR should only be established where sufficient distance is available for the oncoming road users to give way to each other.

In Sweden, edge lane roads were first introduced in 2006 under the name "bymiljöväg" (countryside road). Design guidelines for bike lanes on rural roads are presented in the design standards for rural roads without explicitly mentioning edge lane roads (Meulen and Berg 2018). The width of the edge lane ranges from 0.2 to 1.5 m, while the central driving lane is 5.6 to 3.0 m wide.

In Germany, these facilities are known as "Schutzstreifen" and are governed by the Road Traffic Regulations (StVO, Section 42) (German Road Authority 2016). The regulations stipulate that drivers may enter the bike lane only if necessary. The maximum speed on such a facility is 50 km/h.

The review of design standards is presented in Table 2.

Table 2. Edge Lane Roads Design Recommendations

Country	Central Lane Width		Edge Lane Width		Speed Limit	Max ADT	Reference
	Min	*Preferred*	*Min*	*Preferred*			
Denmark	3.0 m	3.5 m	0.9 m	1.5 m	60 km/h	300/hour	Vejdirektoratet 2013
Germany	4.5 m	-	1.25 m	1.5 m	50 km/h	-	German Road Authority 2016
Ireland	4.0 m	-	2.0 m	2.0 m	50 km/h	-	National Transport Authority 2011
Netherlands	3.0 m	-	1.25 m	1.5 m	60 km/h	4,000	CROW 2017
Sweden	3.0 m	-	0.2 m	1.5 m	50 km/h	1,500	Meulen & Berg 2018
United Kingdom	3.0 m	3.5 m	1.5 m	2.0 m	40 mph = 64 km/h	4,000	TfL 2014
United States	10 ft = 3.0 m	16 ft = 4.9 m	4 ft = 1.2 m	6 ft = 1.8 m	35 mph = 56 km/h	6,000	Alta Planning 2017

2.2 Impacts of Edge Lane Roads

Speed

Williams (2019) analyzed the performance of ELRs in the United States and Canada. The author analyzed six installations and found that there was a reduction or no change in speed and crash rates on these roads.

The Institute for Road Safety Research (SWOV) from the Netherlands published a series of before-and-after studies on "non-compulsory cycle lanes." The studies investigated whether the speed, distance between vehicles, and position of cyclists and car drivers changed as a result of the implementation of edge lane roads. The researchers conducted two sets of measurements in five locations in the Netherlands and inquired whether the means of the two measurements were statistically significant.

One such study investigated an ELR in the village of De Lier. The results indicated that subsequent to ELR installation, the average speed declined by 1.7 km/hour and that bicycles moved laterally toward the middle of the road, which reduced the spacing between cars and cyclists by 3 cm (van der Kooi 2000). Another study investigated the effects of an ELR with speed bumps in the town of Zoetermeer. In the post-treatment period, the average speed declined by 17.9 km/hour. The author was not able to differentiate between the effect of the ELR and the effect of the speed bumps on the speed reduction. Cyclists moved toward the middle compared to the 'before' scenario when they rode closer to the edge. Therefore, the lateral distance between cars and bicyclists was reduced, but the exact amount was not reported (van der Kooi 2001a). The treatment was also implemented in the town of Pijnacker, where edge lanes were added to an existing road having a speed limit of 60 km/h. The effects included an increase in speed by 4.3 km/h and no change in the lateral position of cars or bikers (van der Kooi 2001b). The implementation of an ELR in the city of Zwolle reduced the average speed by 0.6 km/h, and the distance between bikes and cars was reduced by 17 cm (van der Kooi 2001a). Another ELR was located on a rural road in the municipality of Hellendoorn. The centerline was removed, and edge lanes were added. Several speed tables were installed, and the speed limit was reduced from 80 to 60 km/h. The average speed declined by 17.1 km/h. However, the author stated, "The average speed has fallen sharply. However, the new speed tables, one of which is a short distance away from the speed measurement location, are a major cause of this reduction. Both hard breaking and skid marks were observed right before the speed table."[2] The average distance between a car and the cyclist being overtaken decreased by 6 cm (van der Kooi 2001a). Finally, an ELR treatment was implemented on a rural road near the town Raalte, along with several speed tables. The average speed declined by 6 km/h. The cyclists moved closer to the middle compared to their 'before' position relative to the edge of the road. The average distance between cars and cyclists decreased by 8 cm (van der Kooi 2001a). To summarize, these SWOV before-after studies in the Netherlands concluded that ELRs, sometimes in conjunction with other treatments such as speed tables, resulted in lower speeds and reduced distances between motorists and bicyclists compared to the pre-treatment period.

A paper that summarizes these and other Dutch studies (van der Kooi and Dijkstra 2003) found when driving on an ELR, both cars and cyclists moved further away from the edge relative to their position on a two-lane road without bike lanes. When cars overtake cyclists, they often choose not to enter the bike lane in the opposite direction, which leaves less room between vehicles. The

[2] Translated from Dutch.

authors could not assess whether this reduction in lateral distance posed a safety risk. The average driving speed was reduced by a few kilometers per hour after the implementation of an ELR.

Erke and Sorensen (2008) conducted a literature review and found that ELRs did not lead to the expected reductions in speed. Additionally, overtaking vehicles kept less lateral separation from the cyclists because cyclists cycled further from the edge of the road. The authors argued that the safety effects of ELRs might be improved by supplementary measures such as speed limits or speed bumps.

Reports by the Helsingør Municipality in Denmark analyzed the implementation of ELRs in that region and indicated that vehicle traffic volume decreased by 7–15% as a result (Helsingør Kommune 2004). The treatment was implemented on a rural section of road that spanned 7.3 km, and it comprised the removal of the centerline, the addition of edge lanes, twelve new speed bumps, and, in some sections, the introduction of a speed limit (Helsingør Kommune 2006). Based on the questionnaires and surveys, the authors found that the number of "local" drivers increased from 16 to 36%, while the number of cut-through drivers decreased from 86% to 52% (Helsingør Kommune 2004). Additionally, the number of vulnerable users who felt safe on the ELR doubled from 15% to 30% (Helsingør Kommune 2004). Another set of studies analyzed the same treatment and found that average speed increased (Lund, Herrstedt, and Greibe 2005). While these studies do not quantitatively specify the extent of the change, they present data on the average speed after the treatment and show that the speed level was higher than the posted speed limit (See Table 3). The average speeds were reported to be as much as 17 km/h higher than the posted limit.

Table 3. Average and 85th Percentile Speeds Compared to Speed Limits for ELRs Installed in Denmark

Speed Limit (km/h)	Average Speed (km/h)	85th Percentile Speed (km/h)
40 km/h	53–57 km/h	63–68 km/h
50 km/h	60–65 km/h	69–76 km/h
60 km/h	69–70 km/h	78–81 km/h

Source: Lund, Herrstedt, and Greibe 2005

The most extensive study to date was conducted by the Danish Road Directorate (Vejdirektoratet 2013). It analyzed 87 sections of ELR from 32 municipalities in Denmark with a total length of about 80 km. The average width of the middle lane was 3.3 m, and the average width of the edge lane was 1.3 m. Most municipalities reported "satisfaction" with the ELRs but noted that the users need a period to adjust, which must be supplemented by education campaigns. Out of 19 sections where before-and-after speed measurement was conducted, the speed increased on two sections, and it remained the same or decreased by up to 5 km/h on the remaining 17. However, the report indicates that “there is no evidence of long-term effects of 2 minus 1 roads on reducing speed unless the measure is combined with other speed calming measures” (Vejdirektoratet).

In Sweden, ELRs were installed in four small towns in 2006 and 2007 to accommodate pedestrians and cyclists and to increase safety (Johansson, Lyckman, and Rosander 2008). All roads were previously two-lane roads that were 6.5–7.5 m wide. The number of lanes was reduced to one on most roads, and the road shoulder was extended to between 1.15 and 1.80 m.

The average vehicle’s speed decreased by about 7 km/h (10%), and the average speeds were still higher than the speed limit. In some places, the speeds were measured immediately after the installation and one year after the installation. The results, along with the route details, are presented in Table 4.

Table 4. Speeds Before and After Implementation of Edge Lane Road

City	Approx. ADT (vehicles/day)	Length (km)	Speed Limit	Average Speed (km/h)		
				Before	*Just after*	*One year after*
Björsbyn	1,000	1.0	50 km/h (reduced from 70 km/h prior to ELR	67	60	No data
Gäddvik	11,000	2.5	70 km/h (reduced to 50 km/h at the beginning and end of route)	54	48	51
Roknäs	1,000	4.7	50 km/h	53	45	No data
Bonäs	1,700	4.2	50 km/h	74	74	73

Source: Johansson, Lyckman, and Rosander 2008

In Björsbyn, the proportion of cyclists increased from 1% to 6%. In all locations, the traffic volume remained unchanged after ELRs were installed, except in Roknäs, where the volume of car traffic was reduced by 8%.

In summary, the literature indicates that vulnerable users feel safer on ELRs (Helsingør Kommune 2004) and that the distance between cars and bikers is reduced, but the reduction might not have a significant impact on safety (van der Kooi and Dijkstra 2003), and further, considerable speed reduction can be achieved if ELR is complemented by other measures (Erke and Sorensen 2008, Vejdirektoratet 2013). The overview of the results of these studies is presented in Table 5.

Table 5. Overview of the Literature about the Effects of Edge Lane Roads

Location	Change in Car Speed	Change in Distance between Cars and Bikers	Additional Measures
De Lier, Netherlands	-1.7 km/h	-3 cm	None
Zoetermeer, Netherlands	-17.9 km/h	Reduced (exact numbers not reported)	Speed bumps
Pijnacker, Netherlands	+4.3 km/h	No change	None
Zwolle, Netherlands	-0.6 km/h	-17 cm	None
Hellendoorn, Netherlands	-17.1 km/h	-6 cm	Speed tables
Raalte, Netherlands	-6 km/h	-8 cm	Speed tables
Four sites in Sweden	-7 km/h	No data	No data
Eighty-seven sites in Denmark	-5 km/h	No data	No data

Safety

In this section, we review studies that examined the safety of ELRs based on crash data. Jaarsma et al. (2011) examined the safety effects of installing ELRs and imposing speed limits of 60 km/h on Dutch low-volume rural roads. Data were collected in 20 sites for a period of five years before the treatment and three years after the treatment. The study examined 850 km of roads, and the control setting was low-volume rural roads with 80-km/h speed limits and no physical traffic calming measures. The results indicated that crashes were reduced by 25% on the treated roads. However, the exact effect of ELR could not be determined due to the addition of other traffic calming measures.

Cour Lund (2015) conducted a before-and-after study of 55 ELRs in 23 Danish municipalities based on eight years of crashes before the installation and between one and eight years of crashes after the installation. Overall, the study shows that ELRs led to a 29% decrease in the number of crashes. The most significant reduction is a 39% decrease in property damage crashes. Coupling ELRs with additional speed-reducing measures resulted in (statistically significant) 32% decrease in the total number of crashes. In comparison, a non-significant 13% increase was found on ELRs without speed reducing measures. The results suggest that narrowed roads and speed humps in conjunction with other speed-reducing measures have the best impact on safety.

A study by Beenker (2004) found that implementation of ELRs reduced the number of casualties (fatalities or injuries) by 20%. However, the study analyzed roads both with and without additional traffic calming measures. The Danish road agency reviewed the research and concluded that it was not possible to determine whether edge lanes contributed to the reduction in crashes (SWOV 2013). The study also found that the overtaking distance between cyclists and motor vehicles was reduced by "a few centimeters."

2.3 Benefits and Limitations of Edge Lane Roads

Overall, the literature indicates that the benefits of ELRs include:

- Low cost. Can often be accommodated through road re-striping or re-configuration; no physical widening of the road is necessary.
- Low spatial requirements. Can be used on narrow roads that cannot accommodate dedicated facilities for VRUs, so accommodation for VRUs may be provided on more facilities.
- Vulnerable road users have priority.
- Higher predictability of bicycle positioning on the road.
- Damage to road shoulders is reduced along with the associated maintenance costs.

Limitations include:

- Lack of exclusive space for bikers. Some cyclists feel uncomfortable riding adjacent to motor vehicle traffic.
- Education. Not a well-known or widely used facility type; may require user education.
- The road should provide sufficient sight distance, as motorists require a clear view of oncoming traffic.

2.4 Deconstructing Edge Lane Roads

The implementation of edge lane roads on existing 2-lane roads involves several interventions: removing centerline markings, changing lane width, removing one driving lane, and adding edge lanes. These interventions are low-cost since they mostly involve restriping the surface. These interventions aim to increase the comfort and safety of VRUs. While the research on the effects of ELRs on safety is not extensive, there is an extensive body of literature on the individual elements of ELRs. In the following sections, we present up-to-date knowledge of these road design elements.

Removal of Centerline

The research analyzing the connection between lane markings and speed predominantly argues that removing centerline markings in low-speed environments improves safety. Steyvers and de Waard (2000) performed a study with several scenarios to test the effect of the removal of lane markings. The two base scenarios included a road without any lines and a road with only a dashed centerline. The two experimental scenarios included a continuous edge line and a dashed edge line. The centerline-only configuration had the highest speeds, and the unlined road featured the lowest. The centerline-only configuration required the least effort to drive. In another study, Steyvers (1999) measured the occurrence of speeding in two scenarios. The base scenario included a road marked with a broken centerline and continuous edge lines. The experimental scenario considered the same road with edge lines removed. Speeds decreased when edge lines were removed, and the effect lasted after the conclusion of the study.

The analysis by Davidse, Driel, and Goldenbeld (2004) found that adding edge line and centerline road markings to previously unmarked roads increased speed and moved cars closer to the edge of the road. The study also found that broken lines gave less visual guidance and provided a better assessment of their driving speeds to motorists than solid lines. As such, Dutch road safety guidelines recommend the use of broken edge lines in areas where speed reduction is desired (SWOV 2013).

Similarly, a UK study found that centerline removal on 50 km/h roads reduced the number of crashes by 35% and decreased average speed by about 5 km/h (Wiltshire County Council 2004). Another study found that the reduction in speed after centerline removal was between 0.25 and 4.1 mph (Cooper and Wright 2014). Additionally, the absence of a centerline was associated with significantly reduced overtaking speeds (Shackel and Parkin 2014).

One possible explanation for the reductions in speed and crash frequency after the removal of lane markings is increased uncertainty. Kennedy et al. (2005) conducted a simulation to test the psychological effects of uncertainty on drivers. They found that in uncertain and unfamiliar situations, such as when facing a lack of lane markings, drivers drive more carefully. However, as the drivers get accustomed to the environment, the driving speed increases. The same study showed that lower speed due to uncertainty is temporary, and a more sustainable solution can be achieved only by implementing continuous and repeated speed-reducing measures.

The Crash Modification Factors (CMF) Clearinghouse publishes crash modification factors to quantify the potential effects of roadway treatments on crash risk (CMF 2020). A CMF value of 1.0 means that no change is expected, a value less than 1.0 means that the treatment reduces the risk of crashes, and a value greater than 1.0 means that the treatment increases the risk of crashes. Two of the crash modification factors published by the CMF Clearinghouse relate to the use of centerline markings on rural two-lane roads (CMF 2020). CMF ID 87 predicts the impact of centerline markings on serious, minor, and possible injuries resulting from crashes on two-lane rural roads. Its value is 0.99, with an adjusted standard error of 0.06. CMF ID 88 predicts the impact of centerline markings on property-damage-only crashes on two-lane rural roads. Its value is 1.01 with an adjusted standard error of 0.05. Both CMFs are rated at 3 out of 5 stars by Elvik et al. (2004). The star quality rating indicates the quality of or confidence in the results of the study that is used to estimate the reported CMF; the studies are ranked on a scale of 1 to 5, where 5 indicates the most reliable rating.[3] This suggests that the absence of centerline markings could result in an increase, a decrease, or no change in crashes, with no change being the most likely outcome.

[3] http://www.cmfclearinghouse.org/sqr.cfm

Lane Width

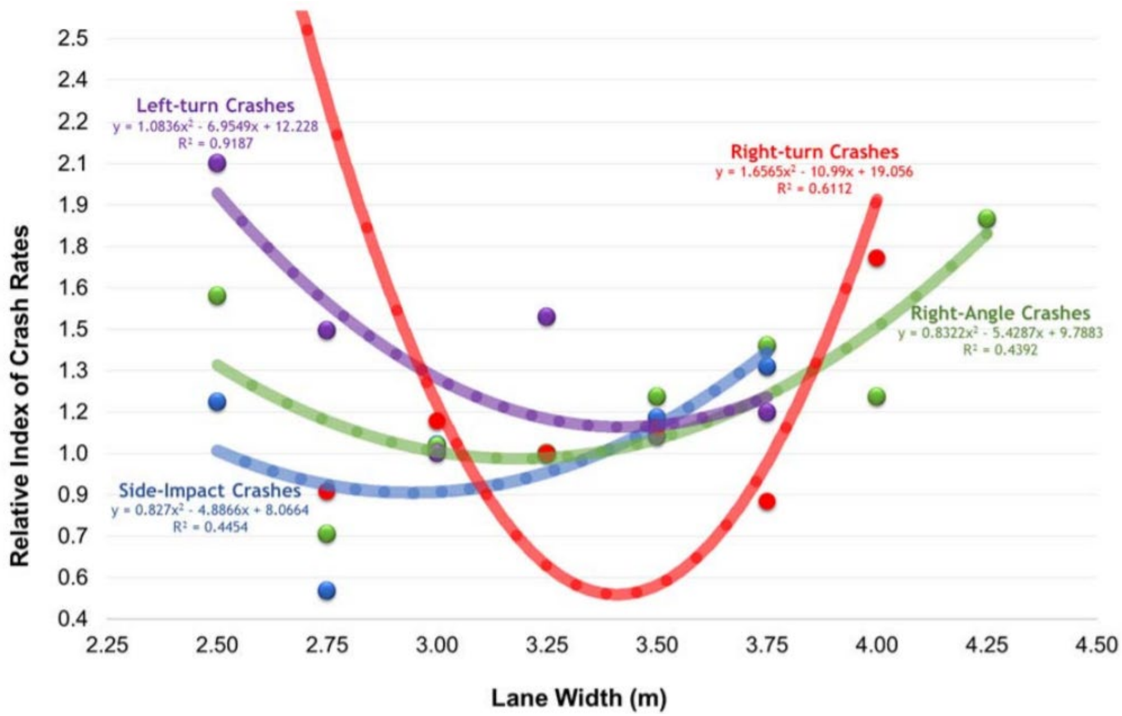
Studies suggest that outside of populated areas, roads with wider lanes are safer than comparable roads with narrow lanes. One of the first studies to indicate this connection was conducted by Zegeer, Deen, and Mayes (1971). The authors conducted an analysis to determine the effect of lane and shoulder widths on crashes by collecting information on geometrics, crashes, and volumes for 25,000 km of roads in the United States. The results indicate that narrow lanes were associated with a higher number of run-off-road and opposite-direction crashes, and roads with wide lanes had lower crash rates than those with narrow lanes.

