V2X Bridging Efficacy Analysis

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Acknowledgements

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Introduction

Background

At the time of this writing, communication-based safety technology, known as CV2X, is receiving a great deal of attention and a number of CV2X-based safety systems have been developed. CV2X technology requires deployment of communication capability in vehicles and infrastructure installations on roadways. While several manufacturers have begun to equip new vehicles with communication technology, infrastructure installations are still on in pilot phases.

Also at this time, the Federal Communications Commission (FCC) is considering whether to allow sharing of the communications band that is currently reserved for CV2X via Dedicated Short-Range Communication (DSRC), though a final proposed ruling has not been released. In addition to DSRC, other communication modes, such as 5G are being considered for the traffic safety use case.

Because of the simultaneous development of different communication modes and because of the potential for DSRC-bandwidth-sharing, a Ford-UM Alliance project was funded to investigate safety benefits in the context of multiple-mode CV2X deployment. In addition, the crash data used here can help inform the conversation on interference potential for certain communication modes. Note that this project was not aimed at investigating or evaluating communication technology itself, but instead is about estimating safety benefits under a number of deployment scenarios.

Specifically, the project was designed to estimate safety benefits of CV2X technology deployed at signalized intersections. This final report explores the relative benefits of single-mode Roadside Units (RSUs) vs. a Gateway device, which allows information to flow among multiple communication modes, and the benefits of having a sensor present as part of the infrastructure package or not. We present an optimal deployment strategy and assess benefits under a range of possible scenarios.

National Data Analysis

In 2018, the most recent year for which national data were available for this project, there were 6,734,000 police-reported crashes[1], of which 1,390,073 occurred at signalized intersections. These numbers are based on analysis of the Crash Reporting Sampling System (CRSS) data, which is a nationally representative probability sample of police-reported crashes in the U.S.[2] (NCSA, 2020).

Using a crash typology developed for NHTSA by Najm et al. [3], we identified the distribution of signalized-intersection crash types, shown in Table 1. The first three rows of the table represent crash types that are addressable by CV2X countermeasures. In the future, bicyclist crashes may be addressable by CV2X countermeasures, but are not considered in this report. Rear-end crashes are the most prevalent single crash type among all police-reported crashes, but especially at intersections, making up almost 44% of signalized intersection crashes.

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[1] https://cdan.nhtsa.gov/tsftables/National%20Statistics.pdf

[2] National Center for Statistics and Analysis. (2020, December). Crash Report Sampling System 2019 CRSS databook (Report No. DOT HS 813 061). National Highway Traffic Safety Administration.

[3] Najm, W. G., Smith, J. D., & Yanagisawa, M. (2007). *Pre-crash scenario typology for crash avoidance research* (No. DOT-VNTSC-NHTSA-06-02). United States. National Highway Traffic Safety Administration.

Table 1 Annual count of police-reported crashes and fatalities at signalized intersections by crash type

Crash Type	Annual Crashes	Annual Fatalities	Fatality Rate	Proportion of Crashes	Proportion of Fatalities
Left Turn Across Path	216568	660	0.30%	15.8%	23.1%
Run Red Light	234159	802	0.34%	17.1%	28.0%
Pedestrian	23855	693	2.91%	1.7%	24.2%
Bicyclist	16827	94	0.56%	1.2%	3.3%
Rear-end	601055	286	0.05%	43.9%	10.0%
Other known crash types	15534	68	0.44%	1.1%	2.4%
Unknown	262611	257	0.10%	19.2%	9.0%
Total	1370608	2860	0.21%		

Table 2 shows the number of people involved in crashes at signalized intersections, broken down by crash type and injury severity. The KABCO scale is the standard scale used in police reports where O=property damage only, C=possible injury, B=minor injury, A=suspected serious injury, and K=killed (fatality). The table gives the percentage of people involved in each crash type who were injured at each level. For example, 86.6% of people in rear-end crashes were uninjured (property damage only), but only 52.8% of people involved in pedestrian crashes were uninjured. This row includes occupants of the vehicle that struck the pedestrian as well as the pedestrian, if applicable. Serious injuries make up a much higher percentage of all three CV2X-addressable crashes than rear-ends and other intersection crash types (e.g., 1.4% compared to 0.3%).

Table 2 Count of people in signalized intersection crashes by crash type and injury level. The KABCO scale, used in police reports, has levels as follows: O=property damage only; C=possible injury; B=minor injury; A=suspected serious injury; K=Killed. Percentages indicate the proportion of people within each crash type who were injured at each level.

Crash Type	O	C	B	A	K
Left Turn Across Path	458,436 (74.4%)	103,886 (16.8%)	45,027 (7.3%)	8,533 (1.4%)	660 (0.1%)
Run Red Light	481,524 (73.0%)	117,512 (17.8%)	50,972 (7.7%)	9,021 (1.4%)	802 (0.1%)
Pedestrian	27,029 (52.8%)	11,366 (22.2%)	8,916 (17.4%)	3,147 (6.2%)	693 (1.4%)
Bicyclist	19,966 (54.8%)	7,245 (19.9%)	7,462 (20.5%)	1,667 (4.6%)	94 (0.3%)
Rear-end	1,428,317 (86.6%)	177,248 (10.7%)	39,050 (2.4%)	4,640 (0.3%)	286 (0.0%)
Other known crash types	575,672 (90.7%)	38,600 (6.1%)	17,199 (2.7%)	3,272 (0.5%)	257 (0.0%)
Unknown	33,710 (85.4%)	4,102 (10.4%)	1,331 (3.4%)	283 (0.7%)	68 (0.2%)
Total	3,024,653	459960	169,957	30,563	2,860

In estimating the economic cost of crashes, NHTSA uses an average cost per person based on their KABCO injury severity[4]. Applying these figures to the counts of people in each of the cells of Table 2, we estimate that all signalized intersection crashes cost approximately $346 billion annually. The three key CV2X-addressable crashes alone cost $166 billion annually. The addressable crashes result in greater injury per crash than rear-ends and other crash types, so although these crashes make up only 35% of signalized intersection crashes nationally, they are responsible for 48% of the associated costs.

Key Addressable Crashes and CV2X Crash Prevention Technologies

Left Turn Across Path (LTAP)

Left Turn Across Path (LTAP) crashes occur when a left-turning vehicle does not appropriately yield the right-of-way to an oncoming vehicle. At intersections with a protected left-turn signal, this should not occur without the left-turning vehicle violating the signal. However, for any unprotected left turn, the turning vehicle should yield to the oncoming vehicle, and failure to do so can result in a serious crash. This scenario is illustrated in Figure 1.

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[4] Blincoe, L. J., Seay, A. G., Zaloshnja, E., Miller, T. R., Romano, E. O., Luchter, S., & Spicer, R. S. (2002). *The economic impact of motor vehicle crashes, 2000* (No. DOT-HS-809-446). United States. National Highway Traffic Safety Administration.
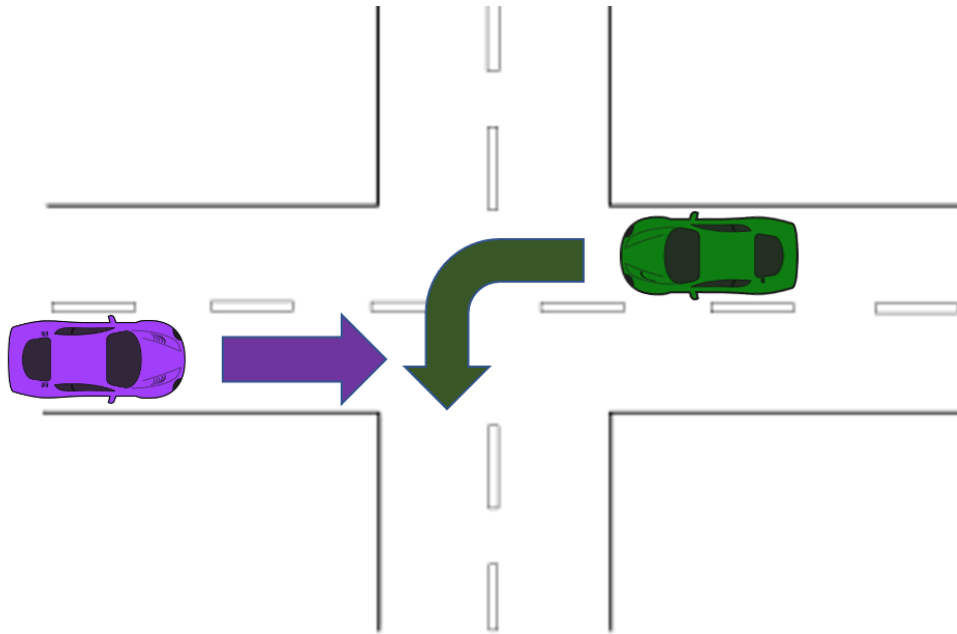
Figure 1 Diagram of Left Turn Across Path (LTAP) crash configuration without a protected left-turn signal. Green vehicle is turning and must yield to the oncoming (purple) vehicle.

Two CV2X technologies are designed to address LTAP crashes. The first, Intersection Movement Assist (IMA), gathers information from the infrastructure (e.g., a roadside unit (RSU)) about the intersection that the host vehicle is about to enter, so that it can alert the host vehicle's driver about the movements of other vehicles that may be in conflict. It acquires information about the location and motion the remote vehicle from the RSU to predict if they will be in conflict. If the host vehicle keeps moving into the intersection and into the path of conflict, IMA can apply braking input for low-speed ranges.

IMA needs location information for both vehicles and either vehicle can be the host vehicle, which can stop the crash. Therefore, in the absence of V2V communication, the intersection needs to have the ability to communicate with *both* the host and remote vehicle to receive information. However, if an intersection is equipped with a sensor, the intersection can detect the remote vehicle and inform only the IMA host vehicle of an impending conflict across path. In this scenario, IMA will be effective if the intersection can communicate with *either* vehicle. Depending on distance between vehicles and speed of the vehicles, effectiveness of IMA is estimated to be between 43-56% [5].

