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POTENTIAL SAFETY BENEFITS ASSOCIATED WITH SPEED LIMIT COMPLIANCE IN SAN FRANCISCO AND PHOENIX

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ABSTRACT

Objective

Safer Speeds represents one part of the Vision Zero and Safe System Approach to eliminate traffic fatalities and serious injuries. The objective of this paper was to estimate the potential safety benefits if all drivers in two U.S. cities complied with roadway speed limits on surface streets.

Methods

Sensor data from a fleet of automated driving system (ADS)-equipped vehicles operating a ride-hailing service were used to determine aggregate traffic speeds during free-flow conditions in Phoenix and San Francisco from over 1 million unique vehicle-road segment traversals. The current human driving speed distribution was estimated using opposite direction traffic speed observations to limit the influence of the ADS-equipped vehicle on surrounding vehicles' travel speeds. The speed limit compliant driving fleet consisted of speed observations involving the ADS-equipped vehicles. To estimate the potential safety benefits from reduced travel speeds associated with speed limit compliance, an exponential model relating the effect of speed reduction on fatal and injury crashes was applied, stratified by roadway speed limit. Recent fatality data from these cities was then used to quantify an estimate for lives saved simply through speed limit compliance.

Results

Across the roadway-location combinations considered, 33-49% of human drivers were observed to be speeding, with 85th percentile speeds 3.6-7.2 mph over the speed limit. Serious injury and fatality reductions associated with altering the current human-driven vehicle fleet speed distribution toward one that is speed limit compliant were observed to vary by roadway from 18-30% and 27-43%, respectively. When considering these fatality reduction rates in conjunction with available fatality data from FARS, an estimated 82 lives could be saved annually simply through speed limit compliance on surface streets, with 75 lives saved in the Phoenix metro area and 7 lives saved in San Francisco.

Conclusion

Using novel data from an ADS-equipped vehicle fleet to estimate the travel speed distribution of both the current human driven and a speed compliant fleet, in conjunction with the Elvik speed framework, this study estimated a 30% reduction in fatalities on surface streets in two U.S. cities, highlighting the impact of speed limit compliance on fatality prevention for all road users and building on the existing body of traffic safety literature capturing the deleterious effects of speeding.

Keywords: Safe Speeds, speed limit compliance, Vision Zero

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INTRODUCTION

Vision Zero and the Safe System Approach

Built out of a traffic safety policy shift in the mid-1990s in Sweden, Vision Zero is an approach toward the elimination of serious and fatal injuries within the road transport system [Larsson et al., 2010; Lie and Tingvall, 2001; Tingvall 1997, 2022]. As of 2019, more than 20 years after the adoption of Vision Zero within Sweden, the traffic fatality rate had decreased by more than 50% [Road Safety Sweden]. Other nations and cities have since adopted the Vision Zero approach in recent years in an attempt to reduce the global harm associated with serious and fatal injuries from traffic collisions. Predominantly in Europe, several nations (e.g., Ireland, Norway) halved their fatalities from 1994 to 2015 and have continued to see improvement in national fatality rate in the following years (through 2019) [Lockard et al., 2022; Yellman and Sauber-Schatz, 2022].

As adopted by the United States, as the Safe System Approach, there are five key objectives aimed toward the elimination of crashes that result in fatalities and serious injuries: Safer People, Safer Vehicles, Safer Speeds, Safer Roads, and Post-Crash Care [U.S. DOT]. An underlying, implicit aspect of Vision Zero is that the biomechanical tolerance of the human body to injury represents the limiting factor in a Safe System [Larsson et al., 2010]. Accordingly, reducing energy available at impact by reducing vehicle travel speeds represents a key way to achieve the goals of Vision Zero. While Safer Speeds is carved out individually in the Safe System objectives, the aspect of controlling speed is present in each of the Safe System objectives. From encouraging safer driving and compliance with roadway speed limits (Safer People) to designing roadways to facilitate safe travel and mitigate potential speeding (Safer Roads), and from advanced vehicle safety features, such as automatic emergency braking, that may mitigate total collision energy when collisions are unavoidable (Safer Vehicles) to ensuring emergency responders have a safe triage environment and avoiding secondary collisions (Post-Crash Care), reducing speed is a critical aspect of a Safe System.