In a similar study by the same lead author, wider lanes were found to be associated with lower crash rates. At the same time, paved shoulders had a marginal safety benefit compared to unpaved shoulders (Zegeer et al. 1987). Similarly, Ogden argues that lanes narrower than 3.0 m contribute to multi-vehicle crashes (Ogden 1996).

A highly relevant analysis for the context of ELRs is the study on crash rates on low-volume roads by Zegeer, Stewart, and Neuman (1994). The authors conducted an analysis to quantify the crash effects of lane widths on rural roads with volumes of less than 2,000 vehicles per day. Accident and roadway information was collected for more than 4,100 miles of two-lane roadway sections in seven states. The results show that narrow lanes were correlated with higher crash rates. Additionally, for lane widths of at least 3.0 m (10 ft), related crash rates were lower where wide rather than narrow shoulders were present. For a given shoulder width, wider lanes were found to be associated with lower crash rates.

In the urban setting, supporters of livable streets promote the safety benefits of narrower lane widths. Karim (2015) indicates that there is an optimal lane width: the safest streets have lane widths of about 3.25 m (Figure 3).

Figure 3. Relationship between Lane Width and Crash Rates for Different Types of Collisions



Source: Karim 2015

According to Karim (2015), narrower lanes have higher crash frequencies, and wider lanes have higher crash severity. Additionally, narrow lane width reduces speed (Daisa and Peers 1997), which in turn correlates with a lower number of crashes. In the context of ELR, the goal is to reduce the frequency of collisions with vulnerable users and the severity of vehicular crashes. In that regard, reducing the effective width of the driving lane, coupled with the addition of edge lanes that act as shoulders, can provide a good safety balance.

Shoulder Width

Shoulders serve a wide range of functions. They provide sufficient horizontal sight distance, an obstacle-free zone, and recovery of temporary loss of control, and they add space for drivers to perform emergency actions (RIPCORD 2007). Additionally, paved shoulders are perceived as extra driving space. In terms of safety, adding a new paved shoulder tends to be more effective on roads with narrow lanes (Li et al., 2013).

Abdel-Rahim and Sonnen (2012) evaluated the relationship between crash rates, shoulder width, and lane width for two-lane rural state highways in Idaho. The results show that roads with very small shoulders (<1 ft) had 16% more crashes than roads with a 3-ft wide shoulder. For roads with a shoulder width of 8 ft or more, the average reduction in crashes is approximately 13% when compared to roads with a 3-ft wide shoulder. The same study also looked at the characteristics of pedestrian and bicycle crashes on two-lane rural highways. The results show that roadway sections with a paved shoulder width of 4 to 6 ft had the lowest number of pedestrian and bicycle crashes.

A study on drivers' behavior found that the presence of paved shoulders causes drivers to drive closer to the road edge, hence reducing the probability of head-on collisions (Abele and Møller 2011).

Based on the studies presented in this section, rural roads without shoulders and with no bike or pedestrian traffic can still benefit from the implementation of ELR since the edge lanes act as shoulders. The overall safety of the facility should be improved with ELR implementation.

Speed and Safety

The relationship between speed and safety is not straightforward. Roads can be designed for safe, high-speed travel by designing elongated curves, controlling access points, separating opposing traffic flows, providing adequate bike infrastructure, and including crash mitigation features (Labi 2006). In the context of a two-lane road, however, a consensus is that speed kills (Ivan et al. 2006). A study by Baruya (1998) analyzed speed and crash data from 139 European rural two-lane highways and found a higher frequency of injury crashes on roads with higher speed limits. The risk of fatality increases as speeds go over 50 km/h for side-impact collisions and over 70 km/h for frontal collisions (Richards and Cuerden 2009). Echoing that finding, the National Transportation Safety Board found that higher speed increases the likelihood and the severity of a crash (NTSB 2017).

Following the increase in rural highway speed limits in British Columbia, there was a marked deterioration in road safety on the affected roads. The number of fatal crashes more than doubled (118% increase) on roads with higher speed limits. Affected roads also had a 43% increase in total auto insurance claims and a 30% increase in auto insurance claims for injuries due to crashes (Brubacher et al. 2018).

One of the causes of these crashes is that opposing traffic flows are not separated. Crashes on rural highways are more than twice as likely to be fatal than crashes on high-speed motorways with separated traffic flows (Martin and Lenguerrand 2008).

Another study (Tefft 2013) found that an increase in vehicle speed increases the risk of severe injury of a struck pedestrian: "10% at an impact speed of 16 mph, 25% at 23 mph, 50% at 31 mph, 75% at 39 mph, and 90% at 46 mph."

However, countermeasures exist. Jalayer, Zhou, and Satterfield (2015) analyzed road collision countermeasures and found three groups of solutions:

- Signs (chevrons, dynamic curve warning systems, and advance curve warnings and advisory speed signs)
- Pavement interventions (high-friction surface treatments, raised pavement markers, edge line pavement markings, safety edge, centerline rumble strips, and shoulder rumble strips)

- Roadside design (cable barrier, guard rail, breakaway supports for signs and lighting, clear zone improvements, and shoulder widening).

Pavement safety countermeasures have proven to be the most effective tool in reducing crashes (Jalayer, Zhou and Satterfield 2015).

ELRs, coupled with additional traffic calming measures, can be an effective solution on roads with a high risk of incidents caused by high driving speed.

2.5 Conclusions from Literature Review

Based on this thorough literature review, we are able to establish that there are several advantages of ELRs, including potential safety benefits. In the subsequent chapters of this report, we assess these potential advantages mathematically (through simulation) and through empirical means (analysis of crash data in the US and Australia).

III. Simulation of an Edge Lane Road

3.1 Background

As with any road treatment, appropriate conditions are necessary for an ELR installation to operate successfully. Criteria for these conditions, called siting criteria, are normally generated from research that explores the envelope within which a treatment performs safely and effectively. Current American guidance (Dickman et al. 2016) specifies that ELRs may be installed on any two-lane street with less than 6,000 ADT and a posted speed limit of 35 mph or less. Dutch siting criteria are more nuanced and consider other factors such as bicycle traffic volume (CROW 2017).

Using (A)ADT values as a siting criterion is easy but lacks precision. Roads with similar ADT volumes can exhibit markedly different hourly or sub-hourly peak volumes, as is the case when comparing a road with high levels of directional peak volumes to one with more balanced directional volumes.

Similarly, the motor vehicle speed is a siting criterion that is easily accessible but fails to capture the operational nuances of the treatment. For example, a low-volume ELR on which vehicles travel at high speeds may not experience many incidents where two vehicles traveling in the opposite direction must pass each other. This setting may be safer than an ELR with slower speeds but higher vehicular volume and higher rates of incidents where vehicles must pass opposite-direction travelers.

To create siting criteria that accurately reflect the safety of this treatment, one must understand the role of traffic flow characteristics and the trade-offs associated with their different values within the ELR envelope of operation. The aim of the present simulation work is to further researchers' and planners' understanding of these characteristics and trade-offs so that the development of future siting guidance may be based on an accurate understanding of the safety of the treatment.

To understand an ELR's safety performance, it is important to know more than the volumes and speeds of its users. For example, asymmetric directional volume splits for motor vehicles (MVs) can greatly reduce the number of interactions between two MVs traveling in opposite directions. If the number of interactions between oncoming MVs is reduced, the likelihood of crashes is reduced proportionately. Also, while higher MV speeds may threaten more severe crashes, they also reduce the number of interactions each MV is involved in due to the reduced time spent on the facility.

When evaluating ELR safety, the primary question regards the safety of vulnerable road users (VRUs).

Because each road user type has an exclusive space available to them, the authors assume that one MV passing a VRU, no matter their respective directions, is a relatively safe event. For the same reason, the assumption is made that two oncoming VRUs passed by an MV is also a safe event.

The potential for an unsafe event to occur is assumed to be much greater when interactions consisting of one or more VRUs with two or more oncoming vehicles occur. These circumstances do not provide exclusive space for each road user and require drivers to accurately judge the space and time needed for a safe encounter. For these reasons, when the safety of VRUs is being examined, the number of meetings of one or more VRUs with two or more oncoming vehicles is assumed to be the key metric.

When evaluating ELR safety for MV drivers, the key metric is the number of interactions involving two or more oncoming cars, with or without VRUs.

In both cases, the interactions of interest involve at least two MVs, with at least one each traveling in opposing directions. In this work, these are called "critical" interactions because these are the interactions most critical to assessing the safety of an ELR. Critical interactions garner the most interest because they offer the potential for head-on crashes between MVs, and if VRUs are nearby, they present a higher probability of MV×VRU collisions.

In addition to critical interactions, an "extended interaction" is also defined. Interactions between road users are said to exist when they are physically alongside each other (each road user type, motorist, bicyclist, and pedestrian, has an assigned length of the roadway they occupy). The exception to this definition is the extended interaction. An extended interaction is meant to capture the possibility of actions taken by a driver upon recognition of an oncoming MV. An extended interaction is defined to be an instance when MVs are traveling on the region of roadway within which the driver of either MV may maneuver in preparation for, or in the resolution of, the passing movement. For each driver, this region begins after the oncoming MV has been perceived and identified. In the real world, once perception and identification have occurred, the driver may immediately choose to initiate a movement. Once the MVs pass each other, they are expected to maneuver back to the center lane. After both drivers return to the center lane, the extended interaction ends. If another oncoming MV is present, a new extended interaction is established. Any VRUs who fall within this extended interaction area are considered to be a party to that interaction. The duration over which these maneuvers may occur is defined in seconds and is called the extended interaction duration.

Because the rate and type of interactions are crucial to understanding the safety performance of an ELR, the authors developed a simulation program that could answer questions about the impact of various factors on the interaction rate of a facility. The simulator was designed to address the following questions:

- What is the role of MV volume in a facility's interaction rate?
- What is the role of motor vehicle speed in a facility's interaction rate?
- What is the role of ELR length in a facility's interaction rate?
- What is the role of VRU volume in a facility's interaction rate?

- What is the role of the directional split in a facility's interaction rate?
- What is the role of extended interaction duration in a facility's interaction rate?
- What interaction rates are permitted by current FHWA guidelines?

To help answer these questions, a Python program written by the authors was used to simulate road user behaviors on an ELR. The program simulates three types of road users (pedestrians, bicyclists, and motor vehicles) on a road segment with no intersections and no turning movements. The program generates all road users at either end of the road. Road users proceed along the road and exit at the opposite end. All road users act as if they occupy their own virtual lane, i.e., they do not move laterally in order to pass, and they do not wait to pass at a more opportune time in the future. All road users are allowed to pass one another, with the exception of MVs traveling in the same direction. All passes occur without a change in speed. MVs traveling in the same direction will platoon behind a slower MV and decrease speed to stay behind the slower MV.

The simulation records a wealth of data on each road user, each interaction, and all parties to an interaction. Post-simulation utilities process these data to create the desired output, e.g., MVxMV interaction rates. These data provide an accurate characterization of the road's operation, laying the foundation for a more consistent siting criterion that promises to allow communities to assess an ELR's safety on roads with unique operating conditions.

The possibility of developing a siting criterion that keeps the rate of less-safe interactions below a chosen threshold becomes possible once the influence of various factors on this rate is known. One might establish a ceiling on the hourly rate of interactions involving oncoming MVs and VRUs. This criterion could replace the commonly used ADT threshold. In this case, vehicular speed would remain as a companion criterion but with a modified role. The allowed rate of VRU×MV×MV interactions would likely be reduced for higher-speed roads to keep risk and/or perceived comfort at an acceptable level.

3.2 Process

To verify the integrity of the results, two different solutions using different approaches were compared. The first simulation employed a Monte Carlo approach to a microsimulation of an ELR populated with three types of road users: motor vehicles, bicyclists, and pedestrians. This simulation is the one used to produce the data in this report.

The second simulation took a list of road users generated by the first simulation as input, plotted their trajectories on a time-space graph, and recorded the interactions that occurred by investigating the intersections of those trajectories. When road user trajectories are plotted on a time-space graph, the intersections of those trajectories indicate that two (or more) road users are at the same place on the facility at the same time. The physical dimensions of those intersections also show the length of time and physical space over which those interactions occurred. The purpose of the second simulation was to ensure that the first simulation was operating correctly.

The higher-level results of the Monte Carlo simulation were also verified against the results published in Appendix G of NCHRP 214 (Glennon 1979). This process was only used to verify the correct operation of the software before it was used to produce the results published in this report.

A test library was developed using the automated test features built into the Python environment. This testing evaluated small portions of the code using a unit testing approach. This automated test was also used to test edge conditions. Edge conditions are variable values or conditions which exist at the edges of the envelopes within which the program is required to operate correctly.

3.3 Product

The Monte Carlo simulation allows the following values to be varied for each simulation run:

- Road length, in meters
- Timespan, in hours
- Extended interaction duration, in seconds
- Road users per hour (unique values for each road user type)
- Directional volume split, 0–100% (unique values for each road user type)
- Arrival timing for each road user type (fixed, equal intervals, or Poisson distribution of arrival intervals)
- Road user speed (unique values for each road user type)
- Distribution of road user speeds (fixed, equal speeds, or normally distributed speeds with input speed at the 85th percentile)

Data collected on each road user include the following:

- Type (pedestrian, bicyclist, or motor vehicle)
- Length, in meters
- Speed, in meters per second
- The direction of travel, eastbound or westbound
- Begin location, position on the road where the road user was created, in meters
- Begin time, time road user was created, in seconds
- Current location, current position on the road, in meters
- End location, position on the road where the road user was removed, or an indication that the simulation ended with the road user still on the road

- End time, time the road user was removed from the road, in seconds
- Platooned status, whether the road user is part of a platoon (MVs only)

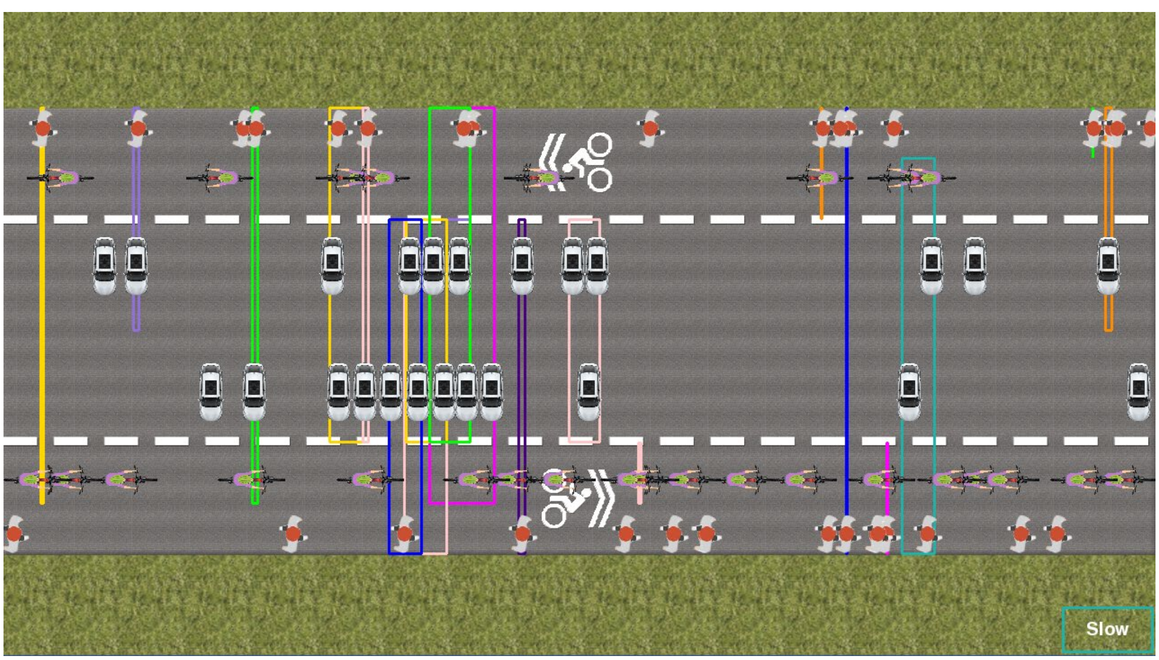
Each road user of a given type is physically identical: for example, among motor vehicles, there are no heavy vehicles with greater length, greater width, less maneuverability, and so on.

Data collected on each interaction include the following:

- Start and end times, in seconds
- Start and end locations (position on the road where the interaction begins and ends)
- Road users involved in the interaction (and all information for each road user)
- For critical interactions, the two MVs which initiated the interaction
- Whether the interaction was initiated as an interaction between two oncoming MVs (known as a critical interaction)
- Whether the interaction was initiated at a distance between two oncoming MVs (known as an extended interaction)

Though the simulator is intended to run unattended with the generated data being its primary output, it can also display the simulation as it progresses. A screen capture of the display is shown in Figure 4. The colored boxes define the limits of the interactions in process, with their vertical reach indicating which road users are parties to the interaction and their horizontal reach showing the physical extent of the interaction.

Figure 4. Screen Capture of Simulation Display



3.4 Results

This section presents graphs of data produced by simulation that illustrate the role of various traffic characteristics on an ELR's interaction rate. Each graph is accompanied by text providing background information and a more detailed explanation of the meaning of the graphed relationships.

Because the simulation randomly draws road user speeds and arrival intervals from statistical distributions, results can vary significantly when short run times are used. To generate the needed data, the simulation was run for 1,000, 5,000, or 10,000 hours per data point in order to reduce the anomalies introduced by statistical variation in shorter simulation runs.

In order to assess the safety of the most vulnerable road users, i.e., bicyclists and pedestrians, the convention in this section is to present the rates of critical interactions involving VRUs over the entire length of the ELR. All results are applicable only to those conditions assumed by the simulation, e.g., no intersections or turning movements.

Unless stated otherwise, the default values for the simulation parameters are as shown in Table 6.