Left turn Assist (LTA) addresses a subset of the crashes addressed by IMA where the host vehicle is the vehicle making a left turn and the remote vehicle is in a likely conflict (see Figure 1 where host vehicle is green and remote is purple). LTA is only activated when the host vehicle is in the left turn lane. If the sensors detect vehicles approaching from the opposite direction but the host vehicle continues to move into the intersection, LTA activates an automatic braking input in a low-speed range up to 10 km/h to prevent a collision. Similar to IMA, LTA needs information about positions and speeds of both the host and the remote vehicle. However,

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[5] Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., ... & Wang, J. (2014). *Vehicle-to-vehicle communications: readiness of V2V technology for application* (No. DOT HS 812 014). United States. National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/v2v_pria_12-12-16_clean-2.pdf

unlike IMA, only the host vehicle can prevent the crash. Thus, the infrastructure must be able to receive information from both vehicles (via communication mode or sensor) and it must be able to send information to a *specific* vehicle (the turning vehicle). The effectiveness of LTA is estimated to be between 37 and 63% depending on speed and distance between vehicles[6].

Since IMA is more flexible in its crash-prevention approach (i.e., either vehicle can prevent the crash), we modeled it as the CV2X-based safety technology addressing LTAP crashes. We assumed that IMA is 50% effective at preventing LTAP crashes.

Red-Light Running

Red-light-running crashes occur when a vehicle continues into the intersection when its lane is controlled by a red signal. This configuration is illustrated in Figure 2. For signalized intersections, Straight Crossing Paths (SCP) crashes are assumed to be red-light-running crashes because the SCP configuration can only occur if one of the vehicles violates the traffic signal.
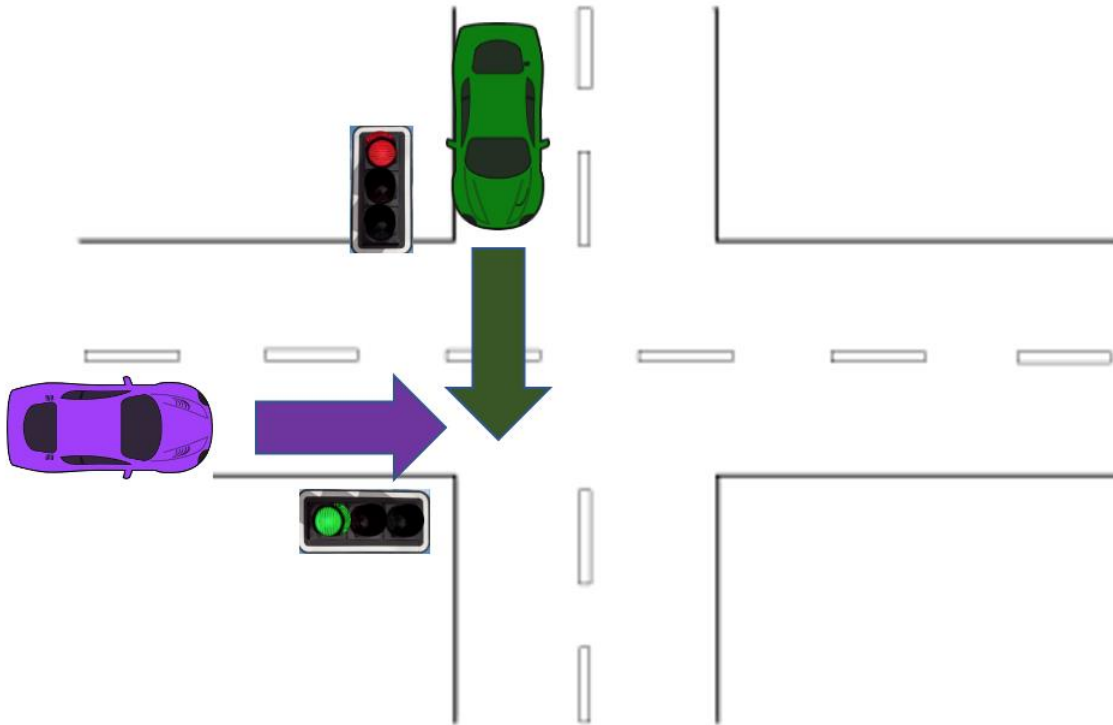

Figure 2 Illustration of red-light-running crash configuration. The green vehicle has a red traffic signal and the purple vehicle has a green signal. If the green vehicle continues into the intersection it will be running the red light and will be in conflict with the purple vehicle, resulting in a crash.

[6] Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., ... & Wang, J. (2014). *Vehicle-to-vehicle communications: readiness of V2V technology for application* (No. DOT HS 812 014). United States. National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/v2v_pria_12-12-16_clean-2.pdf

Cooperative Intersection Collision Avoidance Systems (CICAS) are another type of CV2X-based application, which has the potential to warn drivers about likely violations of traffic control devices and to help them maneuver through cross traffic. CICAS-V is a type of CICAS where either the remote vehicle or the violator can be warned to take action to prevent the crash. CICAS-V collects data on infrastructure, signal phase and timing, and vehicle positions to determine if a violation is likely and can warn either the red-light-running vehicle or the remote vehicle to take action if a conflict is about to happen. Therefore, the CICAS-V infrastructure must be able to take in information from both vehicles, either through communication or sensing, but can prevent the crash if it can communication with *either* vehicle. The effectiveness of CICAS-V is estimated to be about 30-50% for different crash outcome types[7]. We used 45% in our simulations.

Pedestrian Crashes

Pedestrian crashes at intersections occur when a vehicle traversing an intersection is in conflict with a pedestrian who is crossing one of the intersection legs. This most commonly occurs when the vehicle is turning, as is illustrated in Figure 3. However, it can also occur when the pedestrian violates the right-of-way by crossing in front of a car with a green traffic signal.

[7] Li, T., & Kockelman, K. M. (2016, January). Valuing the safety benefits of connected and automated vehicle technologies. In *Transportation Research Board 95th Annual Meeting* (Vol. 1). https://www.caee.utexas.edu/prof/kockelman/public_html/trb16cavsafety.pdf
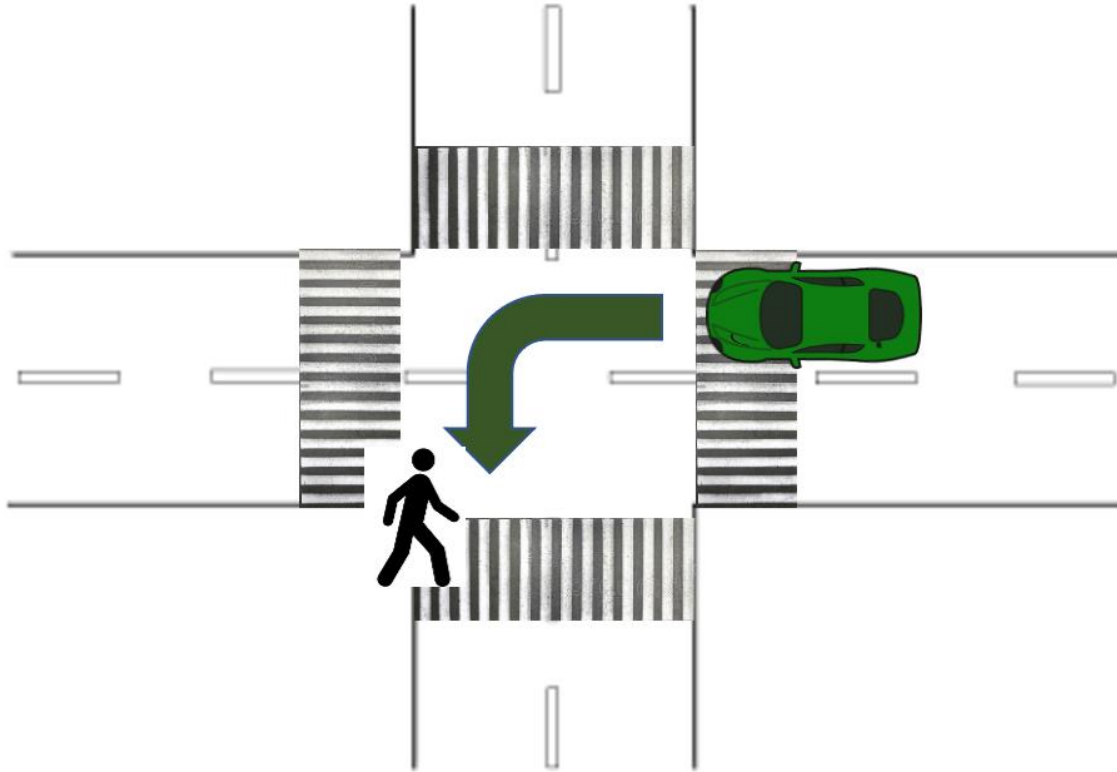
Figure 3 Illustration of one type of pedestrian crash configuration at a signalized intersection.

Current production Pedestrian Crash Avoidance/Mitigation (PCAM) systems are typically vehicle-based, relying on vehicle-mounted sensors and often automatic braking in response to a detected pedestrian in the vehicle's path. However, in principle, infrastructure-based systems can also sense pedestrians and send messages to vehicles at the intersection to prevent a conflict in the same way. In case of infrastructure-based systems, infrastructure-mounted sensors or apps on a pedestrian's smartphone could indicate the presence (location, motion) of pedestrians, which can then be used to predict conflict and warn the vehicles through BSMs. Estimates vary, but USDOT estimates that 52% of pedestrian crashes and 90% of fatal pedestrian crashes are addressable and that effectiveness ranges from 7-77%.[8] Li and Kockelman estimated that the average effectiveness of a V2P system where the pedestrian sends signal via a smartphone app would be ~50% for incapacitating injury, ~40% for fatal injury. For our benefits calculations, we assume that the infrastructure must sense the pedestrian (no P2I app-based communication) and that the system would be 45% effective. In such a case, the infrastructure must be equipped with a sensor and needs to communicate with a *specific* vehicle.

State Crash Data Analysis

While the national crash datasets provide nationally representative samples and support national estimates of crash prevalence, they do not include location information. Moreover, although sample weights allow for national estimates, the raw sample size (about 50,000 crashes

[8] Yanagisawa, M., Swanson, E., & Najm, W. G. (2014). *Target crashes and safety benefits estimation methodology for pedestrian crash avoidance/mitigation systems* (No. DOT-VNTSC-NHTSA-13-02). United States. National Highway Traffic Safety Administration. https://rosap.ntl.bts.gov/view/dot/12068/dot_12068_DS1.pdf

per year) is too small for many analyses. In contrast, state crash datasets can contain hundreds of thousands of police-reported crashes per year, depending on the size of the state (e.g., Michigan has ~350,000 police-reported crashes per year). In addition, many states provide latitude and longitude of crashes in their datasets.