Within the United States, eliminating speeding represents a key challenge toward achieving the goals of Vision Zero and establishing a Safe System. Notably, the National Transportation Safety Board (NTSB) completed a safety study in 2017 related to speeding-related traffic crashes and concluded that “the current level of emphasis on speeding as a national traffic safety issue is lower than warranted and insufficient to achieve the goal of zero traffic fatalities in the United States” (National Transportation Safety Board, 2017). From the most recent available data from 2022, the National Highway Traffic Safety Administration (NHTSA) reported that speeding was a contributing factor in approximately 28% of fatal crashes and 13% of injury crashes, resulting in over 12,000 fatalities for the year, with an additional 300,000 people injured [National Center for Statistics and Analysis, 2024]. These proportions have largely remained unchanged over the last decade.

While national efforts in the U.S. may be lagging, recent efforts associated with Vision Zero in several U.S. cities (e.g., New York City, Seattle, and Boston) to reduce speeds highlight the potential for associated reductions in injuries and collisions. In November 2014, the speed limit for unsigned roadways in New York City was reduced to 25 mph from 30 mph. Researchers investigated the effect on injuries and collisions over a 7-year period (2012-2019) surrounding this change and reported a 39% drop in injuries and a 36% reduction in overall crashes for streets which experienced the speed limit change relative to those that did not [Mammen et al., 2020]. In November 2016, the default speed limit in Seattle was lowered from 30 mph to 25 mph on arterial streets and from 25 mph to 20 mph on non-arterial streets. In comparison to nearby cities in Washington that did not have a similar speed limit reduction, the speed limit change in Seattle was observed to reduce the odds of an injurious collision by 17% in downtown Seattle, with a statistically non-significant reduction of 7% outside of downtown Seattle [Hu and Cicchino, 2024]. In January 2017, the default speed limit in Boston was reduced from 30 mph to 25 mph. Compared to the control city of Providence, Rhode Island, which did not have a similar speed limit reduction, vehicles were observed to have lower odds of traveling above the speed limit (3% reduction), 5 mph above the speed limit (8.5%), or 10 mph over the speed limit (29%) [Hu and Cicchino, 2020]. This effect has also been observed in European cities. A meta-analysis of the effect of reducing roadway speed limits to 30 kph or 20 mph in 40 European cities reported that, on average, collisions were reduced by 23%, fatalities by 37%, and injuries by 38% [Yannis and Michelaraki, 2024].

Achieving Speed Limit Compliance

While reducing speed limits can bring down roadway speeds, there are also several methods to achieve compliance with existing roadway speed limits. For example, geofencing, which governs roadway speed limit based on a geographic boundary (e.g., a school zone) or roadway conditions (variable speed limits), was shown by Swedish traffic safety researchers to be used to limit roadway speeds [Nygårdhs et al., 2023]. Historically, this manifests in posted signage and decreased roadway speed limits where the driver must take action to reduce their speed within the zone. The potential exists to alert drivers to new speed zones and/or to automatically govern vehicle speeds toward the roadway speed limit within these areas. This is commonly referred to as intelligent speed assistance (ISA), which is a mandatory feature for vehicles in Europe, as of July 2024 [Euro NCAP]. A recent survey of drivers in the U.S. carried out by IIHS revealed that more than 60% of respondents would find an audible or visual alert related to speeding acceptable, and approximately 50% of respondents supported an intelligent speed limiter to restrict travel above the speed limit [Reagen and Cicchino, 2025]. Increased enforcement of existing roadway speed limits also offers the potential to reduce speeds. This may be done through the use of speed cameras or increased traffic police enforcement, for example. A meta review of studies investigating speed camera effectiveness reported decreases in speeding vehicles of 14-65%, with overall average speed reductions from 1-15% and decreases of 11-44% in fatal and serious injury crashes [Wilson et al., 2010]. Public service announcements, education, and other marketing communications may also be used to encourage speed limit compliance. Infrastructure-based traffic calming efforts, such as chicanes, speed bumps, or lane narrowing can also encourage reduced travel speeds.

Modeling the Effect of Speed on Collision Outcomes

The effect of speed on collision and injury risk has been well-documented, with numerous researchers creating models to evaluate a variety of research questions. Injury risk models for vulnerable road users and vehicle occupants have been developed to relate crash factors to injury outcomes, which have served as the basis for Advanced Automatic Collision Notification (AACN) systems, which help emergency responders assess collision severity and inform trauma response [Kusano and Gabler, 2014; Weaver et al., 2015]. In the Vision Zero lens, injury risk models have also been used to develop Safe Speed thresholds to inform roadway speed limits for mitigating serious and fatal injuries in traffic collisions [Tingvall and Haworth, 1999; Rizzi et al., 2023; Lubbe et al., 2024; Doecke et al., 2020; Truong et al., 2022; Dean et al., 2023]. Risk functions, which largely focus on the effect of speed on collision severity/injury risk from observed collisions, may also be used to simulate collision events at the individual event level [Lubbe et al., 2022; McMurry et al., 2021; Schubert et al., 2023; Schubert et al., 2024].