Table 6. Default Simulation Parameter Values

Parameter	Setting	Units
Road Length	1,000	Meters
Simulation Time	1	Hours
Extended Interaction Duration	2	Seconds
Cyclist Volume	20	Hour
Ped Volume	10	Hour
MV Volume	60	Hour
Cyclist Directional Split	50	%
Ped Directional Split	50	%
MV Directional Split	50	%
Cyclist Spacing	ON	Arrival intervals sourced from negative exponential distribution
Ped Spacing	ON	Arrival intervals sourced from negative exponential distribution
MV Spacing	ON	Arrival intervals sourced from negative exponential distribution
Cyclist Speed	5.3645	Meters per second (12 mph)
Ped Speed	1.22	Meters per second (4 ft/sec or 2.7 mph)
MV Speed	11.176	Meters per second (25 mph)
Cyclist Speed Distribution	ON	Speed from normal distribution with 85th percentile = Cyclist Speed
Ped Speed Distribution	ON	Speed from normal distribution with 85th percentile = Ped Speed
MV Speed Distribution	ON	Speed from normal distribution with 85th percentile = MV Speed
Statistical Seed	ON	Seed set to fully random

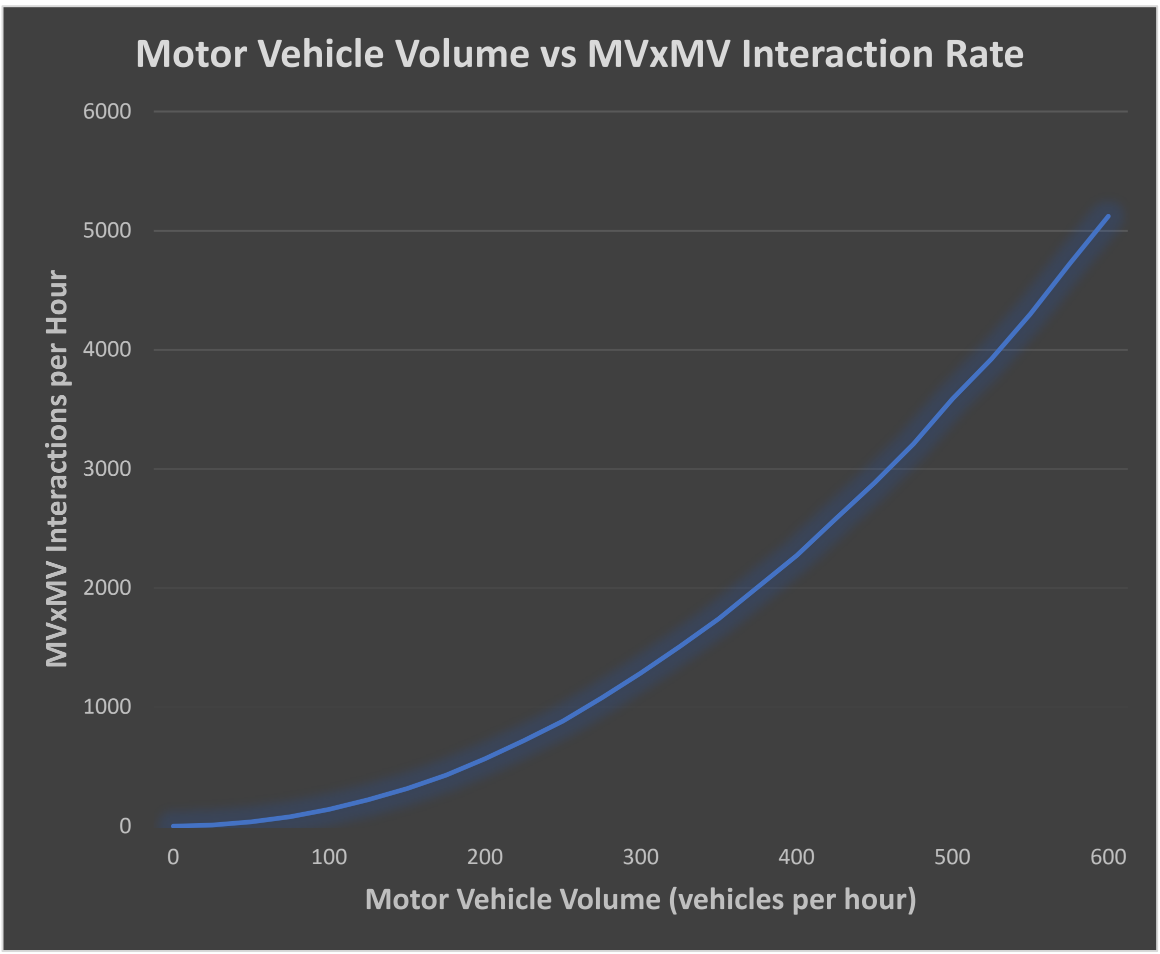
In the following graphs and narrative, the "MV×MV" notation indicates an interaction including at least two oncoming vehicles. The "MV×MV×VRU" notation indicates an interaction occurring between two or more oncoming vehicles and at least one VRU.

Results are presented with respect to the questions listed earlier, which the simulation was intended to answer.

What is the role of MV volume in a facility's interaction rate?

It is helpful to understand the mechanism underlying an ELR's interaction rate when viewing later graphs and data. Figure 5 shows the relationship between a facility's hourly MV volume and its MV×MV×VRU interaction rate.

Figure 5. Facility MV×MV Interaction Rate as a Function of MV Volume



When a motorist enters an ELR, they encounter two groups of oncoming vehicles while transiting the facility. The first group consists of all vehicles which were already on the facility when they entered. The second group consists of all vehicles which enter the facility before the motorist completes their transit.

The two groups of oncoming vehicles encountered by a motorist are reflected in the derivation of the formulas that calculate a facility's MV×MV interaction rate. An equation for a facility's interaction rate was published in Appendix G of NCHRP Report 214 (Glennon 1979):

$$N = 2\left(\frac{R}{2}\right)^2\left(\frac{L}{V}\right)\left(\frac{1}{3600}\right)$$

where:

N = the number of MV×MV interactions per hour on an ELR,
R = the hourly volume of cars in both directions,
L = length of the ELR (in meters), and
V = motor vehicle velocity (in meters per second).

The 1/3,600 value is used to convert the hourly rate of opposing vehicles to a vehicle rate per second. The doubling that occurs (i.e., the initial coefficient, 2) is used to count both groups of oncoming vehicles as described earlier. This equation simplifies to:

$$N = \left(\frac{R}{2}\right)^2\left(\frac{L}{V}\right)\left(\frac{1}{1800}\right)$$

If one desires to know the number of MVxMV interactions that a typical driver will see while transiting a facility, the formula that calculates the number of MV×MV interactions for one motorist is also given in Appendix G of NCHRP Report 214 (Glennon 1979) and is:

$$n = \left(\frac{\left(\frac{R}{2}\right)\left(\frac{1}{3600}\right)}{V} \times L\right) + \left(\left(\frac{R}{2}\right)\left(\frac{1}{3600}\right)\left(\frac{L}{V}\right)\right)$$

where:

n = the number of oncoming MVs a motorist will pass while transiting an ELR,
R = the hourly volume of cars in both directions,
L = length of the ELR (in meters), and
V = motor vehicle velocity (in meters per second).

The first term of this equation (after the equals sign) counts the number of opposing cars already on the ELR when the motorist enters, and the second term counts the number of opposing cars that enter the ELR while the motorist transits the facility. The 1/3,600 value is used to convert the hourly rate of opposing vehicles to a vehicle rate per second.

This formula can be simplified to

$$n = \frac{RL}{3600V}.$$

All of these equations make the following simplifying assumptions:

- Vehicles are uniformly spaced,
- Traffic volume has a 50/50 directional split,
- All cars travel at the same speed, and
- All cars enter and leave the facility at its two ends.

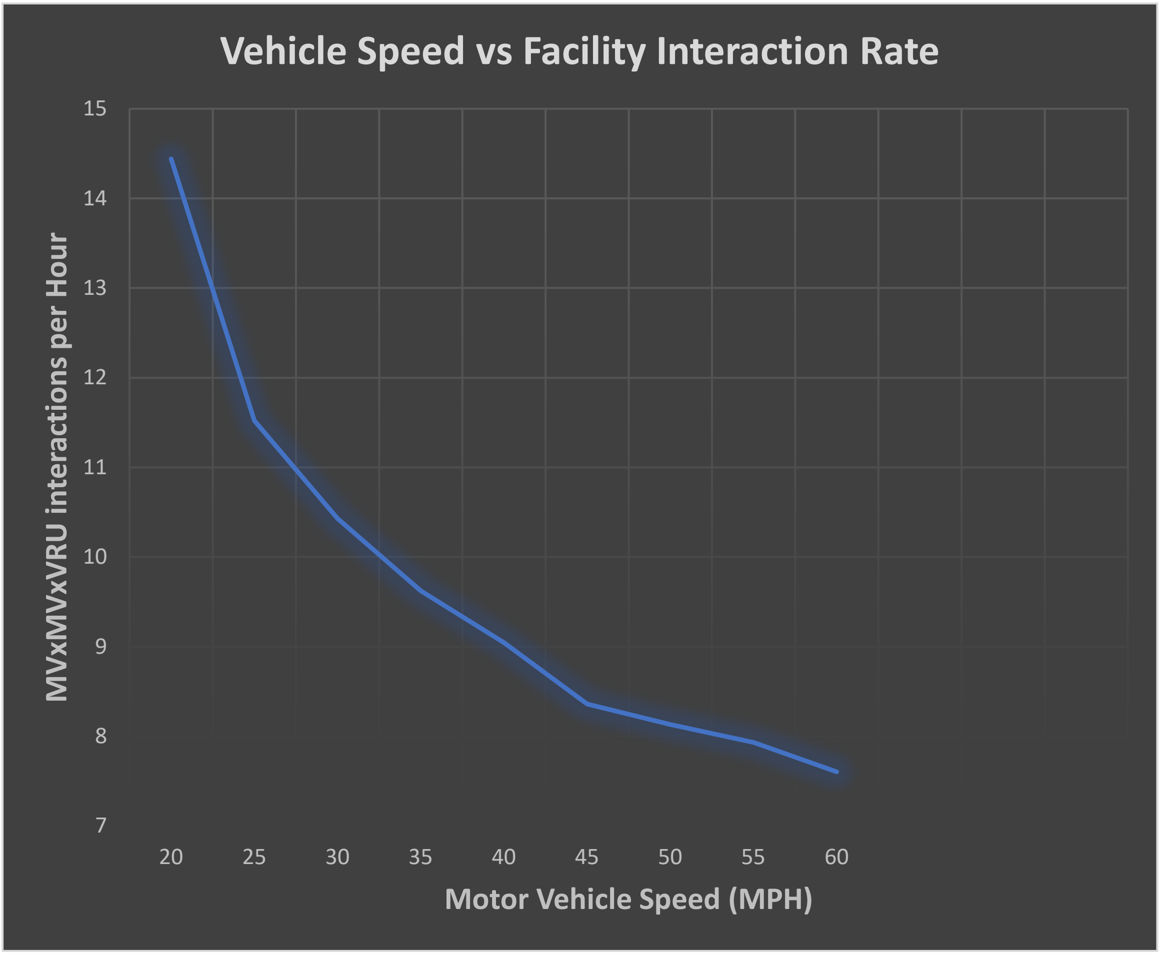
These equations accurately model the impact of MV volume on a facility's interaction rate and provide a formulaic complement to the relationship shown in the simulation data.

These equations and Figure 5 make clear that the dominant factor in the rate of MV×MV interactions on a facility is the product of the vehicle volumes in each direction. The equations also show that a facility's MV×MV interaction rate is directly proportional to the facility length and inversely proportional to the vehicle speed.

What is the role of MV speed in a facility's interaction rate?

Figure 6 shows the relationship between MV speed and facility interaction rate. As MV speeds approach zero, the facility interaction rate will approach infinity (assuming vehicles are already present on the facility). Consideration of the asymptote as MV speeds approach infinity is not useful in this case as 60 mph is likely to be the fastest posted speed for an ELR. The relationship between these two limits appears to be an exponential decay with the greatest reductions in facility interaction rate occurring at the slower speeds. It is interesting and non-intuitive that increasing the speed from 20 to 25 mph has the potential to increase the safety of an ELR by a significant amount, but other factors need to be weighed, and field data should be studied before a conclusion is drawn. Further investigation of this relationship is needed.

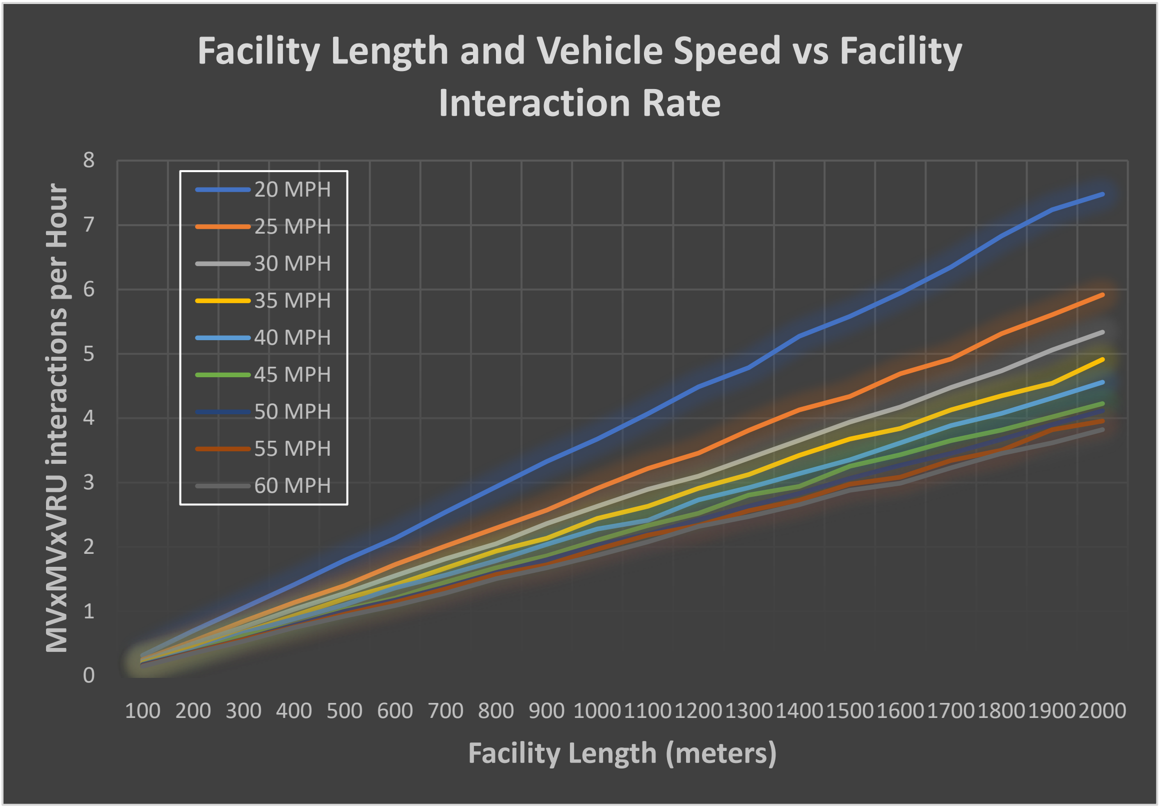
Figure 6. Facility MV×MV×VRU Interaction Rate as a Function of MV Speed



What is the role of ELR length in a facility's interaction rate?

Figure 7 shows that the interaction rate is directly proportional to the length of the ELR treatment but that MV speed helps determine the rate at which the increase occurs. As shown in another graph, as MV speeds increase, the facility's interaction rate decreases because each MV spends less time on the facility.

Figure 7. Facility MV×MV×VRU Interaction Rate as a Function of MV Speed and Facility Length



What is the role of VRU volume in a facility's interaction rate?

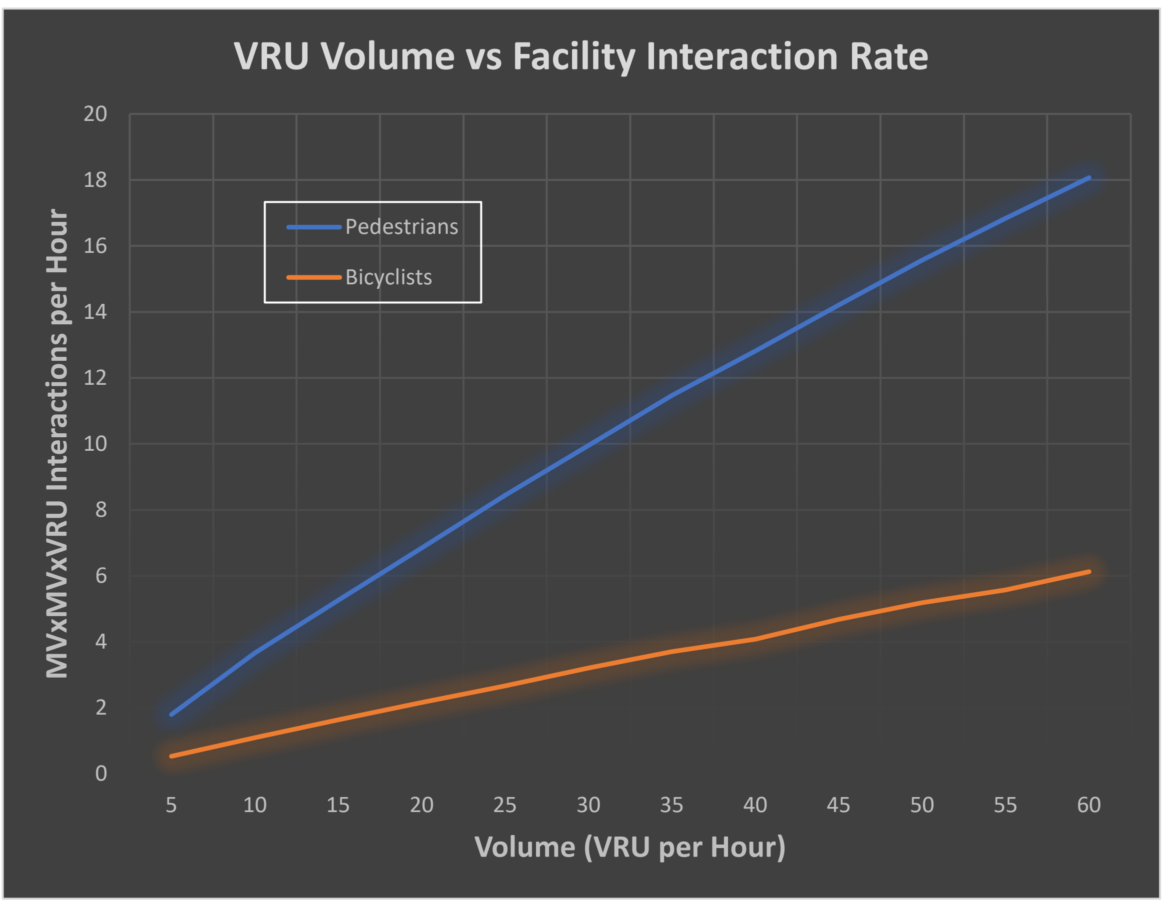
Figure 8 shows the impact of VRU volumes on the facility's interaction rate, with MV volumes held constant at 60 MVs per hour. For the pedestrian volume simulations, bicyclist volumes were held at zero and vice versa. This graph shows a near-linear relationship between VRU volumes and the MV×MV×VRU interaction rate.