For this project, we used state crash data for two key purposes: 1) location information, which allows us to identify crash counts and types by intersection; and 2) distance from intersection, which is provided by a subset of the states whose data we obtained. We obtained state crash data with location information for five years each from eight states: Florida, Kansas, Maryland, Michigan, Missouri, Nebraska, Tennessee and Utah. Maryland data are from 2014-2018 and all other states are from 2015-2019.

Figure 4 shows the number of police-reported crashes that occurred at signalized intersections each year in the states in our sample. Florida, Michigan, and Tennessee provided the majority of the crashes in the dataset. Although states vary in the number of signalized intersections and the traffic volume, we believe that the variety of states in our sample should provide a good estimate of the types and prevalence of intersection crashes in the U.S. Altogether, the combined dataset had 1,253,349 such crashes. The annual crash count is approximately 16.5%, or one-sixth, of the national annual count of police-reported crashes at signalized intersections.
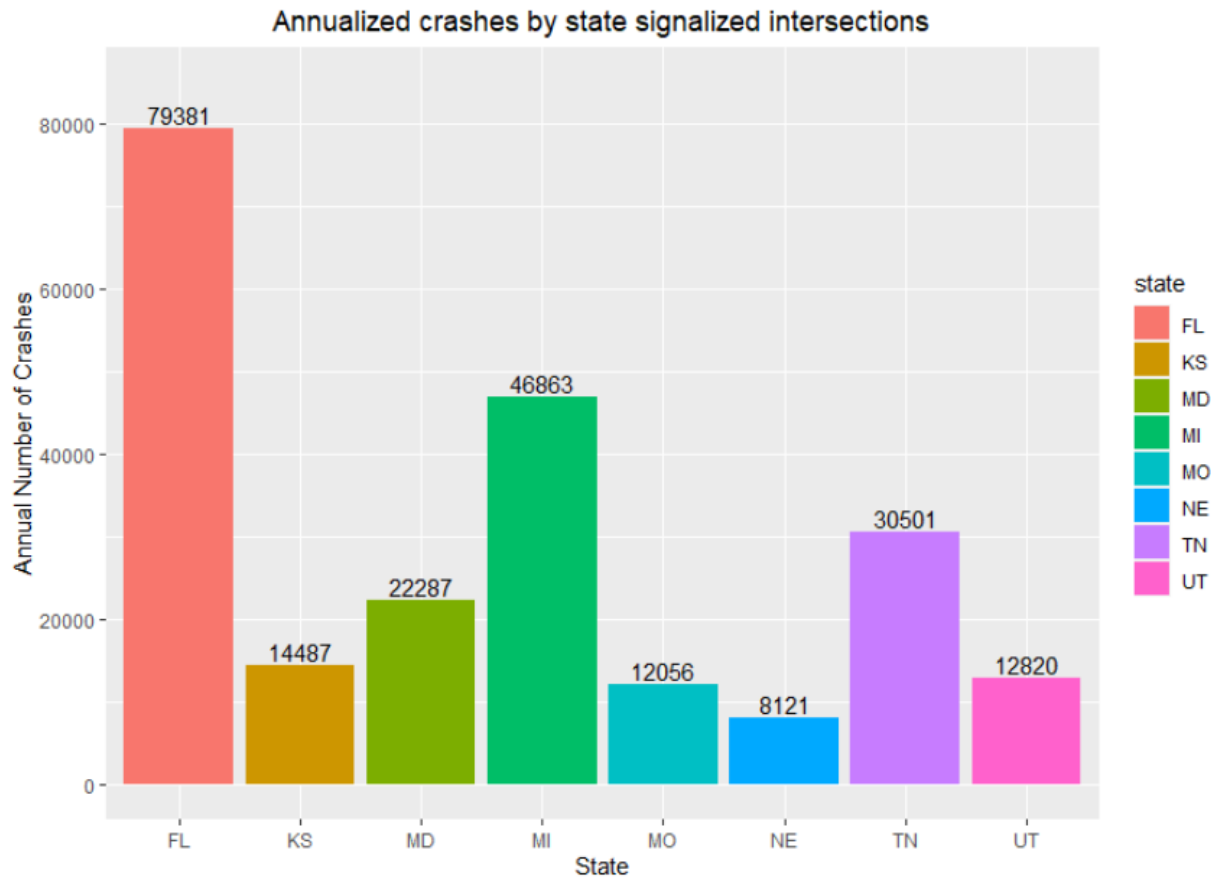

Figure 4 Count of crashes at signalized intersections from each of eight state crash databases

Table 3 shows the counts and proportions of crashes across states, broken down by key crash types. For reference, the national percentages from Table 1 are also shown. Because of

substantial differences in the "Other" category between state and national data, it is useful to compare the crash type distributions as a proportion of the key identified crash types. Out of the five identified crash types, LTAP makes up 12.2% of state crashes and 19.8% of national crashes; red-light-running makes up 29.2% of state crashes and 21.5% of national crashes; pedestrians make up 1.7% of state crashes and 2.1% of national crashes; bicyclists make up 1.2% of state crashes and 1.5% of national crashes, and rear-ends make up 55.8% of state crashes and 55.1% of national crashes. In general, our state crash databases have a similar distribution of crash types at signalized intersections compared to national data. However, LTAP crashes are somewhat underrepresented and red-light-running crashes are somewhat overrepresented in the state database.

Table 3 Distribution of crash types at signalized intersections in state crash data

Crash Type	Total Crashes	Proportion of Crashes	Crash Proportion in National Database (from Table 1)
Left Turn Across Path	74,552	5.9%	15.8%
Run Red Light	178,370	14.2%	17.1%
Pedestrian	10,205	0.8%	1.7%
Bicyclist	7,347	0.6%	1.2%
Rear-end	341,193	27.2%	43.9%
Other known crash types	628,026	50.1%	19.2%
Unknown	13,656	1.1%	1.1%
Total	1,253,349		

Figure 5 shows a histogram of the distance from their associated intersection at which crashes occurred at signalized intersections. Crashes most commonly occurred in the intersection (i.e., 0-2 meters from the intersection). Moreover, 80% of crashes occurred within 10 meters from the intersection, 96% of crashes occurred within 50 meters from the intersection, and 98% occurred within 100 meters from the intersection. This distribution suggests that the communication range needed for crash prevention is fairly short, even taking into account the fact that extra distance needs to be added to these numbers for the systems to detect developing conflict and warn *prior* to the crash occurring.
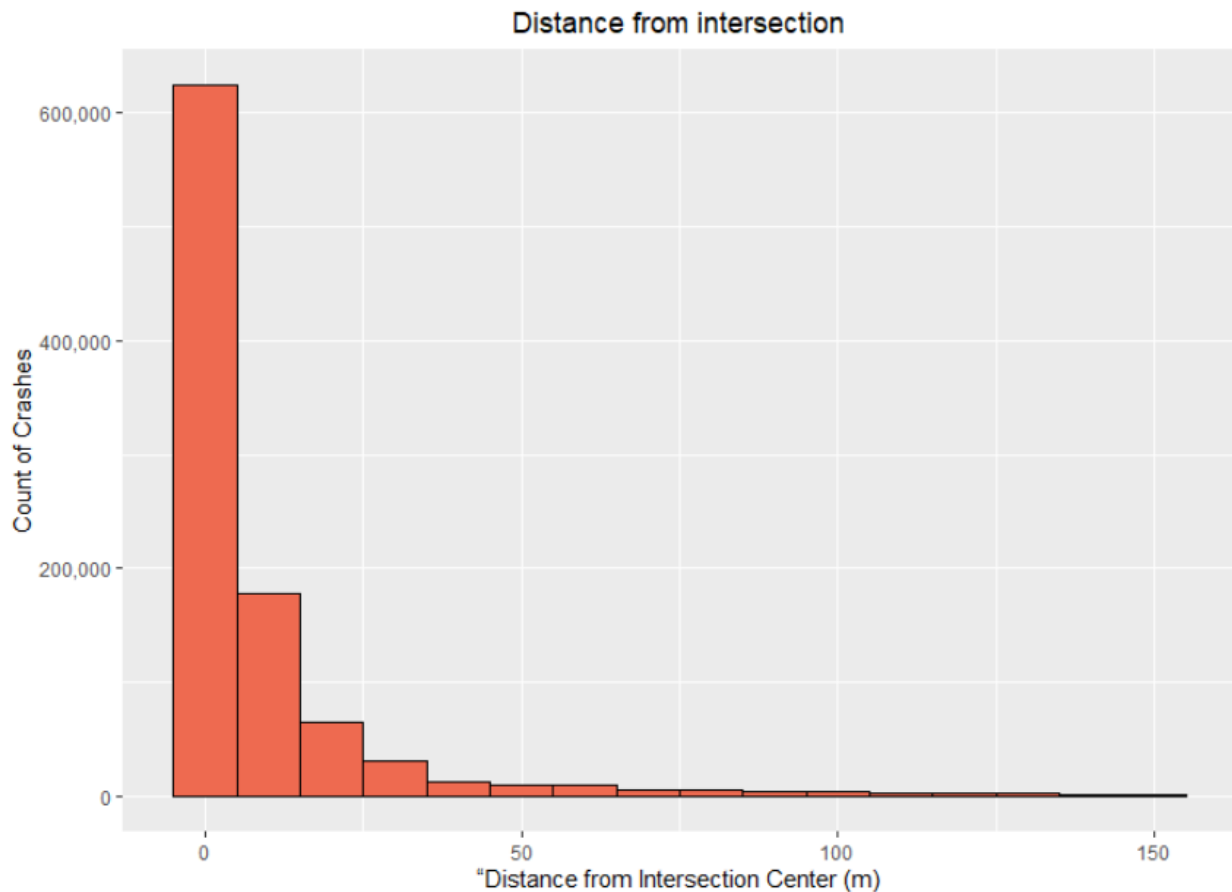
Figure 5 Histogram of distance from intersection for crashes at signalized intersections

High traffic density can produce interference when many vehicles are equipped with the same type of communication mode (especially for modes such as 5G, which are used for purposes other than CV2X communication). Traffic density at the time of the crash is not available in crash datasets. However, a distribution of the time of day of crashes can give an indication of traffic density patterns. This is especially true for rear-end crashes, which are often caused by traffic backups at red lights and other consequences of density.