Other models, principally power models or exponential models, have been developed which strive to evaluate the effect of changes in observed roadway travel speeds on both collision involvement and injury outcomes at the aggregate level. The power model, proposed by Nilsson (2004), relates the frequency of fatal and seriously injurious collisions and injuries with changes in the mean speed of traffic. A notable feature of the power model is that it is dependent on the relative change in speed rather than the initial speed. Conversely, the exponential model, proposed by Elvik (2013), relates the effect on traffic safety due to the absolute change in mean speed. As reported in Elvik et al. (2019), both these models have been shown to have great precision when looking at field collision data sets, though the exponential model was identified as the preferred model given that it performs better for higher speed data points. Elvik (2019) further extended the exponential model to utilize changes in the entire speed distribution (by dividing the distribution into discrete speed intervals) rather than simply relying on mean roadway speed. These mathematical models are fit to empirical speed and collision data and allow for prediction of safety benefits associated with changes in speed (e.g., due to increased speed limit enforcement or a change in roadway speed limit).

Research Objective

Recent deployments of ADS-equipped vehicles designed to follow roadway speed limits present a relevant opportunity to assess what effect this could have on traffic safety. Using data from ADS-equipped vehicles as a stand-in for roadway speed limit compliance, the objective of this paper was to estimate the potential safety benefits if all drivers in two U.S. cities complied with roadway speed limits through an application of the traffic speed impact framework described by Elvik (2019). This analysis builds on the existing body of literature capturing the deleterious effects of speeding on traffic safety. It does not consider any other aspects of the ADS-equipped vehicles that may relate to traffic safety, solely the element of speed limit compliance.

METHODS

Determination of Free-flow Travel Speeds

Sensor data from a fleet of ADS-equipped vehicles operating a ride hailing service were used to determine aggregate traffic speeds during free-flow conditions on surface streets. The ADS vehicle is equipped with various perception sensors that allow the ADS to sense, plan, and act in order to drive safely. The sensing component of the ADS uses multiple sensors to identify the type, position, and speeds of objects around the ADS-equipped vehicle. This study used anonymized ADS perception data to identify the speed of vehicles (i.e., cars, trucks, vans, buses) traveling around the ADS-equipped vehicle. All observations were taken from two consecutive weekdays of driving in September 2024 in which there was no precipitation.

To generate distributions of travel speeds of human-driven vehicles, vehicles traveling in the opposite direction on the same road from the ADS-equipped vehicle were identified. The speed of other vehicles that travel in the same direction as the ADS-equipped vehicle could be influenced by the ADS-equipped vehicle's speed. Relative position constraints were applied to objects to identify those vehicles traveling in the opposite direction as the ADS-equipped vehicle. First, relative position and heading requirements were placed on other vehicles, as shown in Figure 1. In order to be classified as an opposite direction vehicle, the other vehicle must have had an absolute relative heading to the ADS-equipped vehicle of less than 30°. Observations were taken of vehicles where the angle between the center of the ADS-equipped vehicle and the center of the other vehicle was between 45° and 135°, and the distance between the vehicles was less than 30 meters. Furthermore, the ADS sensor data was localized to a lane-level map. Other vehicles were restricted to those identified as driving on lanes that were neighboring and in the opposite direction of travel as the lane segment the ADS-equipped vehicle was traveling on. A neighboring lane was defined as being within 12 m laterally of the travel lane of the ADS. These relative position constraints were done to restrict the analyzed objects to those on the same segment of road as the ADS-equipped vehicle. Opposite direction segments in which an ADS-equipped vehicle was observed (i.e., ADS-equipped vehicle observing an opposite direction ADS-equipped vehicle) were removed from the opposite direction travel observations to avoid double counting observations and any potential effects of ADS-equipped vehicles on the opposite direction traffic.

Next, observations were restricted based on the ADS-equipped vehicle's movement. Observations were restricted to when the ADS-equipped vehicle was traveling straight (path curvature < 0.01 m^{-1}) with a heading within 20° of the lane heading. Lane segments with curvature > 0.01 m^{-1} were excluded. Restricting to these straight traveling scenarios mitigated uncertainty associated with categorizing opposite direction travel on a changing path trajectory.