What Figure 8 makes clear is the importance of time spent on the facility by each road user in terms of the facility's interaction rate. Because pedestrians travel approximately 4.4 times slower than bicyclists in this simulation, they spend more time on the facility and generate many more interactions during their transit.

This graph also illustrates an interesting relationship between the pedestrian and bicyclist volume lines. The authors had hoped to derive an equation that would take the bicyclist and pedestrian volumes as inputs and produce a composite VRU volume as output. This composite VRU volume would accurately reflect the combined impacts of bicyclist and pedestrian volumes in the resulting MV×MV×VRU interaction rates. This concept would reduce the number of variables to consider while exploring design trade-offs and would allow a more straightforward presentation of results. Because a bicyclist's length was twice the length of a pedestrian (2 meters vs. 1 meter) and a bicyclist's speed was 4.4 times greater (12 mph vs. 2.7 mph), the original idea was that a pedestrian would be “equal” to approximately 2.2 bicyclists in terms of their contribution to the interaction rate. Figure 8 reveals that this expected relationship does not exist. Further, the relationship varies as volumes vary. The reason for this variable relationship is still being investigated. It is assumed to result from the different rates at which pedestrians and bicyclists are involved in critical interactions that contain multiple VRUs. An MV×MV×VRU interaction is counted whether there is one VRU present or many. The different rates at which interactions with multiple VRUs occur may be the source of this variable relationship.

The graph was described as showing a “near-linear” relationship between pedestrian volume and facility interaction rate. While the relationship may be adequately modeled as linear when volumes are low, as pedestrians become more numerous, this relationship approaches a value equal to the MV×MV interaction rate. Once pedestrians reach a critical density on the ELR, all MV×MV interactions will be MV×MV×VRU interactions. At this level, the MV×MV×VRU interaction rate will not increase even if pedestrian volumes increase. The same is true for bicyclists, even though higher bicyclist volumes are necessary to reach this same saturation point. A graph of VRU volumes versus interaction rate that included a higher rate of VRUs per hour would show an asymptotic approach to the MVxMV interaction rate.

Figure 8. Facility MV×MV×VRU Interaction Rate as a Function of VRU Volume



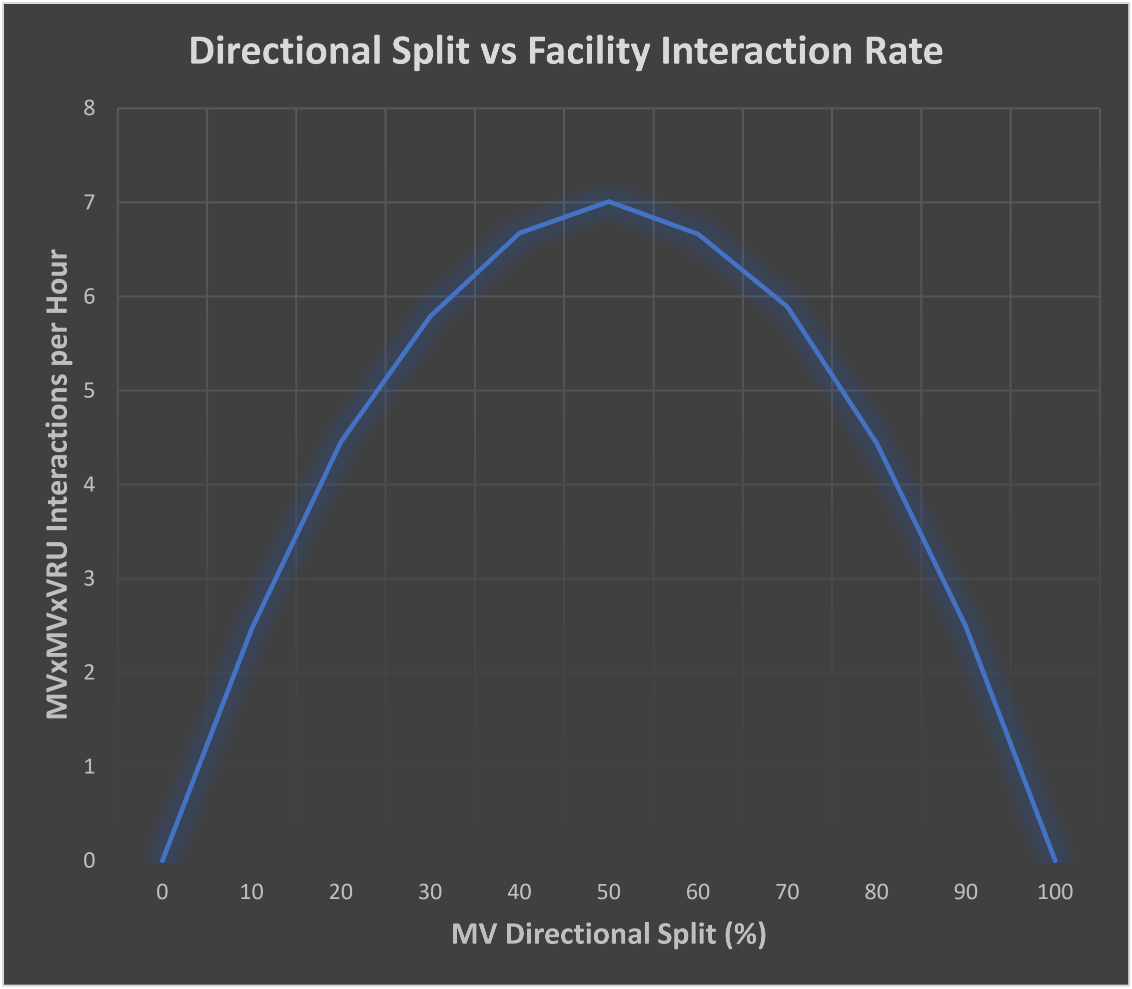
What is the role of the directional split in a facility's interaction rate?

Figure 9 shows a facility's MV×MV×VRU interaction rate as a function of directional motor vehicle volume split. To read this graph, one selects either directional volume percentage for a subject street (e.g., either 25 or 75 for a street with a 75/25 directional volume split) and reads the MV×MV×VRU facility rate using that percentage. For example, a street with a 75/25 directional volume split with the default characteristics previously described shows an MV×MV×VRU facility interaction rate of approximately five critical interactions per hour.

These results align with expectations, given the importance of opposing motor vehicle volumes to interaction rates. This graph shows the effect of traffic volumes moving away from the symmetric 50/50 directional split. The impact of asymmetric directional volumes is small near the 50/50 point but grows rapidly as asymmetry increases.

It is worthwhile to note the rather steep drop-off of interaction rates as the directional split becomes more asymmetric (i.e., moves away from a 50/50 split). This implies that streets with a significant commute traffic pattern, whereby most drivers go in one direction in the morning and most go in the other direction in the evening, may be able to accommodate an ELR configuration at higher volumes than might otherwise be considered.

Figure 9. Facility MV×MV×VRU Interaction Rate as a Function of Directional Split



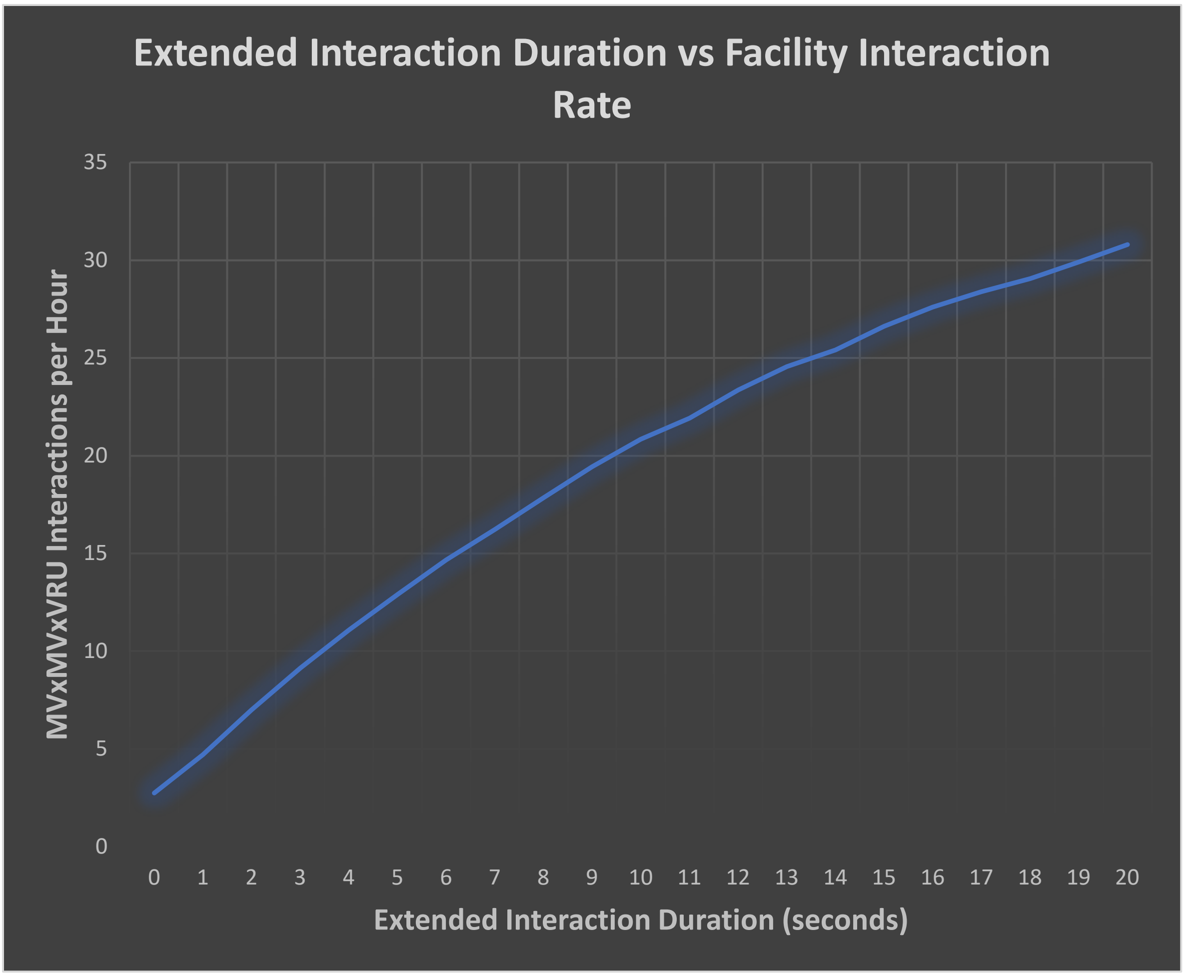
What is the role of extended interaction duration in a facility's interaction rate?

The simulation assumes interactions exist when the road users are physically alongside each other. The one exception is called an extended interaction. The concept of the extended interaction was created to capture the impact on VRUs of approaching MVs maneuvering to pass one another. Extended interactions are defined to exist only between oncoming MVs. Extended interactions include all VRUs within the extent of the interaction. An extended interaction's extent or duration is measured in seconds. The duration of an extended interaction includes the time needed by a motorist to recognize an oncoming vehicle, complete the maneuver needed to pass the vehicle, and return to the center lane after passing. All VRUs located between two oncoming MVs are part of an extended interaction, and in addition, all VRUs within the area needed for a motorist to return to the center lane are part of that interaction as well.

There appears to be no existing research that can establish an average value for the extended interaction duration. The actual value may vary according to a number of factors, e.g., speed or road geometry, and it may need to be site- or condition-specific. The importance of the extended interaction duration for this work lies with its impact on the facility MV×MV×VRU interaction rate, which is the metric presented in most of the results.

Figure 10 shows the gradual growth of the facility interaction rate toward an asymptote, which is the MV×MV interaction rate. Once the extended interaction duration reaches a critical value, all MV×MV interactions become MV×MV×VRU interactions, assuming some level of VRU traffic.

Figure 10. Facility MV×MV×VRU Interaction Rate as a Function of Extended Interaction Duration



What critical interaction rates are permitted by current FHWA guidelines?

Current US federal guidelines, as set out in the 2016 FHWA Small Town and Rural Multimodal Networks, establish two classes of siting guidance (FHWA 2016). The first is the set of conditions labeled "preferred": this class is defined by an ADT of 3,000 or less and a posted speed of 25 mph or less. The second set is labeled "potential": it is defined by an ADT of less than 6,000 and a posted speed of 35 mph or less.

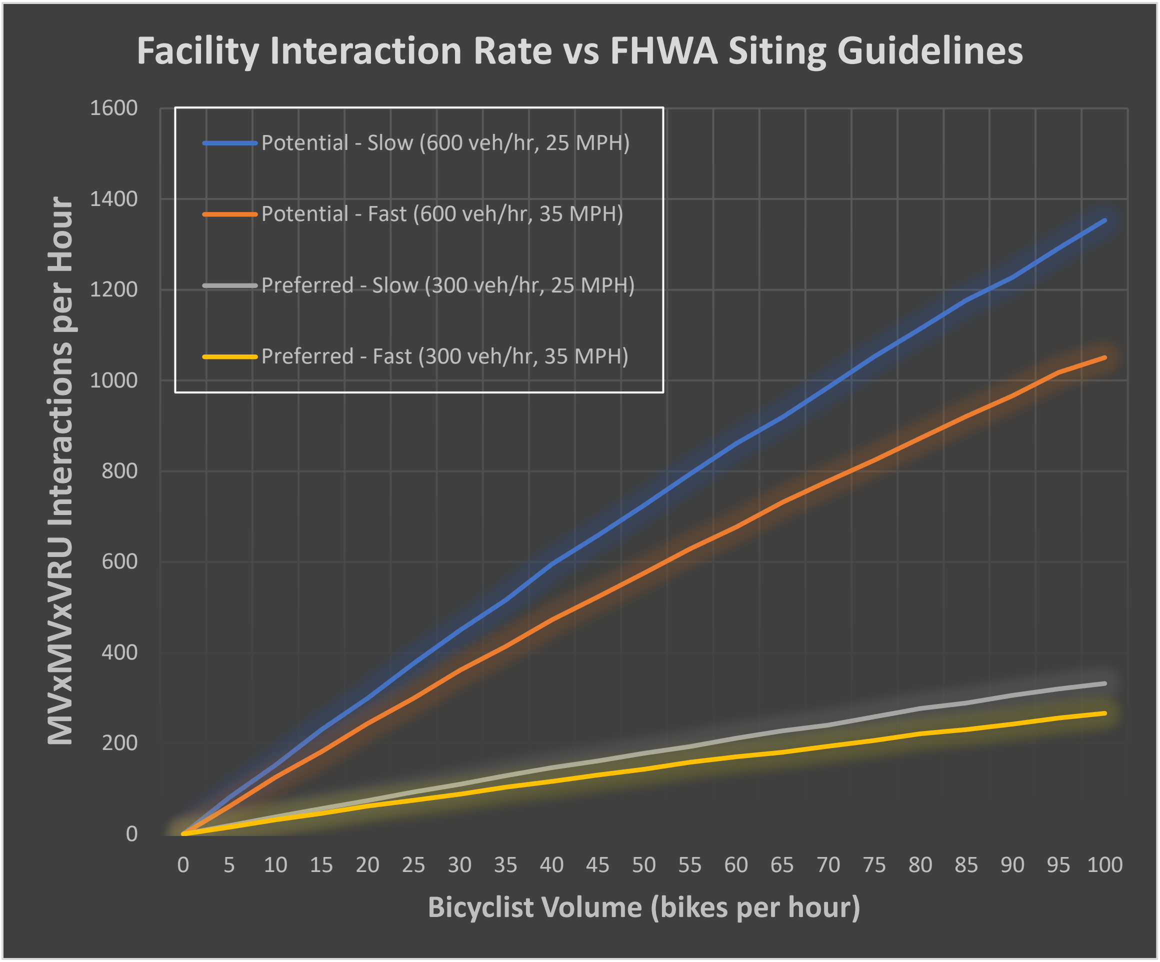
Using the four data points specified in this guidance, a family of resulting interaction rates was graphed. Figure 11 shows the resulting MV×MV×VRU interaction rates for a one-kilometer-long ELR facility with no pedestrians and varying MV volumes. The Preferred/Slow line assumes 300 vehicles per hour and a 25 mph vehicle speed. The Preferred/Fast line assumes 300 vehicles per hour and a 35 mph vehicle speed. The Potential/Slow line assumes 600 vehicles per hour and a 25 mph vehicle speed. The Potential/Fast line assumes 600 vehicles per hour and a 35 mph vehicle speed.

Note that the MV volumes of 300 and 600 vehicles per hour were chosen based on the common rule of thumb whereby the peak hour volume is ten percent of the ADT. Using that relationship, 300 vehicles per hour represents the peak hourly volume for the 3,000 ADT threshold, and 600 vehicles per hour represents the peak hourly volume for the 6,000 ADT threshold. This rule of thumb is often not true of lower-volume roads, and an alternative method of estimating peak hourly volumes is to divide the ADT by eighteen; eighteen reflects the number of hours in a day with appreciable volumes. The ten-percent rule of thumb results in significantly higher peak hourly volumes and is more conservative for that reason.