Figure 6 shows the distribution of hour of the day for rear-end crashes and fatal crashes at signalized intersections in the state database. Rear-end crashes peak during the morning rush from 7-9 am and have a larger peak during the afternoon rush from 3-6 pm. These are likely to be congested periods of time where traffic may back up at intersections. Fatal crashes do show a peak in the afternoon, but they are much more prevalent at night than rear-end crashes. Thus, fatal crashes often happen at times when there will be little traffic volume or interference potential.
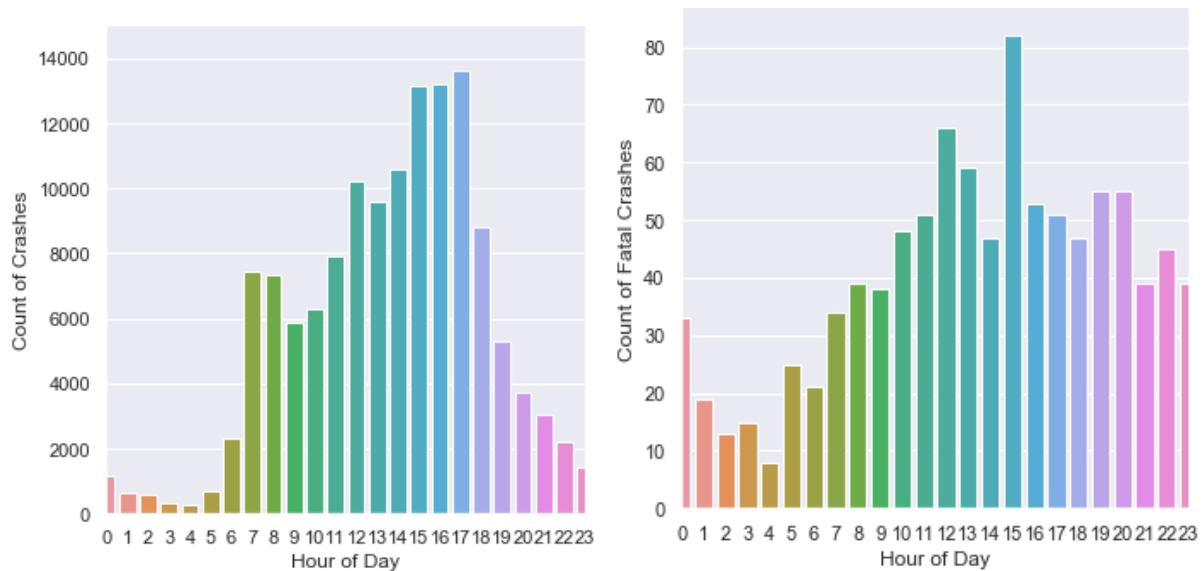
Figure 6 Distribution of hour of the day for rear-end crashes (left) and fatal crashes (right) at signalized intersections

Because state crash data indicate location of crash, we can use map-matching to identify which intersection each intersection-related crash was associated with. Using this information, we aggregated to the intersection level, where we identified the number of each type of crash that occurred at each intersection in the eight states. There were 113,106 signalized intersections that had at least one crash in five years across all states. Scaling up to the national level, we estimate that there are nearly 700,000 such intersections.

However, as shown in Figure 7, crashes are very unevenly distributed across intersections. Figure 7a shows the distribution of crash count by intersection where intersections are sorted by total crash count, descending. Figure 7b shows the same data, but cumulatively, as a Pareto chart. As the figure suggests, 50% of crashes occur at only 10% of intersections, and 95% of crashes occur at only 30% of intersections.

Number of Crashes

(a)
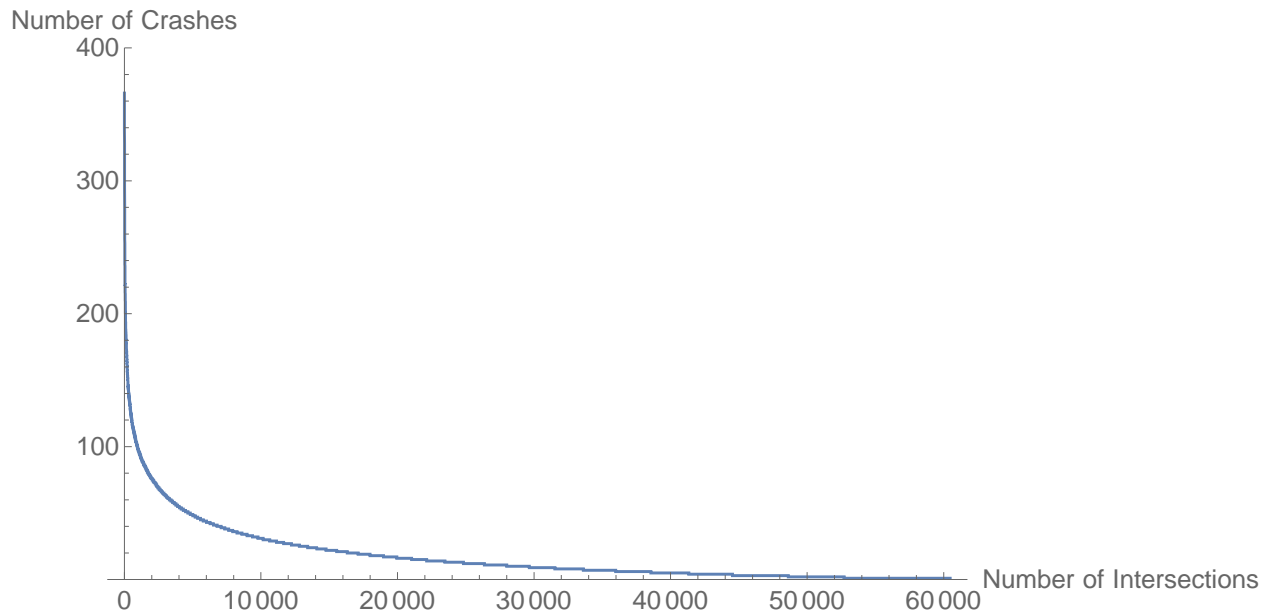
Cumulative Crashes
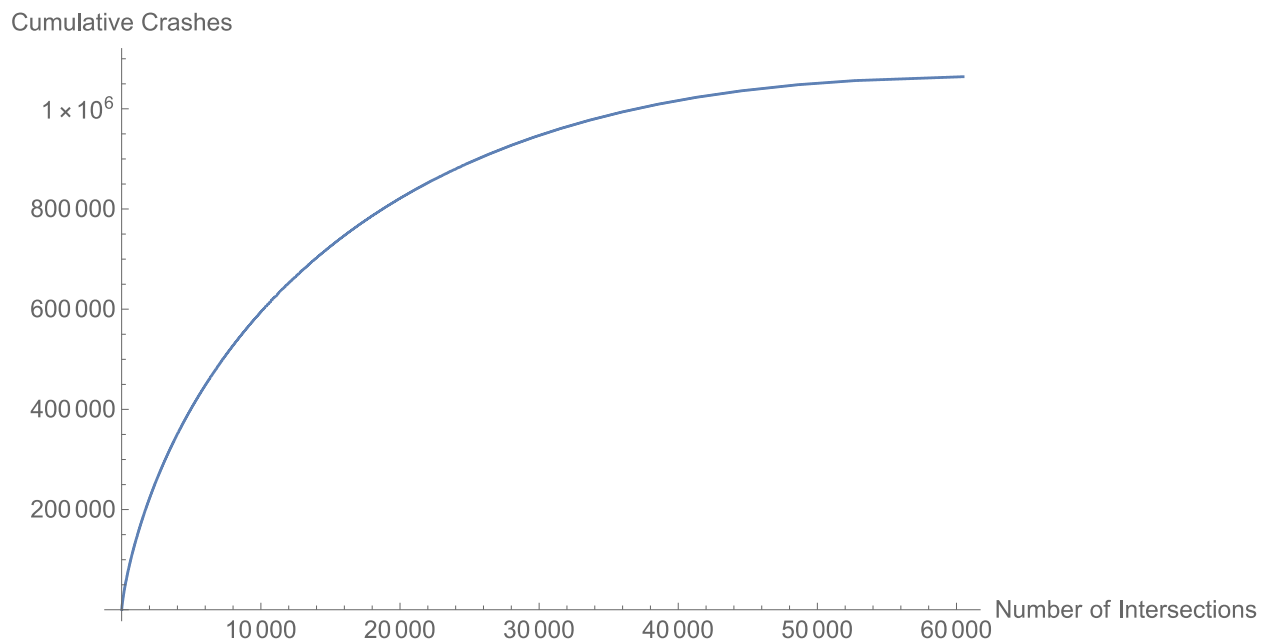
(b)

Figure 7 Crashes per intersection. Graph (a) shows the distribution of crashes per intersection for the 60,000 intersections with the most crashes, sorted by descending crash count. Graph (b) is a Pareto chart that shows the cumulative distribution of crashes for the same set of intersections.