Figure 11 demonstrates the already documented decrease in facility interaction rate as MV speeds increase. The main message of this graph is the dramatically different interaction rates that result from a doubling of the MV volume. Though this effect was already demonstrated in Figure 7, it is useful to see the difference in rates at the outer edges of the design envelope as well as the difference in the growth of those rates as VRU volumes increase.

The FHWA guidelines lack any reference to VRU volumes. This is a deficiency in that guidance. Not only do VRU volumes have an important impact on a facility's interaction rate, but higher volumes also have the potential to reduce or eliminate available gaps in edge lanes that can accommodate vehicles needing to pass an approaching vehicle. A complete set of siting guidelines for ELRs will need to incorporate VRU volumes as well as MV volumes.

Figure 11. Facility MV×MV×VRU Interaction Rates under FHWA Guidelines



3.5 Conclusions

The results generated from the simulator demonstrate a number of relationships that are important to understand when dealing with ELRs. The most important is the rapid rise in the critical interaction rate, and the rate of interactions with motor vehicles approaching one another, as vehicle volume increases. Volume is likely the most important factor to consider when evaluating whether to use an ELR.

These results lay the foundation for an ELR siting criterion which is based on the number of interactions that occur on the facility. That siting criterion may be expressed in terms of the likelihood that any bicyclist or pedestrian will be party to an interaction involving approaching motor vehicles maneuvering to pass one another, or it may be expressed in terms of an acceptable rate of those same interactions for the entire facility.

A siting criterion that uses the facility interaction rate as a fundamental metric directly measures the problem this treatment is intended to manage. It also avoids the problems posed by the current use of ADT, which includes a non-intuitive increase in the interaction rate as motor vehicle speeds decrease. If an agency chooses not to follow sustainable safety principles that dictate low speeds whenever motor vehicles and vulnerable road users are mixed together, then further work would be required to determine an acceptable trade-off between crash severity and frequency.

These results also provide a tool for measuring the effect of asymmetric directional split on interaction rate, potentially allowing for the safe use of ELRs on roads with higher volumes and asymmetric directional volumes. Further, the results indicate that there is a significant difference in the facility interaction rate when one considers pedestrians rather than bicyclists.

Despite the derivation of equations that demonstrate the relationships between individual factors and a facility's MVxMVxVRU interaction rate in this work, an equation that calculates the MVxMVxVRU interaction rate as a function of all factors has not been created. Further work is required to create a tool that can be used by practitioners to estimate the MVxMVxVRU interaction rate given all of the factors existing on a facility.

Further research is also needed to characterize the distances at which motorists begin to maneuver to pass an approaching vehicle and the factors that determine that distance. The results of this research would inform the selection of an appropriate extended interaction distance.

The results demonstrate the range of MV×MV×VRU interaction rates that can occur within the current American siting guidelines for ELRs. It would be instructive to compare these rates to those allowed by guidance from countries with more experience with this treatment, e.g., the Netherlands and Denmark.

That an ELR's interaction rate and appropriate operation depend on both MV and VRU volumes requires that future American guidance on this treatment address the allowable volumes of all types of road users. This will require either more research or an interim adoption of guidelines already used in other countries, or both.

IV. US Crash Data Analysis

Long-term crash data being the most reliable metric for assessing safety, this chapter analyzes the crash data on US ELR facilities before and after the installation of ELRs. The different safety analyses used in this chapter are similar to the ones used in Huang's safety analysis of road diets: specifically, the analysis of crash trends in the 'before' period and the standard yoked comparison (Huang, Stewart, and Zegeer 2002). The present authors decided to include an Empirical Bayes (EB) analysis of these ELRs, as well, to directly compare how many crashes were experienced on the ELR with the expected number of crashes should the facility have remained a two-lane road.

4.1 Study Site Selection

The ELRs chosen for analysis were required to have at least three years of pre-installation and three years of post-installation crash data. There are approximately 38 known ELRs that have been installed in the United States and Canada. Only 13 of the 38 sites met the crash data requirements. Table 7 shows the facilities used for this analysis, along with a few basic attributes. As seen in Table 7, the ELR facilities range in length from 1,100 feet (0.08 miles) to 4,800 feet (0.91 miles). All facilities had a posted speed limit within the range of 20 mph to 30 mph, with most of them having a posted speed limit of 25 mph. Eleven of the 13 ELR installations were classified as urban facilities.

Table 7. List of North American ELRs with Available Crash Data

Group #	ELR Site	City	Rural or Urban	Segment Length (ft)	Speed Limit (mph)
1	*Bridge Street*	Yarmouth, ME	Urban	2,900	25
2	*Eastern Road*	Scarborough, ME	Rural	4,800	25
3	*Morton Road*	Yarmouth, ME	Urban	2,900	25
4	*Harvard Lane*	Boulder, CO	Urban	1,600	25
5	*E 54th Street*	Minneapolis, MN	Urban	4,250	30
6	*E 7th Street*	Bloomington, IN	Urban	2,200	25
7	*Flynn Avenue*	Burlington, VT	Urban	1,600	25
8	*54th Street*	Edina, MN	Urban	1,100	30
9	*Oak Street*	Sandpoint, ID	Urban	1,365	25
10	*2nd Avenue*	Hailey, ID	Urban	3,580	20
11	*W 46th Street*	Minneapolis, MN	Urban	1,300	30
12	*Lakeview Avenue*	Cambridge, MA	Urban	1,600	25
13	*Quaker Street*	Lincoln, VT	Rural	963	30

In addition to these 13 ELRs, the authors also identified 34 comparison sites. Each of these roads is undivided with two lanes and is located near its designated ELRs.

OpenStreetMap (OSM) is an application that allows users to filter through editable maps of the world; it was used to identify the comparison sites. The following characteristics were specified within OSM to find comparison sites for each ELR: functional classification, number of lanes, pavement width, presence of the sidewalk, and type of parking. There were a few instances where OSM was missing information or maps on certain areas, and Google satellite images had to be used instead to identify nearby roads to be used as comparison sites. In these instances, the authors measured the width of the road or verified the presence of a sidewalk. It is important to note that for the North American facilities, AADT and speed limit were not used as criteria for selecting comparison sites. The focus of this analysis was to choose comparison sites based on their physical characteristics and geographic location relative to their respective ELRs. Once this process was complete and the filters were applied to OSM, each ELR had 2–3 comparison sites located within the same vicinity that were identified for use in this analysis. A list of each comparison site and its location accompanied by its respective ELR (to create matched groups) can be found in Table 8.

Table 8. List of Comparison Sites for North American ELRs

Site #	Street Name	Comparison Sites	Location
1	*Bridge Street, Yarmouth, ME*	Yankee Drive	Yarmouth, ME
		Applecrest Drive	Yarmouth, ME
		Royall Point Road	Yarmouth, ME
2	*Eastern Road, Scarborough, ME*	Charles E. Jordan Road	Cape Elizabeth, ME
		Hurricane Road	Gorham, ME
3	*Morton Road, Yarmouth, ME*	Pleasant Street	Yarmouth, ME
		Mill Road	Dedham, ME
		Bagaduce Road	Holden, ME
4	*Harvard Lane, Boulder, CO*	S. Lashley Lane	Boulder, CO
		Apache Road	Boulder, CO
		Brooklawn Drive	Boulder, CO
5	*East 54th Street, Minneapolis, MN*	W 38th Street	Minneapolis, MN
		W 36th Street	Minneapolis, MN
		W 31st Street	Minneapolis, MN
6	*East 7th Street, Bloomington, IN*	East 2nd Street	Bloomington, IN
		Crawford Street	Terre Haute, IN
		East Maxwell Lane	Bloomington, IN
7	*Flynn Avenue, Burlington, VT*	Richardson Street	Burlington, VT
		Pine Street	Burlington, VT
		Harbor Road	Shelburne, VT
8	*West 54th Street, Edina, MN*	W 51st Street	Edina, MN
		W 52nd Street	Edina, MN
9	*Oak Street, Sandpoint, ID*	Cedar Street	Sandpoint, ID
		Pine Street	Sandpoint, ID
10	*2nd Avenue, Hailey, ID*	N River Street	Hailey, ID
		4th Avenue S	Hailey, ID
		Buckhorn Drive	Hailey, ID
11	*West 46th Street, Minneapolis, MN*	E 34th Street	Minneapolis, MN
		W 55th Street	Minneapolis, MN
		W 53rd Street	Minneapolis, MN
12	*Lakeview Avenue, Cambridge, MA*	Lexington Avenue	Cambridge, MA
		Hammondswood Road	Newton, MA
		Standish Road	Watertown, MA
13	*Quaker Street, Lincoln, VT*	Old Turnpike Road	Mt. Holly, VT
		Bowlsville Road S	Belmont, VT

4.2 Data Collection Methods

Moving forward to the data collection step, it is important to first identify what kind of analyses and methods will be used to identify safety effects. A before-and-after approach was optimal for this project as it is effective when conducting safety analyses through comparisons between treatment sites and control sites. As such, the 'before' period for each ELR and its respective comparison sites is defined as the time before the ELR was implemented, while the 'after' period refers to the time after the ELR has been implemented.

For the group of North American ELRs, two analyses will be conducted: (i) a preliminary analysis of crash trends of ELRs and their comparison sites in the years before and after the ELR was implemented, and (ii) an Empirical Bayes (EB) before-after evaluation. Table 9 shows the specific crash and traffic data required for each analysis. A 3-month data exclusion period, centered on the ELR installation date, prevented the collection of data on crashes that may have been caused by lane closures, work zones, or motorists adjusting to the new treatment. It should be noted that the EB approach also requires site context information such as the presence of lighting, on-street parking presence, etc.

The EB-based approaches have more intensive data requirements compared to the yoked comparison used for preliminary exploration. Among the two EB approaches used in this study, the project-based approach requires crash data for intersections as well as the ELR segment.

Table 9. Data Needed for ELR Safety Analysis Approaches

Analyses	Crash Data	Traffic Data	Additional Data Needed
	Preliminary Crash Trends Exploration		
Yoked Comparison	Yearly crash data from 5–7 years before ELR installation date for ELRs and comparison sites Yearly crash data from 2–3 years after ELR installation date for ELRs and comparison sites	Not needed	Not needed
	Empirical Bayes Before-and-After Evaluation		
Corridor-Level Approach	Yearly crash data from 5 years before ELR installation date	ADT on ELR	Context-specific variables (e.g., parking) for safety performance function
Project-Based Approach	Yearly crash data from 3 years after ELR installation date	ADT on ELR and intersecting streets	Context-specific variables (e.g., parking) for safety performance function

Because a total of 47 facilities were chosen for analysis and are located in various cities and states scattered throughout the United States, data were collected and compiled from several sources. For each ELR, the authors identified the official transportation authority in charge of maintaining these roads and used whatever tools, records, and contacts were available to extract the necessary data. Table 10 shows the transportation agencies that were identified as reliable sources from which traffic and crash data could be collected. Data were obtained through a combination of various channels, whether the information was available directly through online records, query tools, and/or GIS databases or obtained indirectly via data request forms and/or contacting local transportation officials. It is important to note that the ELRs and their assigned comparison sites used the same data sources to maintain consistency within the matched groups.

Table 10. Data Sources for Each ELR

Group #	ELR	Crash & Traffic Data Sources
1	Bridge Street, Yarmouth, ME	Maine Department of Transportation Public Crash Query Tool
2	Eastern Road, Scarborough, ME	Maine Department of Transportation Public Crash Query Tool
3	Morton Road, Yarmouth, ME	Maine Department of Transportation Public Crash Query Tool
4	Harvard Lane, Boulder, CO	Colorado Department of Transportation Data provided by Public Information Officer after request was made
5	East 54th Street, Minneapolis, MN	City of Minneapolis Transportation Data Management System Tool
6	East 7th Street, Bloomington, IN	City of Bloomington Traffic Data & Roadline Centerline GIS Data via website
7	Flynn Avenue, Burlington, VT	Vermont Agency of Transit Crash Public Query Tool
8	West 54th Street, Edina, MN	Minnesota Department of Transportation Crash Mapping Tool & Traffic Mapping Application
9	Oak Street, Sandpoint, ID	Idaho Transportation Department Crash Reports & GIS Traffic Data via website
10	2nd Avenue, Hailey, ID	Idaho Transportation Department Crash Reports & GIS Traffic Data via website
11	West 46th Street, Minneapolis, MN	City of Minneapolis Transportation Data Management System
12	Lakeview Avenue, Cambridge, MA	City of Cambridge Open Data Portal for Crash Data and Traffic Counts
13	Quaker Street, Lincoln, VT	Vermont Agency of Transportation Addison County Crash GIS Database & Open Geodata Portal

Table 11 shows a summary of the data collected for each of the North American ELRs. The "Before ELR Installation" data represent the 5–7 years before the ELR was implemented, while the "After ELR Installation" data represent 2–3 years after.

Table 11. Summary of Data Collected for North American ELRs

ELR	ELR Installation Date (M/D/YYYY)	Total Number of Crashes		AADT Before ELR Implementation
		Before ELR Installation	*After ELR Installation*	
Bridge Street	9/1/2017	3 (since 2010)	0	826
Eastern Road	7/1/2016	17 (since 2010)	1	1,009
Morton Road	7/1/2016	2 (since 2010)	1	170
Harvard Lane	9/1/2014	4 (since 2014)	5	51
E. 54th Street	8/1/2013	15 (since 2007)	5	3,058
E. 7th Street	7/1/2013	22 (since 2008)	7	1,397
Flynn Avenue	5/1/2017	2 (since 2013)	0	4,349
W. 54th Street	9/1/2012	7 (since 2007)	11	2,400
Oak Street	7/1/2013	29 (since 2005)	9	N/A
2nd Avenue	8/1/2018	15 (since 2010)	5	3,000
W. 46th Street	8/1/2013	8 (since 2007)	1	4,280
Lakeview Avenue	7/1/2016	7 (since 2010)	4	1,408
Quaker Street	9/1/2019	5 (since 2014)	0	N/A

Table 12 shows a summary of the data collected for the comparison sites. It is important to note that AADT data for the comparison sites were not collected, as we are not analyzing them using the Empirical Bayes (EB) method. Another thing to point out is that that the 'before' and 'after' time periods that were used for ELRs were the same ones used for their respective comparison sites. This was another way to maintain consistency within the matched groups.

Table 12. Summary of Data Collected for North American Comparison Sites

ELR	Comparison Site	Total Number of Crashes	
		Before ELR Installation	*After ELR Installation*
Bridge Street Yarmouth, ME	Yankee Drive	0	0
	Applecrest Drive	3	1
	Royall Point Road	4	1
Eastern Road Scarborough, ME	Charles E. Jordan Road	5	2
	Hurricane Road	2	2
Morton Road Yarmouth, ME	Pleasant Street	5	3
	Mill Road	7	0
	Bagaduce Road	8	6
Harvard Lane Boulder, CO	S. Lashley Lane	3	0
	Apache Road	5	1
	Brooklawn Drive	2	1
East 54th Street Minneapolis, MN	W. 38th Street	56	14
	W. 36th Street	136	49
	W. 31st Street	190	69
East 7th Street Bloomington, IN	East 2nd Street	38	3
	East Maxwell Lane	6	132
Flynn Avenue Burlington, VT	Richardson Street	1	0
	Pine Street	5	0
	Harbor Road	7	7

ELR	Comparison Site	Total Number of Crashes	
		Before ELR Installation	*After ELR Installation*
West 54th Street Edina, MN	W. 51st Street	11	8
	W. 52nd Street	9	3
	W. 53rd Street	9	4
Oak Street Sandpoint, ID	Church Street	60	13
	Cedar Street	132	69
	Pine Street	127	70
2nd Avenue Hailey, ID	N. River Street	21	7
	S. 4th Avenue	12	4
	Buckhorn Drive	6	0
West 46th Street Minneapolis, MN	W. 55th Street	6	3
	W. 53rd Street	9	3
Lakeview Avenue Cambridge, MA	Lexington Avenue	2	0
	Standish Road	1	3
Quaker Street Lincoln, VT	Blood Street	1	0
	Old Turnpike Road	4	0

4.3 Preliminary Exploration: Crash Trends in 'Before' Period

Once all the necessary data had been collected, the first step in this analysis is to calculate and compare crash count trends in the 'before' period for ELRs and their corresponding comparison sites, in a similar fashion to Huang's evaluation of road diets (Huang, Stewart and Zegeer 2002). This is an important step because these comparison sites were initially selected based on their physical characteristics, not for their traffic or crash volumes. Hence, analyzing and comparing the crash trends of the matched comparison groups ensures that the comparison sites that were initially identified for potential use have similar or identical crash trends. This is crucial in justifying and legitimizing their roles as comparison sites for the next step in this analysis.

Year-by-year crash counts in the 'before' period were compiled and recorded for each individual matched group. The number of years before the ELR was installed and for which these data were collected varies based on the availability of data from the respective transportation agency/authority, and it ranges from 5 to 7 years. Table 13 shows an example of how the yearly crash trends were compiled and analyzed for each ELR and their respective comparison sites, with Bridge Street serving as the example. In this specific example, seven years of data were available in the 'before' period.

Table 13. Example of Crash Trends for ELR and Matched Comparison Sites

	Crash Rates (crashes/year)			
Year	*Bridge Street (ELR)*	*Yankee Drive*	*Applecrest Drive*	*Royall Point Road*
2010	0	0	0	1
2011	0	0	1	2
2012	0	0	0	0
2013	0	0	1	0
2014	1	0	0	0
2015	0	0	1	1
2016	2	0	0	0

A statistical t-test was then conducted to compare average annual crashes at each ELR site with their respective comparison sites. The t-test outputs a p-value that represents the correlation of crash trends within the matched comparison groups. This number informs the researcher of whether or not to reject the null hypothesis. For this particular scenario, the null hypothesis is that there are no statistically significant differences between crash counts on the treatment and control sites. If the calculated p-value is less than 0.05, it means that the null hypothesis may be rejected, and the problem requires further consideration. If the calculated p-value is greater than 0.05, we accept the null hypothesis and can conclude that the ELRs have strong comparison sites that can be used for analysis. Table 14 shows the results of the t-test conducted for each comparison group.

Table 14. Results of Statistical Comparison of Crash Trends in 'Before' Period

Site Number	ELR Site	# of Comparison Sites	P-Value
1	Bridge Street	3	0.779
2	Eastern Road	2	0.003
3	Morton Road	3	0.056
4	Harvard Lane	3	0.890
5	E. 54th Street	3	<0.001
6	E. 7th Street	2	0.694
7	Flynn Avenue	3	0.301
8	W. 54th Street	3	0.318
9	Oak Street	3	0.001
10	2nd Avenue	3	0.730
11	W. 46th Street	2	0.896
12	Lakeview Avenue	2	0.014
13	Quaker Street	2	0.410

For four sites (#2, #5, #9, #12), a p-value smaller than 0.05 was yielded, meaning that the null hypothesis stated above could be rejected. The differences between the crash experience of the ELR and their respective comparison sites for these four locations in the 'after' period, if differences are present, may not be attributable to the ELR installation but rather to pre-existing differences between the study and control sites. In addition, the other nine locations generated p-values that showed there was no statistically significant difference in annual average crash counts between each ELR and its respective comparison site. Since the results of this step were favorable and further justified the use of these comparison sites, this analysis can continue into its next step.

4.4 Preliminary Exploration: Standard Yoked Comparison

Once the crash trends of the 'before' period were analyzed, the standard yoked comparison could begin. A yoked comparison is when a treatment site, which in this case is an ELR, is matched with one or more control sites to observe the effects of the treatment. This approach is similar to the one adopted by Huang, Stewart, and Zegeer (2002) for the evaluation of complete street, or road diet, treatments.

For the analysis in this report, the ELRs were matched with two-lane roads, and crash data were classified into periods before and after the ELRs were installed. Thus, the crash data were assembled into four groups: ELRs in the ‘before’ period, ELRs in the ‘after’ period, comparison sites in the ‘before’ period, and comparison sites in the ‘after’ period.

The length of the ‘before’ period length varied considerably from site to site, depending on the data available to the responsible authorities/jurisdictions and when the ELRs were installed. A two-way contingency table analysis was performed on all 13 ELRs and their 34 corresponding comparison sites to observe the crashes occurring in the ‘before’ and ‘after’ period for each matched group. Table 15 shows these crash counts along with the percentage of crashes occurring in the ‘after’ period for each site. This calculation is important because it allows us to assess the effectiveness of the ELRs to see how many of them report a lower percentage of crashes in the ‘after’ period compared to their corresponding comparison site. A Fisher’s exact test was called for since several of the study sites have small crash counts. Similar to the ‘before’ period crash trend analysis, a p-value is provided as an output for each matched group to show the correlation between ELRs’ crash trends and their comparison sites’ crash trends.

As seen in Table 15, 9 of the 13 ELRs exhibited lower percentages for the ‘after’ period relative to their comparison sites and are displayed as the sites with green highlights. For the four sites that saw ELRs exhibiting higher ‘after’ percentages, some of this effect may be attributed to the pre-existing conditions and not to the safety performance of the ELRs themselves. Moreover, based on Fisher’s exact test, only one of these four sites had a p-value of less than 0.05, which indicates that the differences in crash trends between site eight and its comparison sites are statistically significant. For this site, the results from the yoked comparison analysis were deemed inconclusive. To help provide a more robust safety analysis that better estimates and identifies ELRs’ safety effects post-installation, an Empirical Bayes (EB) approach is used next.

Table 15. Results of Standard Yoked Comparison

Site Number	Site Type	Months of Data Collected		Crashes		% After	Fisher's Exact Test
		Before	*After*	*Before*	*After*		*P-Value*
1	ELR	87	36	3	0	0%	N/A
	Comparison Sites	87	36	7	2	22%	
2	ELR	75	36	17	1	6%	0.134
	Comparison Sites	75	36	9	4	31%	
3	ELR	74	36	2	1	33%	1
	Comparison Sites	74	36	20	9	31%	
4	ELR	77	36	4	5	56%	0.159
	Comparison Sites	77	36	10	2	17%	
5	ELR	77	36	15	5	25%	1
	Comparison Sites	77	36	364	132	27%	
6	ELR	60	36	22	7	24%	< 0.0001
	Comparison Sites	60	36	26	135	84%	
7	ELR	38	36	2	0	0%	N/A
	Comparison Sites	38	36	18	7	28%	
8	ELR	42	36	5	11	69%	0.009
	Comparison Sites	42	36	34	15	31%	
9	ELR	91	36	29	9	24%	0.3645
	Comparison Sites	91	36	323	152	32%	
10	ELR	104	36	15	5	25%	0.3645
	Comparison Sites	104	36	55	11	17%	
11	ELR	80	36	8	1	11%	0.3932
	Comparison Sites	80	36	15	6	29%	
12	ELR	80	36	7	4	36%	1
	Comparison Sites	80	36	5	4	44%	
13	ELR	80	36	5	0	0%	N/A
	Comparison Sites	80	36	5	0	0%	
	Confidence Interval	*95%*	*36*				

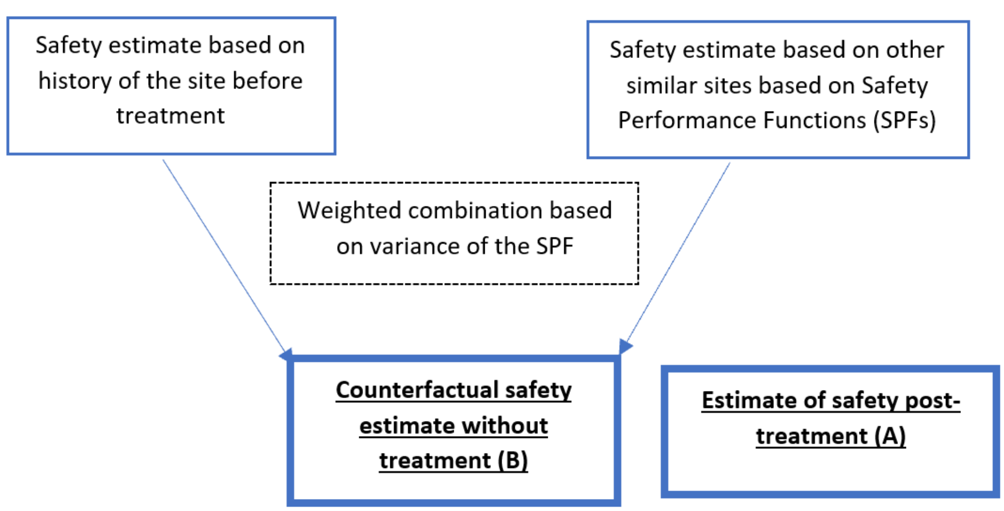
The yoked comparison based on preliminary crash data provided by the jurisdictions, while encouraging, is ultimately inconclusive. The above analysis is followed up in the next section with more robust HSM-recommended EB-based approaches.

4.5 Empirical Bayes Analysis

The EB method is a statistical before-and-after analysis method that estimates the safety effects of road treatments (ELRs, in this case). This method has been used heavily by transportation engineers for the past 20 years because it is based on the assumption that crash counts are insufficient to accurately characterize the safety of a facility. It is an approach that can be readily applied once a calibrated model has been developed for particular site types (intersections, rural roads, urban roads, etc.). The EB method has been officially recommended in Part C of the Highway Safety Manual (2010) to be used for site-by-site evaluation of treatments.

We first provide a brief overview of the EB process for estimating road safety as described by Hauer et al. (2002). The expected crash frequency is estimated using Safety Performance Functions (SPFs). SPFs utilize a facility's characteristics, e.g., AADT and length, to produce an average crash frequency. This average crash frequency is refined using Crash Modification Factors (CMFs). These CMFs adjust the average crash frequency to reflect the impact of geometric design and other road characteristics such as lighting or the presence of on-street parking. Once the CMF-adjusted crash frequencies have been calculated, the relative numerical weights to be used for the calculated crash frequency versus actual crash data are calculated. These weights are an indication of the strength of the observed crash dataset and the role of the SPF-derived crash frequency. The actual crash history, the SPF-derived crash frequency, and their respective weights are combined to produce an expected crash frequency for the site. Figure 12 provides a visual understanding of the framework used to conduct a before-and-after EB evaluation as proposed by Hauer et al. (2002).

Figure 12. EB-Based Before-and-After Evaluation Framework



For this project's EB analysis, the authors followed the HSM's instructions for completing EB analyses on urban/suburban two-lane roads and rural two-lane roads. Five years of crash data before the ELR was installed were consistently used, along with three years of crash data after. It is important to note that this portion of the work does not use comparison sites. Instead, the approach requires the estimation of expected, counterfactual crash counts as a weighted average of two sets of crash counts:

1. Predicted crash counts obtained using the Safety Performance Function (SPF) equations for urban/suburban or rural two-lane roads, where Crash Modification Factors (CMFs) were used to modify SPF predictions based on site-specific characteristics.
2. Average crash counts based on the 5-year crash history of the sites before ELR installation.

Data used for the EB analysis excluded some crashes that were used in the preliminary evaluation based on yoked comparison: excluded were crashes that involved pedestrians or bicyclists (the SPF calculations also excluded the bicyclist and pedestrian crash rate additions), crashes occurring within a three-month window centered on the ELR installation date, crashes occurring within the intersections at either end of a facility, and crashes that could not be accurately located as on or off the facility. All other crashes were used, including crashes within interior intersections and all other crash types. The most up-to-date data from relevant jurisdictions were used in this study.

Segment-Level Evaluation

For the segment-based EB analysis, the SPF calculations made some simplifying assumptions. All facilities were treated as single segments. No intersection calculations were performed. All driveways and street intersections were treated as minor residential driveways. This causes the SPF calculations to predict fewer expected crashes (i.e., to underestimate expected crashes for the counterfactual scenario). This results in the safety of the two-lane configuration being overestimated and the safety of the ELR treatment being underestimated by an unknown amount: that is, the actual safety of the ELRs will be better than estimated by this analysis.

While the general EB approach to safety evaluation is applicable to any roadway entity, Safety Performance Functions (SPFs) used in Chapter 12 of the HSM are based on data collected on arterials. Per the HSM, "The term 'arterial' refers to facilities the meet the FHWA definition of 'roads serving major traffic movements (high-speed, high volume) for travel between major points.'" We did not determine the functional classification of these sites, but the ADT values make it clear that few, if any, are arterials.

Quaker Street and 2nd Avenue were not included in the EB analysis because they did not have three years of post-installation data available. This left eleven sites for analysis.

The results of the completed EB analysis can be seen in Table 16. For each site, the table compares the number of expected crashes if the facility had remained a two-lane road (referred to as N_{exp} in Table 16), with the observed crashes that actually happened on the ELR (referred to as N_{obs} in Table 16), giving us a direct means of observing ELRs' safety effects. We estimated Crash Modification Factors (CMFs) for each site by calculating the ratio of the actual crash counts to the expected crash counts. A CMF of less than one means that the facility experienced fewer crashes as an ELR than it would have had it remained a two-lane road. This analysis provides a comparison of a site's safety performance as an ELR and its expected (counterfactual) safety performance as a standard two-lane road.

Table 16. Results of Segment-Based EB Analysis

ELR	Urban or Rural	Speed Limit (mph)	Segment Length (feet)	ADT (MV/day)	Actual Crashes, 5 years pre-install	Expected Crashes, 3 years post-install	Actual Crashes, 3 years post-install	CMF
Bridge Street Yarmouth, ME	Urban	25	250	926	0	0.08	0	0.00
Flynn Avenue Burlington, VT	Urban	25	1,400	4,349	1	0.84	0	0.00
Eastern Road Scarborough, ME	Rural	25	4,800	1,009	7	2.03	0	0.00
W 54th Street Edina, MN	Urban	30	1,100	2,400	1	0.64	0	0.00
Lakeview Ave Cambridge, MA	Urban	25	1,600	1,741	3	1.48	2	1.35
W 46th Street Minneapolis, MN	Urban	30	1,300	4,280	2	1.40	1	0.71
Harvard Lane Boulder, CO	Urban	25	1,500	380	1	0.24	1	4.10
E. 54th Street Minneapolis, MN	Urban	30	4,250	4,300	16	8.81	8	0.91
E. 7th Street Bloomington, IN	Urban	25	2,200	200	4	0.53	2	3.79
Oak Street Sandpoint, ID	Urban	25	913	810	5	0.97	2	2.06
Morton Road Yarmouth, ME	Urban	25	2,900	170	0	0.20	0	0.00
Totals				*20,565*	*40*	*17.22*	*16*	

Seven of the eleven ELRs showed a reduction in crashes after ELR installation. Five ELRs did not report any crashes in the three-year 'after' period, resulting in CMF values of 0.

Because individual site CMFs are based on small sets of data and may not have wide applicability, an aggregate CMF was calculated by dividing the total number of observed crashes during the three-year period by the total number of expected crashes for the same time. In this case:

$$^{16.00}/_{17.22} = 0.93.$$

It is important to mention that the CMFs for urban/suburban roads differ from those for rural roads. CMFs corresponding to on-street parking, roadside fixed objects, and lighting were the CMFs applied to the urban/suburban facilities. CMFs corresponding to Lane width, shoulder width, driveway density, and lighting were the CMFs applied to the rural facilities.

Also, it should be emphasized that the estimated CMF, 0.93, obtained using segment-based analysis is a conservative estimate since the predicted crash counts for this analysis are only estimated using the SPF for the two-lane road segments. Since no SPFs for intersections crashes are used, the expected crashes underestimate the counterfactual crash counts. Hence, one may treat the 0.93 as a very conservative estimate for the CMFs resulting from the ELR installation.

In the next step, a project-level evaluation is carried out, which provides a more realistic CMF—but the approach has more extensive data requirements, including the daily traffic estimates for the intersecting streets.

Project-Level Evaluation

For the next step in the analysis, EB evaluation was performed using the project-level approach described in section A.2.5 of the Highway Safety Manual (2010). The project-level approach allows for the aggregate analysis of a facility containing any number of segments and intersections. This approach requires more information than the segment-level analysis presented in the previous section. To conduct this analysis, the authors requested intersecting street traffic data from the relevant jurisdictions. Because ADT information was not available for all of the intersecting streets, unavailable side-street ADTs were estimated using a value of two passenger car trips daily (i.e., ADT) per dwelling unit served by the street. This is a conservative choice and is significantly lower than the 9.44 and 7.32 trips per dwelling unit quoted by the ITE Trip Generation Manual (Institute of Transportation Engineers 2020) for single-family residences and multi-family housing, respectively. Alleys were classified as minor residential driveways for the analysis. As a result of these choices, the number of predicted crashes will likely be lower than if more accurate data had been available. This may cause ELR safety to be underestimated. In other words, the estimated CMF, while it is more realistic than the segment-based evaluation presented in the previous section, is still conservative.

The required data on-road characteristics (such as the number of driveways, amount of on-street parking, presence of lighting, etc.) were gathered using the latest information available on Google Street View. The results of the completed project-level EB analysis are provided in Table 17.

Table 17. Results of Project-Level EB Analysis

Site	ELR	Urban or Rural	Length (feet)	ADT (vehicles/day)	N_{exp} (3 years)	N_{obs} (3 years)	Site CMF
1	Bridge Street	Urban	250	926	0.05	0.00	0.00
2	Flynn Avenue	Urban	1,400	4,349	1.87	0.00	0.00
3	Eastern Road	Rural	4,766	1,019	3.97	0.00	0.00
4	W 54th Street	Urban	1,196	2,400	1.00	0.00	0.00
5	Lakeview Ave	Urban	1,600	1,741	1.31	2.00	1.53
6	W 46th Street	Urban	1,304	4,280	4.97	1.00	0.20
7	Harvard Lane	Urban	1,497	380	0.46	1.00	2.19
8	E. 54th Street	Urban	4,250	4,329	10.75	8.00	0.74
9	E. 7th Street	Urban	2,507	200	1.55	2.00	1.29
11	Oak Street	Urban	913	810	2.30	2.00	0.87
12	Morton Road	Urban	2,900	200	0.16	0.00	0.00
Totals				*20,634*	*28.39*	*16*	

Based on the results of the EB procedure, eight of the eleven facilities showed a reduction in crashes, and three showed an increase in crashes. Sites #1, #2, #3, #7, and #8 reported no crashes in the three-year 'after' period, resulting in a CMF value of 0.00.

Because the site CMFs are based on small amounts of data, an aggregate CMF was calculated by dividing the total number of observed crashes during the three-year period by the total number of expected crashes for the same period. In this case:

$$16.00/_{28.39} = 0.56.$$

The aggregate CMF value of 0.56 represents a 44% crash reduction in the post-installation period for ELRs. Among the individual sites, three have an estimated CMF greater than 1.0. Since the number of observed crashes is a discrete variable, i.e., it can only take integer values, individual CMFs for sites with a small number of expected crashes may be biased in either direction. For example, consider a site that expects 1.5 crashes in the after period per the EB approach. Observing two after-period crashes on this site would make the CMF 1.33, while observing one crash would make the CMF 0.67. The issue is not as acute when dealing with sites with larger number of crashes. Therefore, aggregate CMF (obtained by dividing the total number of observed crashes by the total of expected crashes on all sites; rather than averaging individual CMFs) provides a more reliable estimate of the crash reduction. Summing all site ADTs and multiplying the result by

2,920 (the number of days in 8 years) shows that the aggregate CMF value is based on more than 60 million motor vehicle trips.

4.6 Results & Discussion

The results of the yoked comparison were somewhat inconclusive on the safety effectiveness of ELRs. Nine of the 13 ELRs analyzed had smaller crash percentages in the 'after' period than their respective comparison sites, which is promising. However, it cannot be ignored that the other four ELRs exhibited higher 'after' crash periods than their comparison sites. Recalling the discussion on how the comparison sites were chosen, these differences in crash trends may be attributed to the 'pre-existing' conditions and not to the safety performance of the ELRs themselves. Thus, more robust analysis is required that will better inform the research community of the safety effects that ELRs offer compared to two-lane roads.

Fortunately, the segment-level and project-level EB analyses were able to produce more robust results. An aggregate CMF value of 0.93 was calculated over all eleven sites analyzed using the segment-based method. A more realistic CMF accounting for the intersection as well as segment crashes was estimated to be 0.56 using the project-level analysis. This CMF is calculated on data acquired over an estimated 53,967,440 motor vehicle trips (Total ADT × 8 years × 365 days/year). Eight of the eleven ELRs saw crash rate reductions.

These results tell us two things. The first is that after the 3-month adjustment window used in this study, drivers did not have a difficult time transitioning to the ELR treatment. This mirrors findings in previous studies and is supportive of this treatment's wider use. The second is that ELRs provide improved safety compared to their two-lane counterparts. These findings lead us to conclude that ELRs continue to be suitable for use in the United States.