Figure 7 gives the big picture of all crashes at signalized intersections. However, the three CV2X-addressable crashes are not distributed in perfect proportion to total crashes per intersection. For example, Figure 8 compares the count of red-light-running crashes to total crashes. Each point is an intersection, and while there is a general positive correlation, it is clear

that some intersections have a much higher percentage of red-light-running crashes than others. This is important for deployment of CV2X technology, which should be prioritized by addressable crashes rather than total crashes. The same pattern is shown for LTAP and pedestrian crashes in Figure 9 and Figure 10.
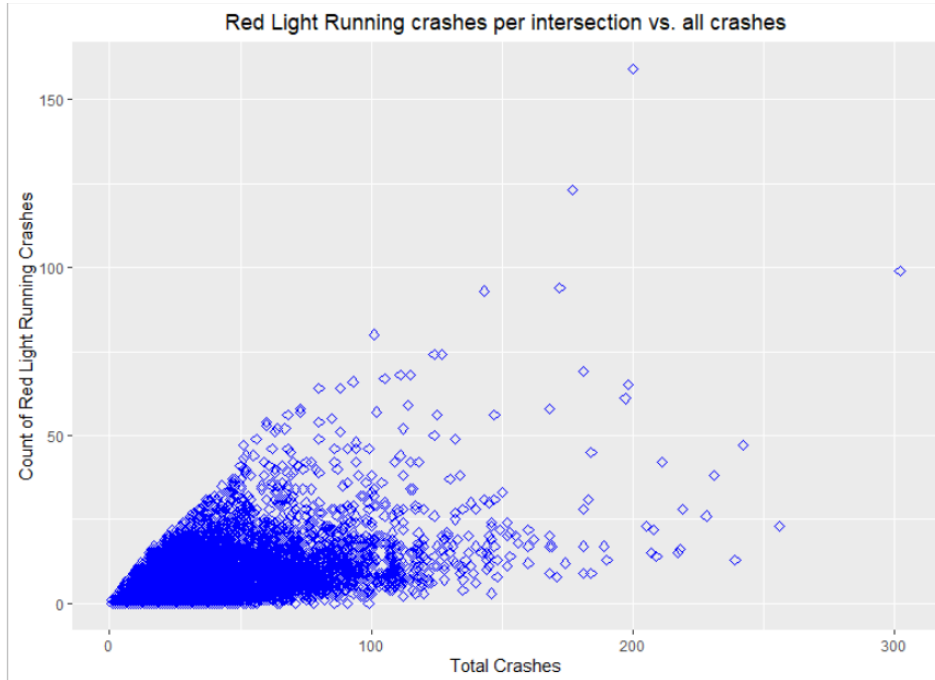

Figure 8 Scatter plot of red-light running crashes against total crashes at each signalized intersection.
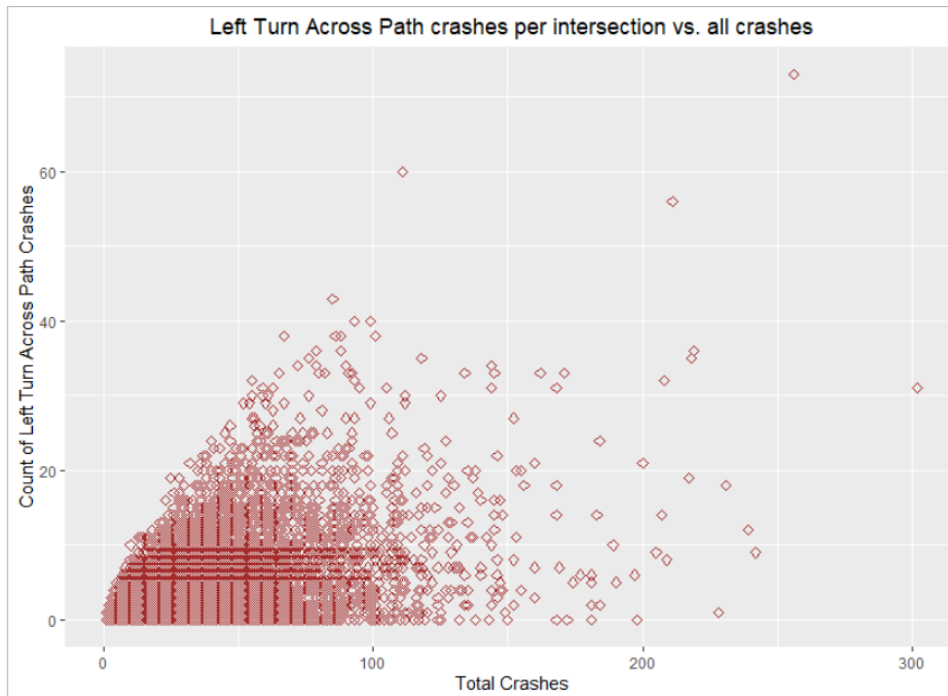

Figure 9 Scatter plot of LTAP crashes against total crashes at each signalized intersection.
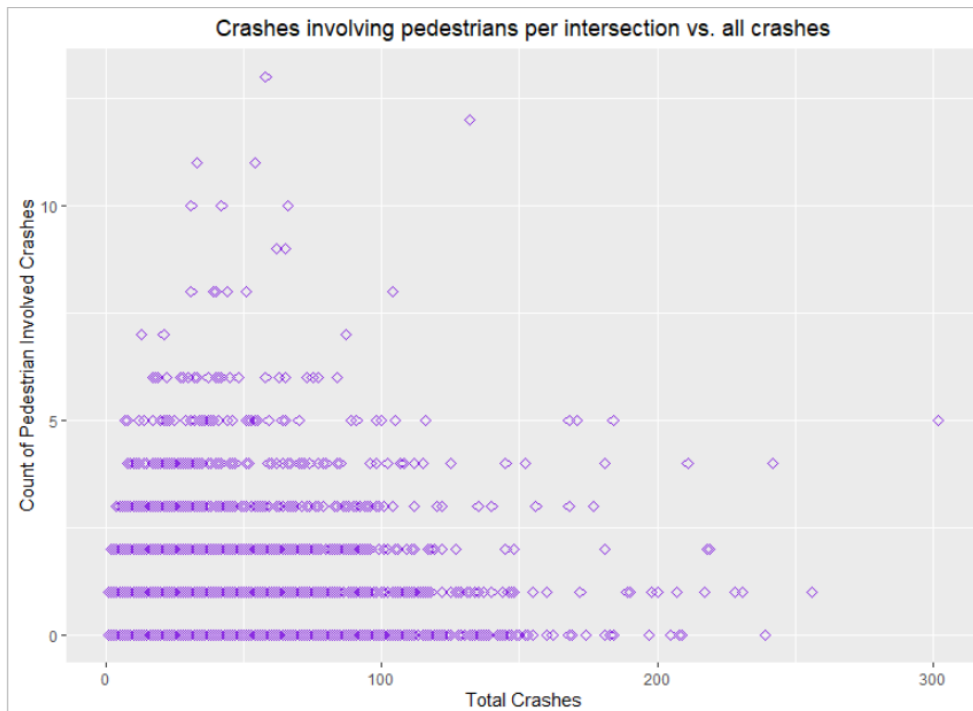
Figure 10 Scatter plot of pedestrian crashes against total crashes at each signalized intersection.

Looking only at the three addressable crash types, just over 47,000 intersections in our dataset are responsible for 95% of these crashes. Scaling up to the national level, equipping ~285,000 intersections nationally with CV2X technology would cover nearly all such crashes that occur at signalized intersections.

Safety Benefits

Methods

Deployment Strategy

Based on the state data analysis results, an optimal deployment strategy will focus on equipping intersections with the most addressable crashes rather than the most total crashes. Moreover, these crash types should be weighted by their potential for harm. In the analyses we conducted here, we weighted the three crash types by their representation among fatalities. For LTAP, red-light-running, and pedestrian crashes the mean cost per crash is $330,612, $338,920, and $706,620, respectively. Thus, we weighted the total five-year count of these three crash types by their relative cost and summed the result. This approximates the total harm caused by these crashes.

Calculating Benefits

To calculate the potential benefits of different infrastructure-based safety technologies, we first make two assumptions:

1. There are two communication technologies, which we call Mode A and Mode B. Mode A is considered the "background" technology and Mode B is the target technology.
2. There is no current deployment of infrastructure equipment for either mode. This reflects the current reality that only pilot projects have been deployed so far.

3. Vehicles with communication technology are also equipped with countermeasures and thus can make use of the information (BSM) being transmitted from the infrastructure.
4. Three countermeasures are used: CICAS-V with 45% effectiveness for red-light-running crashes, IMA with 50% effectiveness for LTAP crashes, and Pedestrian prevention with 45% effectiveness.

The elements of the simulation that will change are:
1. Fleet penetration of vehicles equipped with Mode A and Mode B communication capability
2. Proportion of intersections equipped (ordered by the harm-weighted addressable crash count)
3. Type of equipment: Mode B RSU, Gateway, Mode B RSU + Sensor, Gateway + Sensor