High-speed rural ELRs may be effective in reducing roadway departure crashes due to wider shoulders in the form of edge lanes. The ELR on Eastern Road in Scarborough, ME, shows the potential of this format for that purpose. Eastern Road is a rural road with no curb, gutter, or sidewalk. It is a straight road that connects to individual homes on large lots and small clusters of recently-developed single-family homes. It is signed as 25 mph, but the setting and crash history implies a road that likely sees higher speeds from many drivers. Eastern Road was converted to an ELR in July 2016. From 2003 to 2016 inclusive (14 years), Eastern Road experienced 14 crashes, with 12 of these being coded as "Went Off-Road" crashes by the Scarborough Police Department. From its conversion to an ELR in July 2016 to mid-2020 (approximately four years), Eastern Road has reported no crashes whatsoever. Even though this single installation is unable to predict performance in other settings at higher speeds, it does provide a tantalizing glimpse into the possibilities that this format offers.

A more complete evaluation of the use of ELRs on higher-speed rural roads must be conducted using data from foreign countries since there are no such installations in the US. The next chapter provides an analysis of data from the Department of Transport and Main Roads from Queensland, Australia, to assess the safety of high-speed, low-volume rural ELRs.

V. Australian Crash Data Analysis

The reason the authors decided to include Australian ELRs in the analysis and not just make recommendations based on analyzing North American ELRs is simple. We are looking to see whether or not ELRs are feasible for implementation on rural roads in California. Most North American ELRs are located in urban settings and experience different volumes and user behavior that may not accurately inform their effectiveness in rural settings. As such, we decided to include ELRs in Australia as part of this analysis because they could provide us with that insight. More specifically, the State of Queensland has a few of these ELR-type facilities that are located in rural settings and have significantly lower traffic volumes that more accurately mirror rural roads in the US. Incorporating these facilities into the analysis ensures that this safety assessment is more holistic because it provides us with a general insight into the suitability of these facilities in high-speed rural settings.

Before getting into the analysis itself, it is important to first consider what ELRs look like in Australia and take note of some of the differences between Australian facilities and the ones found in North America. To start, there is no official classification for ELRs. In some parts of the country, they are known as Class 5b roads, though in Queensland, Australia, the state where all the ELRs for this analysis are located, transportation planners do not use any official terms or classifications for these facilities. However, a contact within Queensland's Department of Transport and Main Roads was helpful in establishing criteria for these ELR-type roads while also providing us with Queensland road network data and crash data. These facilities are classified in Queensland as one-lane roads with greater-than-normal lane widths and no sidewalks. While they aren't explicitly classified as ELRs, the movement patterns on these roads mirror ELRs, which is why they were included in this analysis. Vehicles are expected to travel in the middle of the lane, while cyclists and pedestrians stick to traveling on the outside of the lane. If two vehicles are approaching each other, they are also allowed to dip into the shoulders on their respective sides to safely navigate around each other. More details on the criteria used to identify the ELRs in Queensland are provided in the Study Site Selection section.

Another important thing to note is that the ELRs in Australia are actually older facilities that have been in effect for a long time. Hence, the improvements made to the roads are actually to expand the facility to a two-lane road to accommodate higher traffic volumes. We will be analyzing crash data on these facilities using a variation of the EB before-after evaluation approach. Contrary to how the United States has recently implemented ELRs as treatments to existing two-lane roads in an effort to help support VRUs on urban roads, the process is flipped in Australia. There, the road sections were originally ELRs but were expanded to two-lane roads as treatments. The variation of the EB method has not been considered before, but this new method will be detailed more extensively in its own section.

The safety analysis conducted for the ELR-type facilities in Australia will differ from the one done for North American ELRs. The reason is that we were unable to identify any two-lane roads to use as comparison sites. Contrary to using geographical criteria to select comparison sites, the researchers decided to try to identify comparison sites that more closely mirrored the ELRs' traffic volumes. However, there were not enough two-lane roads identified that had similar AADTs to the identified ELRs. Hence, comparison sites were not used for the Australian analysis.

5.1 Study Site Selection

For the Australian ELR facilities, one group of study sites was selected for each type of safety analysis conducted. Starting with the standard analysis of the relationship between traffic volumes and crash history on ELR-type roads, the first group of study sites was chosen from the 2018 Queensland roadway network inventory. We filtered it to identify ELRs based on-road facilities. This inventory showed every 100-m section of road present in the State of Queensland, and the following criteria were used to identify ELR facilities based on consultation with local transportation authorities in Queensland:

- One lane
- Located in a rural area
- Speed limit > 60 km/hr
- Seal width < 6 m
- No centerline rumble strips or shoulder rumble strips

Because many of the rural roads in Queensland span hundreds of kilometers, it was common to find several continuous sections of ELRs along one road. The 2018 AADT of each section was provided in the Queensland roadway network inventory, so this was also included for each ELR section in Table 18. In order to narrow down the finalized list of ELRs to use for analysis, facilities with less than 15 km of ELR sections along their roadways were excluded. While these ELRs are much longer than the North American ELRs, this is acceptable for analysis because rural roads often have longer segment lengths than urban roads do, especially in Queensland. Table 18 displays the 20 roads used in the first part of this analysis. 'Tdist' is the Queensland equivalent to American post-miles and is used by Queensland transportation officials to identify road sections.

Table 18. Queensland ELRs Identified for Analysis

#	Possible ELR	*TDist* *Starting Point*	*TDist* *Ending Point*	Total Length of ELR (km)	2018 AADT
1	*Kingaroy-Jandowae Road*	1.4	1.9	20.9	135
		2.7	4.3		135
		11.2	12		135
		12.9	13.5		135
		14.1	14.9		135
		15.4	18.7		135
		18.9	25.1		135
		25.6	26.3		135
		29	31.8		135
		32.3	34.6		135
		36.5	37.8		135
2	*Eidsvold-Theodore Road*	91.6	95.3	18.3	204
		111	114.9		204
		118.5	118.6		204
		124.3	134.8		204
		141.5	141.6		204
3	*Millmerran-Cecil Plains Road*	1.9	2.6	29.6	335
		2.8	3.7		335
		4	4.2		335
		4.8	5.7		335
		11.7	12.1		335
		16.8	19.4		335
		20	26		335
		26.1	31.2		335
		31.4	44.2		335
4	*Chinchilla-Tara Road*	37.3	41.1	27.2	893
		41.8	44.7		893
		45.2	49.6		321
		51.5	51.9		321
		52.4	68.1		321

#	Possible ELR	TDist		Total Length of ELR (km)	2018 AADT
		Starting Point	*Ending Point*		
5	*Roma-Condamine Road*	63.1	77.8	33.9	105
		80.2	93		255
		96.5	102.5		255
6	*Jackson-Wandoan Road*	3.3	7.1	26.5	119
		8.7	10		119
		10.7	12.5		119
		13.4	29		119
		54.8	55.2		119
		66.7	70.3		609
7	*Isisford-Ilfracombe Road*	0.5	0.6	82.4	55
		3	17		55
		19	57.2		80
		58.8	88.9		80
8	*Aramac-Torrens Creek Road*	0.1	6.8	119.3	47
		9.3	11.8		47
		14.7	124.8		47
9	*Cramsie-Muttaburra Road*	3.5	61.3	79.4	43
		82.8	83.4		43
		91.6	112.6		43
10	*Quilpie-Thargomindah Road*	0.1	44.1	108.1	66
		49.4	84.9		35
		92.1	97.5		35
		105.5	109.4		35
		166	184.3		17
11	*Pampas-Horrane Road*	0.1	0.6	20.1	128
		1.3	2.8		128
		3.1	4.6		128
		5.1	9.9		128
		10.3	17.1		128
		26.1	31.1		128
12	*Meandarra-Talwood Road*	72.1	80.3	43.9	115
		92.1	127.8		115

#	Possible ELR	*TDist*		Total Length of ELR (km)	2018 AADT
		Starting Point	*Ending Point*		
		0.8	5.8		34
		38	38.6		34
13	*Jundah-Quilpie Road*	49.8	58	34.5	34
		70.5	80.5		34
		91.8	102.5		34
		0.7	12.6		190
		15.6	20.6		190
14	*Millmerran-Leyburn Road*	20.8	23.1	29.4	190
		23.3	34.2		141
		34.7	36		141
		9.6	10.2		114
		11	56.6		114
		69	80.9		114
		108.8	137.6		75
15	*Mitchell-St. George Road*	149.6	156.8	101.9	120
		166	166.3		120
		191.5	197.9		120
		201.5	202.6		120
		1	1.8		38
		2.4	35.7		38
16	*Isisford-Blackall Road*	43.1	49.9	100.5	38
		60.8	120.4		69
		0.6	18.2		48
17	*Ilfracombe-Aramac Road*	50.2	55.6	26.5	48
		88.2	91.7		48
18	*Richmond-Winton Road*	0.1	38.7	41.7	39
		61	64.1		39
		0.3	18.2		32
		34.7	76.2		32
19	*Julia Creek-Kynuna Road*	95.6	99.1	64.4	32
		107	108.5		32

#	Possible ELR	*TDist*		Total Length of ELR (km)	2018 AADT
		Starting Point	*Ending Point*		
20	*Brookstead-Norwin Road*	0.2	4.8	23.1	170
		5.5	7.4		170
		9.4	11		170
		13.8	21.1		170
		21.4	29.1		170

The focus is now on identifying roadway sections that were expanded from one-lane ELR-type roads to two-lane roads in order to conduct a reverse EB analysis. This will allow us to analyze the differences between how each roadway section actually performed as an ELR versus the projected performance of the roadway section had it been a two-lane road all along. The roads that experienced infrastructure changes were identified by looking at the yearly Queensland roadway network from 2014–2018. To identify roadways to include in this analysis, we looked specifically for road sections that exhibited ELR characteristics one year but had another lane added the next year to form a conventional two-lane facility. Table 19 shows the sites that saw these changes and were selected for a reverse EB analysis once the authors had filtered through each yearly inventory. Like in the last group of study sites, facilities were only selected for analysis if they had 0.5 km or more of roadway that saw these infrastructure updates.

Table 19. Queensland Corridors for Reverse EB Analysis

Facility Road Name	*TDist*		Year ELR Converted to Two-Lane Roads	Segment Length (km)	AADT Year After Conversion	# Crashes One Year Before Conversion	Total # Crashes One Year Before Conversion
	Starting Point	*Ending Point*					
Bruce Highway	9.3	10.2	2015	0.9	5,395	0	0
Warwick-Yangan Road	1.5	6.2	2015	7.5	1,074	0	
	10.7	13.5					0
Carnarvon Highway	17	20	2015	4.7	287	1	
	49.8	51.5				0	1
Peaks Down Highway	53	81.3	2016	28.3	649	1	1
Burnett Highway	11.5	14	2016	2.5	2,492	0	0
Baralaba-Woorabinda Road	1	3.1	2016	2.1	188	0	0
Collinsville - Elphinstone Road	56.7	79.739	2016	23.039	470	0	0
Crystal Brook Road	17.8	24.1	2017	6.3	491	2	2

5.2 Data Collection Methods

Unlike the North American ELRs, the crash dataset was the same for all the study sites in Queensland. The contact who provided the roadway network inventory also provided the complete crash history database of all the crashes that occurred on Queensland roads from 2014 to 2018. Each row in the crash dataset represents one crash, with the crash type, crash severity, date/time of the crash, and location of the crash based on the road it was located on along with the 'TDist' for that given roadway. Because each ELR section's TDist start and endpoints were identified when the study sites were selected, it was easy to create filters in the crash dataset to identify all the crashes that occurred on these sections. Out of the 20 ELRs in Queensland that were selected to be used in the safety analysis, only 10 of them had experienced any crashes from 2014 to 2018. Table 20 shows a sample of crash data collected for these ELRs. Since the crash data all came from one uniform place and were formatted differently than the crash data for the North American facilities, the authors could analyze different types of crashes that occurred on Australian facilities.

Table 20. Crash Data Collected for Queensland ELRs

#	Possible ELR	*TDist*		Total km of ELR	2018 AADT	# of Bike/Ped Crashes	# of Runoff Road Crashes	# of Head-On Crashes	Total # of Crashes from 2014–2018	Total # of Crashes on Roadway Segment
		Starting Point	*Ending Point*							
1	*Kingaroy-Jandowae Road*	1.4	1.9	20.9	135	0	0	0	0	2
		2.7	4.3		135	0	0	0	0	
		11.2	12		135	0	0	0	0	
		12.9	13.5		135	0	0	0	0	
		14.1	14.9		135	0	0	0	0	
		15.4	18.7		135	0	1	0	1	
		18.9	25.1		135	0	1	0	1	
		25.6	26.3		135	0	0	0	0	
		29	31.8		135	0	0	0	0	
		32.3	34.6		135	0	0	0	0	
		36.5	37.8		135	0	0	0	0	
2	*Eidsvold-Theodore Road*	91.6	95.3	18.3	204	0	0	0	0	1
		111	114.9		204	0	0	0	0	
		118.5	118.6		204	0	0	0	0	
		124.3	134.8		204	0	1	0	1	
		141.5	141.6		204	0	0	0	0	

#	Possible ELR	TDist		Total km of ELR	2018 AADT	# of Bike/Ped Crashes	# of Runoff Road Crashes	# of Head-On Crashes	Total # of Crashes from 2014–2018	Total # of Crashes on Roadway Segment
		Starting Point	*Ending Point*							
3	*Millmerran-Cecil Plains Road*	1.9	2.6	29.6	335	0	0	0	0	2
		2.8	3.7		335	0	0	0	0	
		4	4.2		335	0	0	0	0	
		4.8	5.7		335	0	0	0	0	
		11.7	12.1		335	0	0	0	0	
		16.8	19.4		335	0	2	0	2	
		20	26		335	0	0	0	0	
		26.1	31.2		335	0	0	0	0	
		31.4	44.2		335	0	0	0	0	
4	*Chinchilla-Tara Road*	37.3	41.1	27.2	893	0	0	0	0	2
		41.8	44.7		893	0	0	0	0	
		45.2	49.6		321	0	0	0	0	
		51.5	51.9		321	0	1	0	1	
		52.4	68.1		321	0	1	0	1	
5	*Roma-Condamine Road*	63.1	77.8	33.9	105	0	1	0	1	1
		80.2	93		255	0	0	0	0	
		96.5	102.5		255	0	0	0	0	
6	*Jackson-Wandoan Road*	3.3	7.1	26.5	119	0	0	0	0	2
		8.7	10		119	0	0	0	0	
		10.7	12.5		119	0	0	0	0	
		13.4	29		119	0	1	0	1	
		54.8	55.2		119	0	1	0	1	
		66.7	70.3		609	0	0	0	0	

#	Possible ELR	TDist		Total km of ELR	2018 AADT	# of Bike/Ped Crashes	# of Runoff Road Crashes	# of Head-On Crashes	Total # of Crashes from 2014–2018	Total # of Crashes on Roadway Segment
		Starting Point	*Ending Point*							
7	*Isisford-Ilfracombe Road*	0.5	0.6	82.4	55	0	0	0	0	2
		3	17		55	0	0	0	0	
		19	57.2		80	0	1	0	2	
		58.8	88.9		80	0	0	0	0	
8	*Aramac-Torrens Creek Road*	0.1	6.8	119.3	47	0	1	0	1	2
		9.3	11.8		47	0	0	0	0	
		14.7	124.8		47	0	1	0	1	
9	*Cramsie-Muttaburra Road*	3.5	61.3	79.4	43	0	0	0	1	1
		82.8	83.4		43	0	0	0	0	
		91.6	112.6		43	0	0	0	0	
10	*Quilpie-Thargomindah Road*	0.1	44.1	108.1	66	0	1	0	1	1
		49.4	84.9		35	0	0	0	0	
		92.1	97.5		35	0	0	0	0	
		105.5	109.4		35	0	0	0	0	
		166	184.3		17	0	0	0	0	

The data needed for reverse EB analysis were as follows: the number of crashes that occurred in the final 1, 2, or 3 years when the road section was an ELR, depending on when it was converted to a two-lane road; the total length of road (in km) expanded from an ELR to a two-lane facility along the roadway; and the AADT of these two-lane facilities. The data collected are summarized in Table 20.

5.3 Analysis of Different Crash Types & Rates

Since there are no defined comparison sites or definite 'before' or 'after' ELR installation periods for any of the 20 facilities identified in the first group of study sites, the standard yoked comparison and traditional EB analysis employed for North American ELRs cannot be used here. The first part of this analysis will look at the different crash types and the rates with which these crashes occur on each of the 20 ELRs identified for analysis. The types of crashes considered in this analysis were:

1. Off-road crashes
2. Head-on crashes
3. Crashes involving cyclists and/or pedestrians

Each of these crash types may be perceived to happen more frequently on ELRs due to the facility's unconventional roadway design. The risk of an off-road crash is attributed to the single, wide center lane used for bidirectional travel: drivers may overcorrect or react too late when seeing an oncoming vehicle and drive off the road. The risk of a head-on crash is also attributed to the wide center lane; such a collision would occur if drivers approaching from both directions did not notice each other and react in time to avoid hitting each other by dipping into their respective edge lanes. The risk of crashes involving bikes or pedestrians stems from vehicles, bicyclists, and pedestrians all sharing the same pavement space on the road and the concern that this may put VRUs in danger rather than providing them with more access. It was important to analyze these crash types specifically to either reinforce or disprove the road users' perceived risks when it comes to traveling on ELRs.

Table 21 shows how many kilometers of the road is an ELR, the 2018 AADT provided for each roadway, and the counts of different crash types experienced on each road, as well as the total count of crashes that occurred. It differs from Table 19 in that it includes the 10 ELRs that did not have any crashes from 2014–2018.

One thing to notice from Table 21 is no head-on crashes or crashes involving bikes and/or pedestrians occurred on any of the 20 ELRs chosen for analysis. That being said, most of the crashes that did occur at the study sites were run-off crashes where the driver lost control of the vehicle and drove off the road either to avoid an object in the middle of the road or due to loss of control. Further research indicated that there were two main causes. The first and most frequent cause for a majority of the recorded off-road crashes was drivers losing control of their vehicles at curves, which can place blame on the driver and not necessarily the ELR design. The other common cause among the off-road crashes was objects being present in the roadway that drivers did not notice until it was too late, causing them to swerve off the road.

Table 21. Crash Counts for Queensland ELRs

Facilities with ELR Sections	Total km of ELR	2018 AADT	# of Off-Road Crashes	# of Head-on Crashes	# of Bike/Ped Crashes	Total Crashes on ELRs
Kingaroy-Jandowae Road	20.9	135	2	0	0	2
Eidsvold-Theodore Road	18.3	204	1	0	0	1
Millmerran-Cecil Plains Road	29.6	335	2	0	0	2
Chinchilla-Tara Road	27.2	321	2	0	0	2
Roma-Condamine Road	33.9	255	1	0	0	1
Jackson-Wandoan Road	26.5	119	2	0	0	2
Isisford-Ilfracombe Road	82.4	80	1	0	0	2
Aramac-Torrens Creek Road	119.3	47	2	0	0	2
Cramsie-Muttaburra Road	79.4	43	0	0	0	1
Quilpie-Thargomindah Road	108.1	35	1	0	0	1
Pampas-Horrane Road	20.1	128	0	0	0	0
Meandarra-Talwood Road	43.9	115	0	0	0	0
Jundah-Quilpie Road	34.5	34	0	0	0	0
Millmerran-Leyburn Road	29.4	190	0	0	0	0
Mitchell-St. George Road	101.9	114	0	0	0	0
Isisford-Blackall Road	100.5	38	0	0	0	0
Ilfracombe-Aramac Road	26.5	48	0	0	0	0
Richmond-Winton Road	41.7	39	0	0	0	0
Julia Creek-Kynuna Road	64.4	32	0	0	0	0
Brookstead-Norwin Road	23.1	170	0	0	0	0

After these crashes had been compiled, the crash rates for each crash type were calculated for each facility. The FHWA provides guidance for calculating these crash rates. See Figure 13 for the equation and its inputs.

Figure 13. FHWA Method for Calculating Crash Rates

$$\text{Crash rate per 100 million vehicle miles traveled} = \frac{(C \times 100{,}000{,}000)}{(V \times 365 \times N \times L)}$$

C = Number of crashes in the study period

V = Traffic volumes using average annual daily traffic (AADT) volumes

N = Number of years of data

L = Length of the roadway segment in miles

Table 22 shows these calculated crash rates for each ELR based on crash type. Relatively speaking, the crash rates for each ELR and their specified crash types are very low, as there is no crash rate that exceeds 62.508 crashes per million VMT, which already in itself is a very low value. Even then, half of the facilities examined did not experience any crashes on their ELR sections. Thus, it can be assumed that these ELRs provide positive safety effects that provide all users with a safe travel experience. A reverse EB analysis will be conducted next to provide more robust findings that more clearly determine how safe these rural ELR facilities are in Queensland, Australia, compared to the subsequent two-lane roads.

Table 22. Calculated Crash Rates for Queensland ELRs

#	Facilities with ELR Sections	Total km of ELR	2018 AADT	Off-Road Crash Rate (per 100 million VMT)	Head-on Crash Rate (per 100 million VMT)	Bike/Ped Crash Rate (per 100 million VMT)	Total Crash Rate (per 100 million VMT)
1	Kingaroy-Jandowae Road	20.9	135	62.508	0.000	0.000	62.508
2	Eidsvold-Theodore Road	18.3	204	23.621	0.000	0.000	23.621
3	Millmerran-Cecil Plains Road	29.6	335	17.786	0.000	0.000	17.786
4	Chinchilla-Tara Road	27.2	321	20.200	0.000	0.000	20.200
5	Roma-Condamine Road	33.9	255	10.201	0.000	0.000	10.201
6	Jackson-Wandoan Road	26.5	119	55.927	0.000	0.000	55.927
7	Isisford-Ilfracombe Road	82.4	80	13.377	0.000	0.000	26.755
8	Aramac-Torrens Creek Road	119.3	47	31.454	0.000	0.000	31.454
9	Cramsie-Muttaburra Road	79.4	43	0.000	0.000	0.000	25.828
10	Quilpie-Thargomindah Road	108.1	35	23.307	0.000	0.000	23.307
11	Pampas-Horrane Road	20.1	128	0.000	0.000	0.000	0.000
12	Meandarra-Talwood Road	43.9	115	0.000	0.000	0.000	0.000
13	Jundah-Quilpie Road	34.5	34	0.000	0.000	0.000	0.000
14	Millmerran-Leyburn Road	29.4	190	0.000	0.000	0.000	0.000
15	Mitchell-St. George Road	101.9	114	0.000	0.000	0.000	0.000
16	Isisford-Blackall Road	100.5	38	0.000	0.000	0.000	0.000
17	Ilfracombe-Aramac Road	26.5	48	0.000	0.000	0.000	0.000
18	Richmond-Winton Road	41.7	39	0.000	0.000	0.000	0.000
19	Julia Creek-Kynuna Road	64.4	32	0.000	0.000	0.000	0.000
20	Brookstead-Norwin Road	23.1	170	0.000	0.000	0.000	0.000

5.4 Reverse EB Analysis

In North America, ELRs replace two-lane facilities to improve multimodality. However, as mentioned earlier in this chapter, ELR-like facilities have existed in Australia for many years and are the original treatment for many of these rural roads. In this setting, two-lane facilities replace these original ELR sections as motor vehicle volume increases. While there were no concrete criteria or explanations for why the facilities had a lane added to them, it is highly possible that the lanes were expanded to accommodate higher traffic volumes.

While the same EB method from Chapter II is used here, it is reversed because we are no longer trying to calculate the expected number of crashes that would have happened along the corridor after ELR implementation. Instead, we are looking to calculate the expected number of crashes that would have happened on the two-lane roads (in the 'before' period) should they have always been two-lane roads. The goal is to compare those predicted crashes to the actual number of crashes experienced on that facility along the ELR. Hence, it is considered a reverse EB analysis because the calculations made for this analysis describe expected crash trends in the 'before' period using the methods outlined by the HSM two-lane rural roads and compare it with the actual crash history experienced on the ELR road sections. Ultimately, it is an almost identical comparison between ELR and two-lane road crash history that was done in Chapter II, with the only difference between that analysis and this one being the temporal direction in which the crash data are analyzed. Instead of being provided a glimpse of the future, this study gives better insight into the past ELR facilities that were converted to two-lane roads.

For this reverse EB analysis, the instructions outlined by the HSM were adapted for completing EB analyses on rural two-lane roads since all of the sites are located in rural areas. This approach requires the estimation of expected, counterfactual crash counts as a weighted average of two sets of crash counts:

1. Predicted crash counts obtained using the SPFs for rural two-lane roads
2. Average crash counts based on the years after the road was expanded to two lanes and the ELR removed

The resulting yearly crash frequencies calculated using this reverse EB method represented the number of crashes that would have occurred on those sections of road if they had always been two-lane roads and had not been ELRs at any point. These were compared with the observed crash frequencies on the ELRs one year before being changed to a two-lane road. This allows us to compare the predicted crashes that would have occurred along the facility if it had always been a two-lane road with the observed crashes that actually happened on the ELR leading up to its infrastructure change, giving us a direct means of observing ELRs' safety effects.

The CMF for each study site was calculated using a ratio of the actually experienced crash rate on the ELR over the counterfactually expected crash rate. A CMF of less than one implies that the facility experienced a crash reduction and shows that the ELR has experienced fewer crashes than predicted. The results of the reverse EB analysis can be seen in Table 23. It is important to note that the calculated number of crashes the facility is expected to have experienced reflects the number of crashes that would have happened on that facility if the ELR had never existed and the roadway had always had a conventional two-lane design. The CMF for each facility is presented in Table 23 and is calculated by dividing the number of observed crashes on the facility when it was an ELR (N_{obs}) by the number of crashes expected if the facility had been a two-lane road using reverse EB (N_{exp}).

For those facilities that were converted in 2015, the reverse EB analysis only compares the one-year expected crash counts with the actual counts that occurred on the ELR a year before it was expanded to a two-lane road. Similarly, the data describing the ELRs that were expanded in 2016 compare the two-year expected crash frequency with two years of crash counts observed on the ELR before it was converted. The corresponding comparison period for the ELR expanded to two lanes in 2017 is three years of crash counts. The reason is the amount of data made available by the Queensland Department of Main Roads and Transport. Access was only provided for crashes occurring from 2014–2018. For the sites expanded in 2015, this meant only one year of crash data was available for the facility before conversion to a two-lane road. Different durations of crash count data are chosen as opposed to one consistent amount is that the more years of data are used for the EB method, the more reliable the estimated CMF will be. The small number of crashes makes the individual site estimate of the CMF unreliable. However, even in aggregation over all eight sites, it appears that sites would have experienced a higher number of crashes had they been left as ELRs.

Table 23. Results of Reverse EB Analysis

Former ELR	Urban or Rural	Segment Length (km)	Year ELR Converted to Two-Lane Facility	AADT	N_{exp}	N_{obs}	Calculated CMF
ELRS Converted to Two-Lane Road in 2015					*N_{exp} (1 year)*	*N_{obs} (1 year)*	
Bruce Highway	Rural	0.9	2015	5,395	0.211436852	0	0.000
Warwick-Yangan Road	Rural	7.5	2015	1,074	0.046806543	0	0.000
Carnarvon Highway	Rural	4.7	2015	287	0.153491098	1	6.515
ELRs Converted to Two-Lane Road in 2016					*N_{exp} (2 years)*	*N_{obs} (2 years)*	
Peaks Down Highway	Rural	28.3	2016	649	0.423461593	2	4.723
Burnett Highway	Rural	2.5	2016	2,492	0.24498556	2	8.164
Baralba-Woorabinda Road	Rural	2.1	2016	188	0.120409836	0	0.000
Collinsville-Elphinstone Road	Rural	23.039	2016	470	0.425574371	1	2.350
ELR Converted to Two-Lane Road in 2017					*N_{exp} (3 years)*	*N_{obs} (3 years)*	
Crystal Brook Road	Rural	6.3	2017	491	0.738370445	2	2.709

5.5 Results & Discussion

Starting with the analysis of crash counts and rates experienced on the Australian ELRs from 2014–2018, the results were promising. The highest number of crashes a road experienced along its ELR sections over five years was 2. In addition, there were no crashes that involved head-on collisions or bikes and/or pedestrians, which is another good indicator that the road users traveling along this road have a good understanding of how to navigate and travel along ELRs. While there was a relatively high volume of off-road crashes, a lot of these incidents were attributed to the following two scenarios: objects being in the middle of the road that caused drivers to react and swerve in an attempt to avoid these objects, and drivers not properly navigating curves and going off-road as a result of taking the turn too quickly or incorrectly. Thus, it can be assumed that the off-road crashes that did occur along the ELR sections were not caused by the ELR's unconventional design, but rather that they were due to extenuating, unpredicted circumstances or driver error in navigating a curve. The results from this analysis indicate that ELRs in Australia are safe for road users to navigate. However, because there are no control sites to compare these crash counts and rates with, we cannot definitively conclude that these facilities are safer than two-lane roads.

A reverse EB approach was used to compare the safety effects of converting ELRs into two-lane roads. Out of the eight facilities that were expanded from an ELR to a two-lane road, five of them experienced CMFs higher than 1, indicating higher than expected crashes with the ELR configuration. Of those, three had significantly high CMFs, with values of 4.723, 6.515, and 8.164, even though each of those facilities had only experienced 1 or 2 crashes in the last year before conversion to two-lane roads. On the other hand, the three ELRs that saw a reduction in crashes all had CMF values of 0, indicating that no crashes occurred along these facilities when they were ELRs. This does seem to indicate that conversion from ELR to two-lane configuration was the right course of action since five of eight facilities observed more crashes as ELRs than they would have as two-lane roads. It is likely that these sites were systematically chosen for the conversion.

The reason why these CMF values are so varied is that there are only one or two years of expected and observed crash data available for comparison (on 7 out of 8 facilities). The more years are available to conduct the EB analysis; the more reliable the CMFs would be. We need more data from recently converted facilities to conclusively estimate the safety effects of ELRs in rural higher-speed contexts.

VI. Conclusions and Future Research

An ELR is a roadway striping configuration that provides for two-way motor vehicle traffic in a single central travel lane, while the bicycle, pedestrian, or other vulnerable road users (VRUs) travel in "advisory" or edge lanes on either side. VRUs are given movement priority on the edge lanes, but MVs can encroach into the edge lanes in order to pass other vehicles after yielding to VRUs there. The unconventional aspect of the ELR—the use of a single moving lane for vehicles traveling in two directions—may be one of the reasons why there have been limited installations in the US despite several advantages documented in extant literature (see Chapter II). This research provides the most detailed safety evaluation of ELRs documented in the literature. The evaluation involved an analysis of interactions between motor vehicles (MV×MV) and between motor vehicles and vulnerable road users (MV×VRU) via simulation and analysis of historical crash data from the US and Queensland, Australia.

6.1 Conclusions and Future Scope: Simulation Analysis

The results generated from the simulator developed for this research (see Chapter III) revealed several relationships important in ELR siting. These include quantitative estimates for:

- Rapid rise in the critical head-on interaction rate, i.e., the rate of interactions involving motor vehicles approaching each other from opposite directions, as vehicle volume increases. Volume is likely the most important factor to consider when evaluating whether to use an ELR.
- Asymmetric directional split which may reduce the critical interaction rate and potentially allow for the safe use of ELRs on roads with higher volumes *and* asymmetric directional volumes.
- Facility interaction rate that varies significantly depending on which VRUs use the facility, i.e., pedestrians vs. bicyclists.

These results lay the foundation for ELR siting criteria based on the estimates of the interactions obtained from the simulation tool. That siting criterion may be expressed in terms of the likelihood that any bicyclist or pedestrian will be a party to an interaction involving approaching motor vehicles maneuvering to pass each other, or it may be expressed in terms of an acceptable rate of those same interactions for the entire facility.

Here are some questions that remain to be addressed before definitive siting criteria may be established by either state DOTs or FHWA:

- How is VRU comfort impacted by MV volume? More specifically, how much time does a VRU spend with an MV near or alongside them?

- How is VRU comfort on a standard two-lane road with a striped centerline is affected by the number and duration of interactions between VRUs and MVs traveling in the same direction and between VRUs and MVs passing one another?. Addressing this through research would add rigor to the subjectively derived Wisconsin Bike Map methodology (Van Valkenburg 1993) that happens to be the current state of practice.
- For smooth operation, ELRs on narrow roadways rely upon the existence of gaps in VRU traffic, which provide space for MVs to maneuver into when they must pass an approaching MV. Without these gaps, one or both MVs would need to stop and wait for a suitable gap to arise. What level of VRU and/or MV volumes will reduce or eliminate these gaps and degrade both safety and operation?
- What safety performance should be expected from an ELR with given characteristics? A measure of a facility's overall risk could be estimated if the probability of a crash for each interaction could be accurately estimated. Further, one should be able to derive injury and fatality rates if crash severity can be estimated from the respective speeds of the road users involved. This would require investigation of surrogate measures for crashes on ELRs.

6.2 Conclusions and Future Scope: Crash Data Analysis

This study is the most comprehensive observational before-and-after evaluation of ELRs to date. The project-based EB analysis, which is the gold standard for the before-and-after analysis of safety treatments, estimated the aggregated CMF to be 0.56 for the ELR treatments, indicating a 44% reduction in crashes over the pre-existing two-lane configuration. Possible explanations for these reductions include decreased speed and increased attentiveness as a result of the treatment's novelty or drivers' concerns about approaching vehicles. See Williams (2019) for further discussion on possible causes of crash reduction.

For the Australian context, ELRs considered in this analysis are exclusively rural roads that are sometimes candidates for being converted to two-lane roads to accommodate increased travel demand. In other words, the ELRs almost always had lower AADT than the candidates for comparable two-lane corridors, and we could not find comparable two-lane facilities that had similar AADT to the ELRs.

We estimated CMFs for ELR in the Australian context using a reverse EB approach. We estimated the expected crashes on recently converted two-lane facilities if they had been two-lane roads all along (i.e., in the period before conversion). The ratio of actual crashes on the pre-existing ELR versus this expected count was used to estimate CMFs. We were able to estimate CMFs for eight sites. Three of the sites did not observe any crashes as ELRs during the period for which we had data available, and hence the estimated CMF was 0.0. For the other five sites, the CMF was higher than 1.0 and ranged from 2.35 to 8.16, which indicated that ELRs, had they not been converted to two-lane roads, would have experienced more crashes. In other words, the two-lane conversion is effective in improving safety. However, this finding cannot be generalized to say that converting ELRs to two-lane roads would always reduce crashes for the following reasons: (i) Among the five sites, only one site had the recommended three years of crash data, and (ii) the ELR sites selected for two-lane conversion may, in fact, have been systemically chosen due to their crash experience and may not have been randomly selected sites.

As for future directions, it is important to note that while there are about 40 known ELRs (Advisory bicycle lanes - Home, n.d.) already existing in the US, only 11 of them had sufficient crash data (from the before and after period) available for EB analysis. As the newer installations of ELRs mature, we recommend that EB analyses be conducted for the remaining ELRs. In addition, there is also a need for bicycle and pedestrian volume data to estimate the extent to which ELRs encourage active modes of travel. We recommend an analysis of bicycle and pedestrian volumes before and after the ELR was implemented. As data from more installations become available for conducting safety evaluations, researchers may consider consulting the robust meta-analysis proposed by Elvik (1995) to combine CMF estimates from multiple sites.

ELRs likely have non-safety benefits that were beyond the scope of this study. These may include benefits generally associated with road diets (Huang, Stewart, and Zegeer 2002), that is, making the MVs seem less dominant and improving the overall quality of movement along the street. These benefits should be evaluated more thoroughly in future research. We also suggest that responsible agencies hold public meetings and forums to help alleviate any concerns citizens may have surrounding this new treatment and educate them on how to use these new roadways. A lack of public outreach may derail an otherwise safe implementation of the treatment. This has been the case in Edina, MN, and Cambridge, MA, where ELRs had to be removed after public outcry (Advisory bicycle lanes - Home, n.d.).

In conclusion, the findings from this research indicate that ELRs may be effective in improving safety in the urban context, but in the rural higher-speed context, the evidence remains mixed due to a lack of sufficient empirical data. We also find that vehicle volume and the directional split need to be considered in decisions regarding ELR siting. We would recommend that jurisdictions in the State of California experiment with ELRs.

Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ELR	Edge Lane Road
FHWA	Federal Highway Administration
MPH	Miles per Hour
MUTCD	Manual on Uniform Traffic Control Devices
MV	Motor Vehicle
VRU	Vulnerable Road User

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