The key determiner of effectiveness is whether the infrastructure equipment will need a communication pathway with two involved vehicles, one specific vehicle, or either of two vehicles. These are listed in order of increasing probability of successful communication. The appropriate choice among these is dependent on the equipment and the intervention type. Table 4 describes the considerations for each countermeasure (rows) and infrastructure installation type (columns). The ability to communicate is then influenced by the probability that the communication mode(s) of the infrastructure match the mode(s) of the vehicle or vehicles with which communication is necessary. Appendix A provides the math for each condition in Table 4.
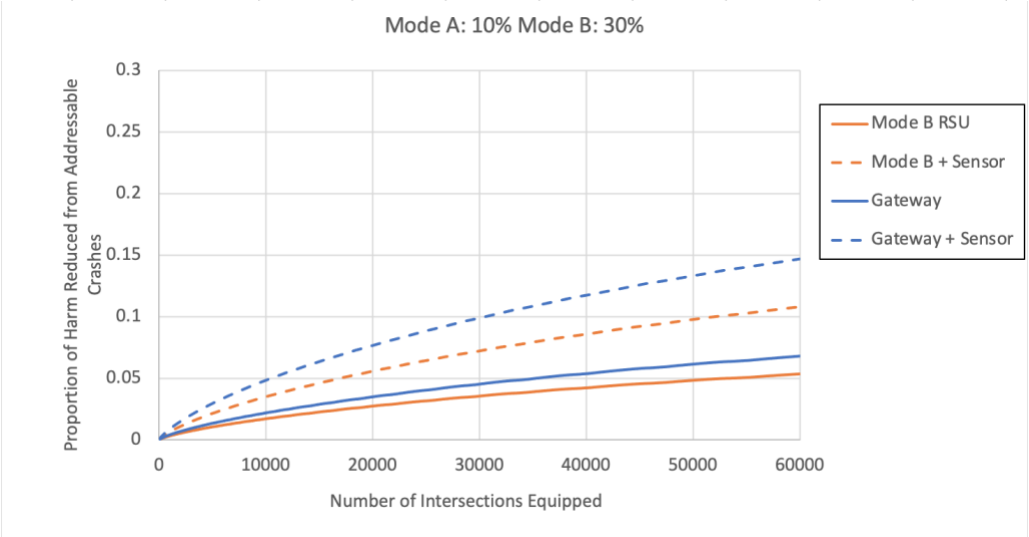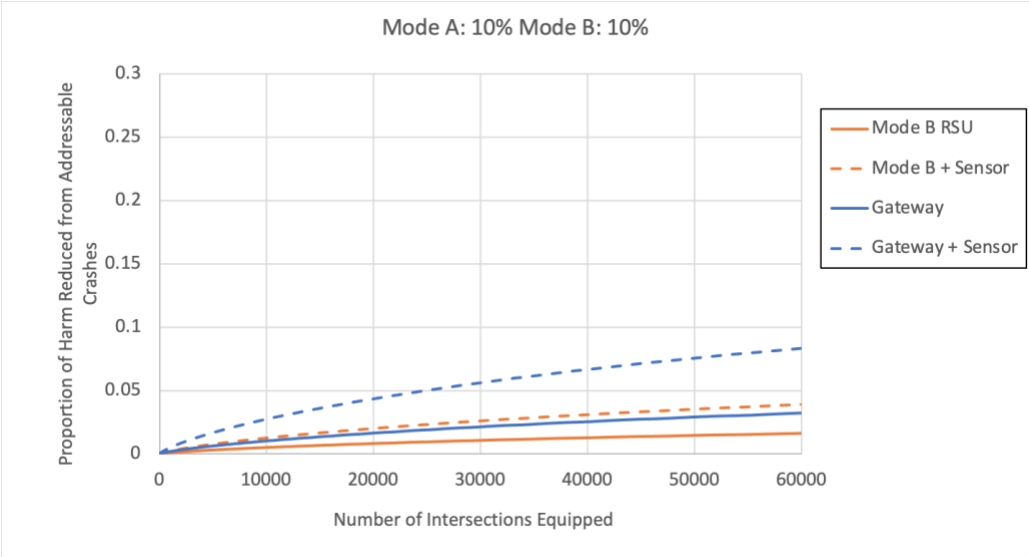
Table 4 Considerations for calculation of benefits for each countermeasure and infrastructure technology
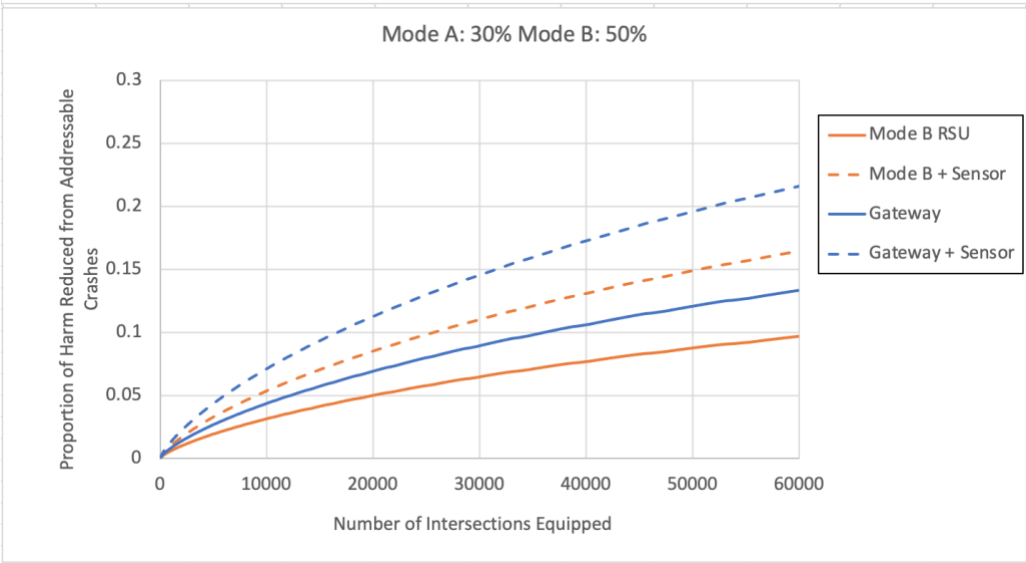
Intervention	Mode B RSU	Gateway	Mode B + Sensor	Gateway + Sensor
CICAS-V (Red-light running)	Specific vehicle (violator), Mode B only	Specific vehicle (violator), either mode	Either vehicle, Mode B only	Either vehicle, either mode
IMA (LTAP)	Both vehicles, Mode B only	Both vehicles, either mode	Either vehicle, Mode B only	Either vehicle, either mode
Pedestrian	No benefit	No benefit	Specific vehicle, Mode B only	Specific vehicle, either mode

A simulation scenario is defined by the vehicle fleet penetration of Mode A and Mode B communication, as well as the infrastructure equipment type. For each scenario, we calculate the estimated reduction in crashes and associated harm at each intersection in the dataset. We then assume deployment is ordered as described above, and we cumulate benefits across intersections in order. We also weight up the intersection count to the national level by multiplying by 6.05.

Results

Figure 11 shows the proportion of harm from addressable crashes that is *reduced* under a variety of conditions. Each plot shows how harm reduction changes as intersections are equipped and based on the equipment being used. Mode B RSUs are in orange and the Gateway is in blue. Solid lines indicate no sensor and dotted lines indicate that as sensor is included. As noted earlier, 285,000 intersections nationally account for 95% of addressable crashes. The graphs in Figure 11 are scaled for national deployment (e.g., different from Figure 7b, which shows only data from our state dataset) and extend to 60,000 intersections, which represent just over 20% of the 285,000 intersections but 54% of total harm from addressable crashes at those intersections. The diminishing returns of equipping further intersections is apparent in the graphs. If the horizontal axis were extended to 285,000 intersections, the maximum harm reduction would be about 45%, which is the limit of the effectiveness estimates that we used in the simulation. As shown in the last plot in Figure 11, equipping the first 60,000 intersections can prevent just over 25% of preventable harm, given nearly universal vehicle fleet penetration.

Mode A: 10% Mode B: 10%

Mode A: 10% Mode B: 30%

Mode A: 10% Mode B: 50%

Mode A: 30% Mode B: 10%

Mode A: 30% Mode B: 30%
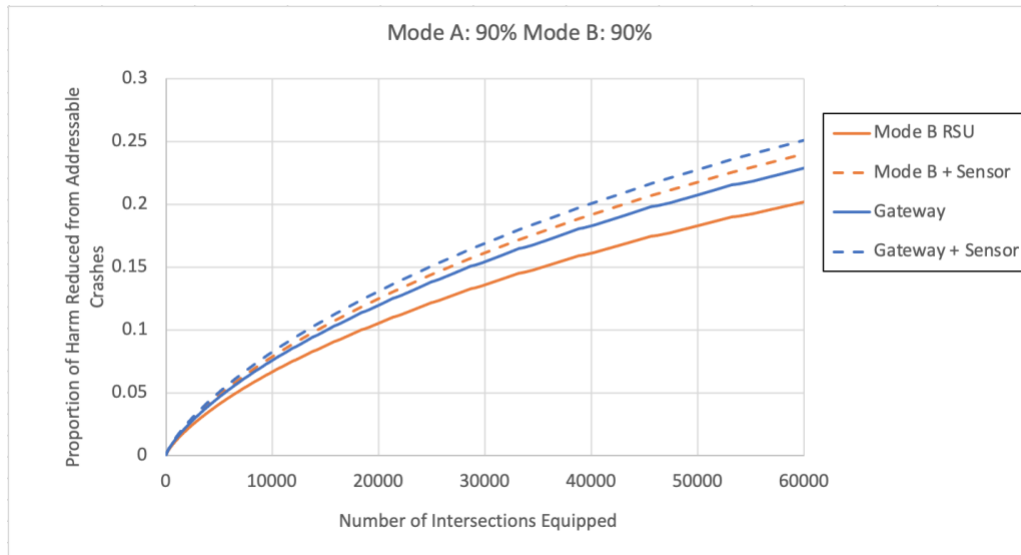

Mode A: 30% Mode B: 50%
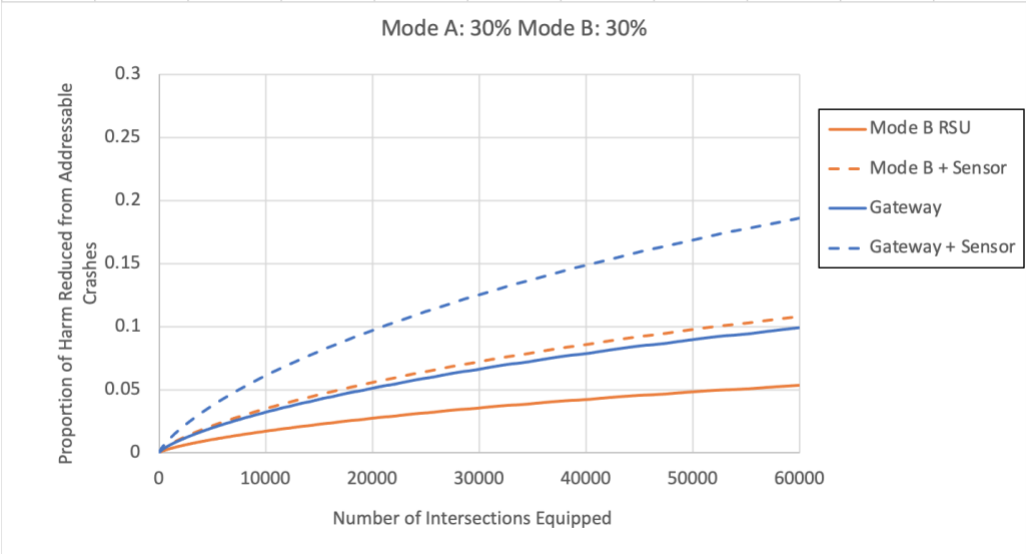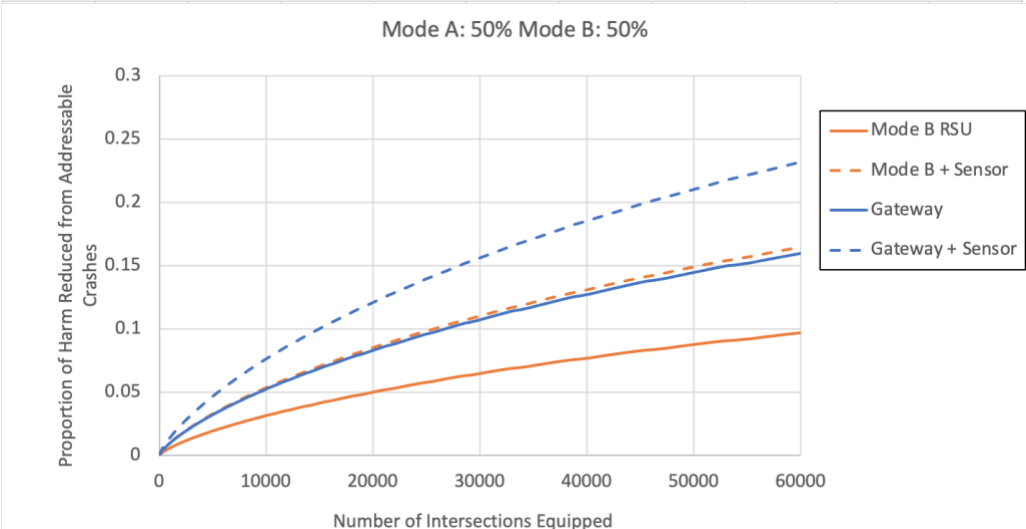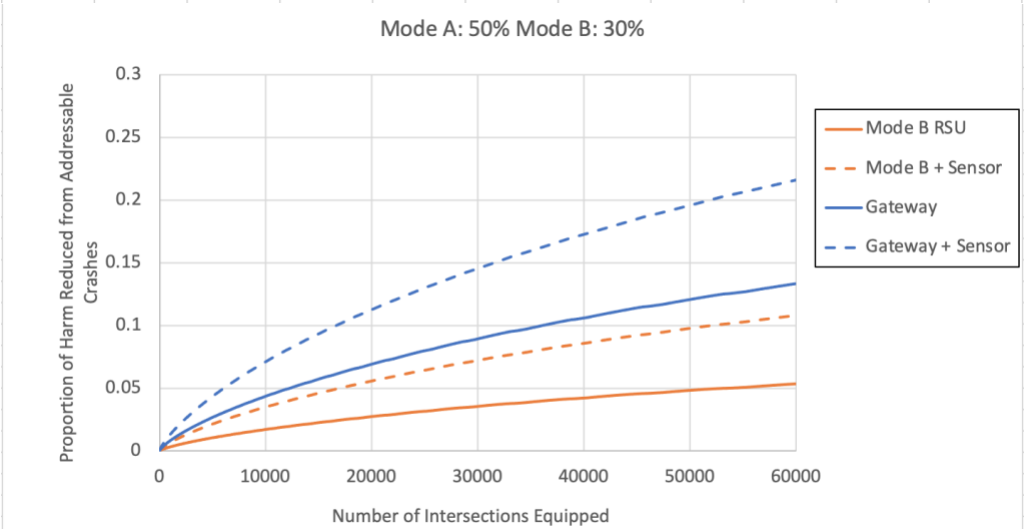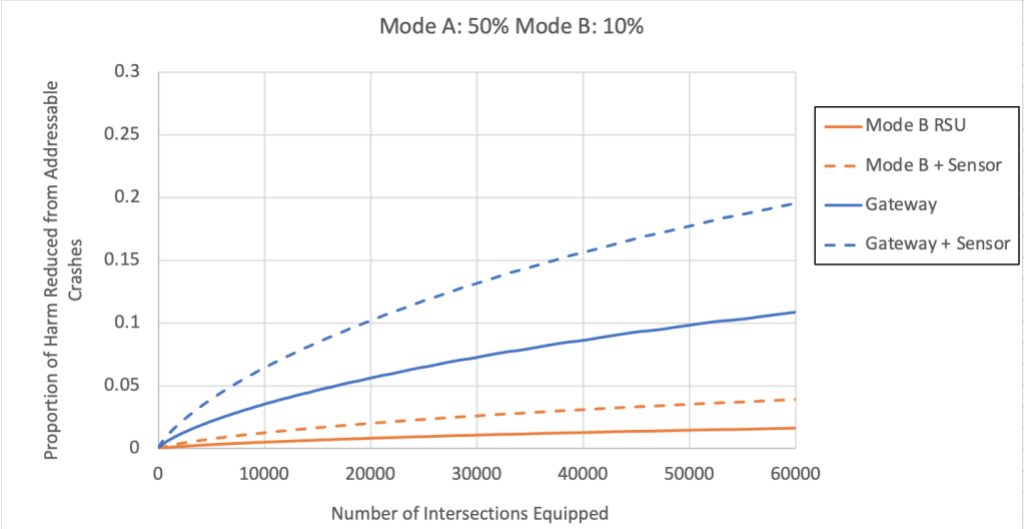
Figure 11 Proportion of harm reduced as a function of Mode A and B fleet penetration, equipment type and number of intersections equipped (nationally).

Figure 11 also shows some consistent patterns across the intersection equipment types. First, the benefit of the Gateway depends on the fleet penetration of communication Mode A. In the first three graphs, when Mode A fleet penetration is 10%, the Gateway does not provide substantial additional benefit over the Mode B RSU (e.g., compare solid blue (Gateway) and solid orange (Mode B RSU) lines). However, when fleet penetration of Mode A is substantial (e.g., 50%), then the Gateway's benefit is also substantial, preventing more harm than the Mode B RSU with sensor. Once both modes are ubiquitous in the fleet (e.g., last graph in Figure 11), all types of equipment are nearly equally effective, though the sensor is required for pedestrian crash prevention.

Figure 12 makes is easier to see how changes in Mode B vehicle fleet penetration change harm reductions for each of the types of equipment. The three graphs in Figure 12 show three different levels of Mode A fleet penetration (10%, 50%, and 90%). For all graphs, the harm reduction is based on 60,000 intersections equipped with CV2X technology. In all three graphs, the curves for the Mode B RSU (orange lines) are the same because the background fleet penetration of Mode A does not change the RSU's ability to prevent crashes. In contrast, the Gateway curves are elevated even at low fleet penetration of Mode B when there is significant fleet penetration of Mode A (e.g., 50-90%). That is, the Gateway is most effective when there are vehicles that communicate via other modes, and in general the Gateway is most effective when the distribution of communication modes is most variable.
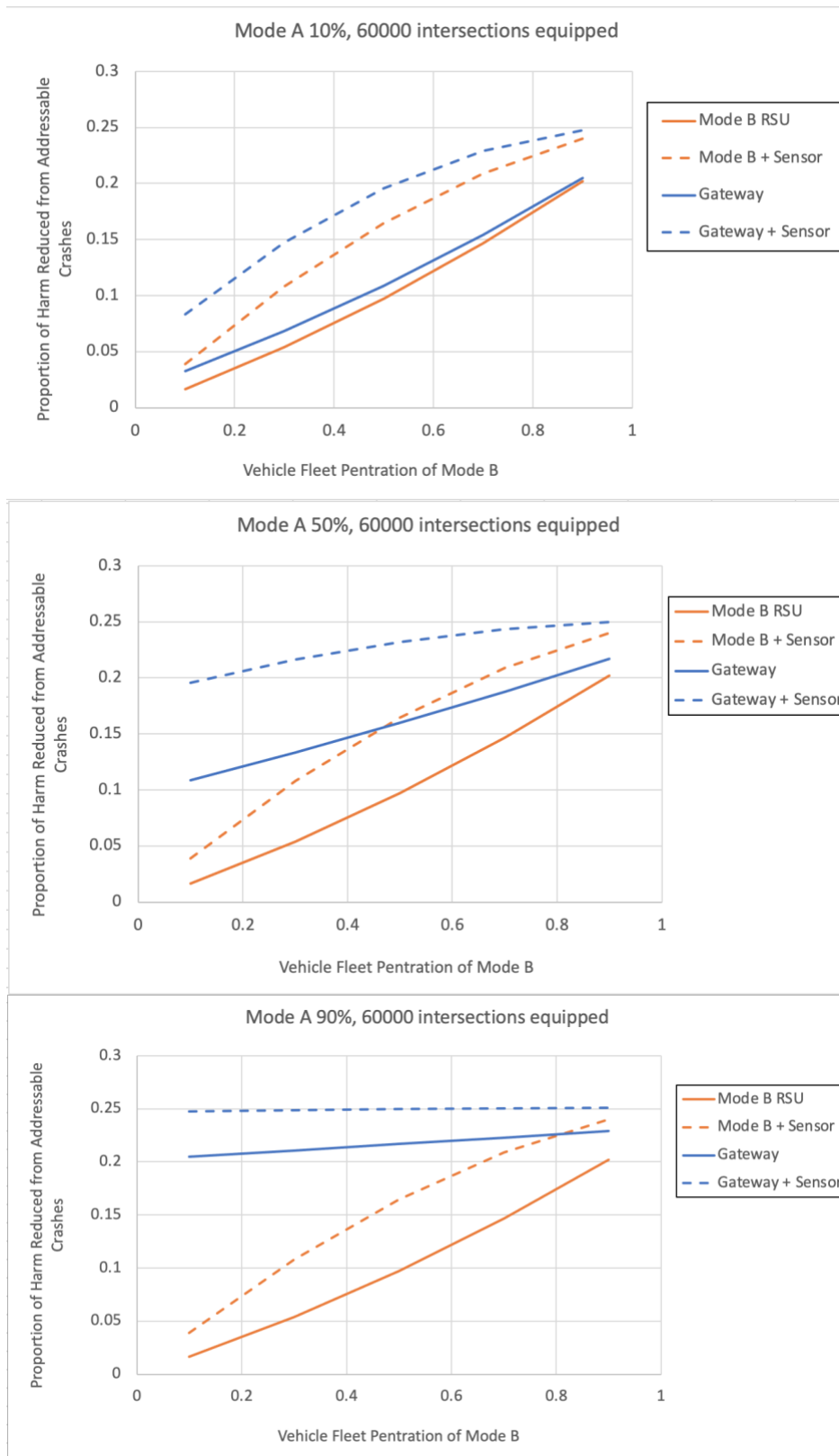
Figure 12 Illustration of harm reductions as a function of Mode A and B fleet penetration and equipment type when 60,000 intersections are equipped.

Figure 12 also emphasizes the way in which the sensor changes benefits. In particular, we can think of the Mode B (and/or Mode A) fleet penetration as increasing over time. Early in deployment, the sensor produces the greatest increase in benefits because it lessens the burden of being able to communicate with multiple vehicles. When communication capability is limited in the fleet, the probability of being able to communicate with two vehicles that are in conflict is low. This leads to the sensor curves (dotted lines) bending up and to the left, while the no-sensor curves (solid lines) bend down and to the right as fleet penetration of communication increases.

In our simulation, the sensor always has greater benefits, even with 90% fleet penetration of both forms of communication, because it is required for pedestrian crash prevention. This can be seen at the right end of each graph, where the sensor curves are above the corresponding no-sensor curves.

Discussion

We evaluated the potential benefits of equipping signalized intersections with different types of CV2X technology. In particular, we focused on the relative harm reduction from using a single communication-mode RSU vs. a Gateway, which rebroadcasts messages in different communication modes, making them more likely to be received by vehicles that might be using different communication modes. We also investigated the additional benefits of installing a sensor at intersections as a way of gathering information on vehicle locations and trajectories without relying on communication. Finally, we evaluated an optimal deployment strategy that prioritizes intersections that have larger numbers of *addressable* crashes, weighted by the expected harm (measured as cost of injuries in dollars) caused by those crash types.

Three key crash types are addressable by current or developing CV2X technology: Left Turn Across Path (LTAP), red-light running, and pedestrian crashes. These crashes make up 35% of crashes at signalized intersections in the U.S each year, but 48% of the harm. The estimated annual economic cost of these addressable crashes is $166 billion.

CV2X safety technologies that can address these crashes are CICAS-V, IMA and pedestrian crash avoidance. CICAS-V addresses red-light running crashes and is estimated to be 45% effective. IMA addresses LTAP crashes and is estimated to be 50% effective, and pedestrian crash avoidance is intended to prevent a vehicle from hitting a pedestrian at an intersection. It is estimated to be 45% effective.

Using police-reported crash data from eight states, we observed that total crashes per intersection follows a Pareto curve such that 50% of crashes occur at only 10% of signalized intersections and 90% of crashes occur at only 30% of intersections. Importantly, intersections with the most crashes are not always the same as those with the most *addressable* crashes. Thus, deployment should emphasize the number of addressable crashes observed at each intersection in recent years. Finally, we also recommend weighting addressable crashes according to expected harm, which results in weighting up intersections with large numbers of pedestrian crashes (which cause about twice the harm per crash as LTAP and red-light-running crashes).

Looking only at the three addressable crash types, just over 47,000 intersections in our dataset are responsible for 95% of these crashes. Scaling up to the national level, we estimate that equipping ~285,000 intersections nationally with CV2X technology would cover nearly all such crashes that occur at signalized intersections.

We conducted simulations of a variety of scenarios of vehicle fleet penetration of two communication modes (called Mode A and Mode B) and intersection installations of four different CV2X equipment types. These were Mode B RSU or Gateway (multi-mode

communication) with or without a sensor. Using our optimal deployment strategy (ordered by the harm-weighted total addressable crashes at each intersection), we estimated the number of crashes that could be prevented at each intersection in our dataset, based on the vehicle fleet penetration of Mode A and Mode B communication technology. These estimates were then cumulated and scaled up to the national level.

The difference in benefits between the four infrastructure technologies arises from the requirements that each puts on the ability to communicate with vehicles involved in a conflict. In some cases, the RSU or Gateway must communicate with both vehicles in conflict; in others, communication is only with one specific vehicle; and in a third case, the infrastructure can prevent the crash by successfully communicating with *either* vehicle. When fleet penetration of communication is low or when communication pathways are limited (e.g., Mode B RSU with no sensor), the probability of communicating successfully is low. However, the more communication pathways are open, the more likely it is to be successful.

In general, the Gateway provides the most additional safety benefits over a single-mode RSU (Mode B in our analysis) when the fleet penetration of the background communication mode (Mode A in our analysis) is large and/or there is more variety of modes in the vehicle fleet. In that case, the Gateway has many opportunities to communicate with vehicles than any single-mode RSU. Adding a sensor to either a single-mode RSU or a Gateway brings substantial additional safety benefits, especially early in communication deployment in the vehicle fleet. The sensor reduces the communication burden to only outgoing information, which can often be acted on by either vehicle in a conflict situation.

With deployment of CV2X capability at 285,000 signalized intersections in the U.S., there is the potential to save $75 billion per year by eliminating injuries associated with LTAP, red-light-running and pedestrian crashes at those intersections. These savings depend also on the growth of communication capability in the vehicle fleet. However, with sensors and Gateways, benefits can be realized fairly quickly even when there is relatively low vehicle fleet penetration of communication modes. In addition, strategic deployment of this technology at intersections with the highest number of addressable crashes first can also help produce the largest gains at the lowest cost.

Appendix A Details of Benefits Calculations

For benefits calculations in this project, we assumed there are two communication modes, labeled Mode A and Mode B. We also assume that there is no appreciable existing deployment of equipment at intersections, though there can be existing vehicle fleet penetration of either mode.

For each countermeasure, depending on the equipment, communication is required in one of three ways:

  A. Communication is required with both involved vehicles
  B. Communication is required with one specific involved vehicle
  C. Communication is required, but can be with either involved vehicle

The communication requirements affect the probability that there is a communication match between the equipment and the vehicle(s) with which it must communicate.

As background, the following terms are defined:

f_A: vehicle fleet penetration of Mode A
f_B: vehicle fleet penetration of Mode B
p_B: proportion of intersection crash events occurring at intersections with Mode B RSU equipment installed
p_G: proportion of intersection crash events occurring at intersections with Gateway installed
e: effectiveness of countermeasure (proportion of crashes eliminated)

Case A: Communication is required with both involved vehicles

Case A1: Mode B RSU

If an intersection is equipped with a Mode B RSU, then both vehicles must also be equipped with the ability to communicate using Mode B. The proportion of such crashes reduced by the Mode B RSU is given by Equation A1.

$$r_{AB} = e p_B f_B^2 \tag{A1}$$

where r_{AB} is the proportion of relevant crashes reduced by the Mode B RSU for crash types and countermeasures in which the RSU must communicate with both vehicles to prevent the crash. The resulting benefits depends on the fleet penetration of vehicles with Mode B communication and the proportion of intersections equipped with the Mode B RSU, as well as the effectiveness of the countermeasure.

Case A2: Gateway

If an intersection is equipped with a Gateway, then both vehicles must also be equipped with the ability to communicate, but can use either Mode A or Mode B. The proportion of such crashes reduced by the Gateway is given by Equation A2.

$$r_{AG} = e p_G \left(1 - (1 - f_A)(1 - f_B)\right)^2 \tag{A2}$$

where r_{AG} is the proportion of relevant crashes reduced by the Gateway for crash types and countermeasures in which the Gateway must communicate with both vehicles to prevent the crash. The resulting benefits depend on the fleet penetration of vehicles with Mode A and Mode B communication and the proportion of intersections equipped with the Gateway, as well as the

effectiveness of the countermeasure. The probability inside the squared term is 1 minus the probability that a vehicle has neither communication mode.

Case B: Communication is required with one specific involved vehicle

Case B1: Mode B RSU

If an intersection is equipped with a Mode B RSU, then the specific vehicle must also be equipped with the ability to communicate using Mode B. The proportion of such crashes reduced by the Mode B RSU is given by Equation A3.

$$r_{BB} = ep_B f_B \tag{A3}$$

where r_{BB} is the proportion of relevant crashes reduced by the Mode B RSU for crash types and countermeasures in which the RSU must communicate with one specific vehicle to prevent the crash. The resulting benefits depend on the fleet penetration of vehicles with Mode B communication and the proportion of intersections equipped with the Mode B RSU, as well as the effectiveness of the countermeasure.

Case B2: Gateway

If an intersection is equipped with a Gateway, then the specific vehicle must also be equipped with the ability to communicate, but can use either Mode A or Mode B. The proportion of such crashes reduced by the Gateway is given by Equation A4.

$$r_{BG} = ep_G (1 - (1 - f_A)(1 - f_B)) \tag{A4}$$

where r_{BG} is the proportion of relevant crashes reduced by the Gateway for crash types and countermeasures in which the Gateway must communicate with one specific vehicle to prevent the crash. The resulting benefits depend on the fleet penetration of vehicles with Mode A and Mode B communication and the proportion of intersections equipped with the Gateway, as well as the effectiveness of the countermeasure.

Case C: Communication is required with either involved vehicle

Case C1: Mode B RSU

If an intersection is equipped with a Mode B RSU, then one of the two involved vehicles must also be equipped with the ability to communicate using Mode B. The proportion of such crashes reduced by the Mode B RSU is given by Equation A5.

$$r_{CB} = ep_B (1 - (1 - f_B)^2) \tag{A5}$$

where r_{CB} is the proportion of relevant crashes reduced by the Mode B RSU for crash types and countermeasures in which the RSU can communicate with either of two vehicles to prevent the crash. The resulting benefits depend on the fleet penetration of vehicles with Mode B communication and the proportion of intersections equipped with the Mode B RSU, as well as the effectiveness of the countermeasure.

Case C2: Gateway

If an intersection is equipped with a Gateway, then either vehicle must also be equipped with the ability to communicate, but the communicating vehicle can use either Mode A or Mode B. The proportion of such crashes reduced by the Gateway is given by Equation A6.

$$r_{CG} = ep_G \left(1 - ((1 - f_A)(1 - f_B))^2 \right) \tag{A6}$$

where r_{CG} is the proportion of relevant crashes reduced by the Gateway for crash types and countermeasures in which the Gateway can communicate with either vehicle to prevent the crash. The resulting benefits depend on the fleet penetration of vehicles with Mode A and Mode B communication and the proportion of intersections equipped with the Gateway, as well as the effectiveness of the countermeasure. The term inside the parentheses is 1 minus the probability that both vehicles have no communication in either Mode A or Mode B.