One difficulty in studying speeds on local roads is differentiating between free-flow speeds and those affected by traffic controls, like traffic lights, or congestion. Level of service (LOS) represents one way to assess traffic flow on a given roadway, capturing factors like speed, density, and congestion. The Highway Capacity Manual (HCM) provides speed thresholds for various LOS given free-flow travel speed, where free-flow travel speed may be taken to be equivalent to the roadway speed limit. For this study, LOS A and B, which are "primarily free-flow" and "reasonably unimpeded" operations, respectively, were used to establish the speed thresholds listed in Table 1 [TRB 2016]. The speed thresholds were taken from the Highway Capacity Manual (HCM) Exhibit 16-3, which describes the thresholds for different LOS for motorized vehicles on urban street facilities, which generally include urban arterial and collectors [TRB 2016]. To attempt to capture free-flow traffic speeds, the average observed speeds of opposite direction vehicles was taken over each lane segment to determine an approximate level of service (LOS) of that lane segment. If the average speed of other vehicles on that lane segment was above the threshold listed in Table 1, all objects on that lane segment were included in this dataset of free-flow conditions. The average speed of other vehicles was aggregated for each time the ADS-equipped vehicle traveled on each lane segment, where all segments originate/terminate at an intersection.

The Discretized Exponential Model

To estimate the potential safety benefits from reduced travel speeds associated with a speed limit compliant vehicle fleet, the model of the effect of speed reduction on fatal and injury crashes described in Elvik (2019) was applied. The exponential model of the relationship between mean travel speeds and relative crash risk states that the relative rate of collision (λ) can be described as

$$\lambda = e^{(\beta*(\mu'-\mu))} \text{ (Equation 1)}$$

where β is a coefficient fit to data at a given crash outcome level (e.g., fatal, serious injury, or slight injury), μ' is the mean travel speed on a roadway after some traffic treatment, and μ is the original mean travel speed on a roadway prior to the traffic treatment. Elvik et al., 2019 provided empirical exponential model coefficients based on crash data for fatal (β=0.08), serious (β=0.06), and slight (β=0.04) injuries. For example, if a treatment decreases the road speed by 5 kph, the relative fatal crash rate would be 0.67 (i.e., a 33% reduction in fatal crashes) based on the exponential model coefficient (β=0.08) as defined in Elvik et al., 2019.

The model developed in Elvik (2019) extends the exponential model presented in Equation 1 to compute an overall reduction in collisions by discretizing the normal distribution of speed observations into 12 intervals between ±3 standard deviations from the mean (μ), with a width of 0.5 standard deviations (σ) for each interval. Thus, the area under the probability density function of speed observations between any two points (i.e., the cumulative distribution function) can be interpreted as the probability of observing a speed value within that interval (e.g., approximately 68% of all speed observations are expected to be within ±1 standard deviation of the mean for a normal distribution). This can be simplified by translating to the standard normal distribution as follows:

$$z = (x - \mu)/\sigma \text{ (Equation 2)}$$

where x represents the desired comparison value and z is the standard score, which represents how many standard deviations from the mean the comparison value is. By way of example, the probability (P) of a speed observation being between 0.5 and 1 standard deviations above the mean is approximately 15% and can be represented as

$$P(0.5<z<1) = \Phi(1) - \Phi(0.5) \text{ (Equation 3)}$$

where Φ represents the cumulative distribution function of the standard normal distribution.

Equation 1 can then be used to compute the relative crash risk (λ_i) for each speed interval (*i*) as follows:

$$\lambda_i = e^{(\beta*(u_i-\mu))} \text{ (Equation 4)}$$

where u_i is the mean speed within a given interval, and β and μ have the same definition as in Equation 1. So instead of having a single estimate for relative crash risk based on the mean, there are 12 individual components based on the discretization of the speed distribution. The contribution of a given speed interval (*i*) to the overall crash risk (C) may then be expressed as

$$C_i = P_i * \lambda_i \text{ (Equation 5)}$$

Prime notation (u_i', λ_i', C_i') may be used to denote post-treatment crash risk. Summing each of these weighted contributions then reflects the total effect on crash risk. The aggregate effect of the speed treatment on the relative crash rate may then be expressed as

$$\lambda = (\sum C_i')/(\sum C_i) \text{ (Equation 6)}$$

In the case where the mean speed is reduced by a treatment and the standard deviation is unchanged, the relative crash proportion using the method from Elvik (2019) in Equation 6 is equivalent to the standard exponential model described in Equation 1. The advantage of the discretized exponential method from Elvik (2019) over the traditional exponential model is that changes to speed that affect the speed distribution asymmetrically can be evaluated. For example, Elvik (2019) examines hypothetical treatments where the mean is unchanged but variance is reduced or when the proportion of the population in the highest intervals are redistributed to near the mean speed (e.g., due to speed enforcement). In these examples, the traditional exponential model would state there is no change in relative crash rate in the former (because the mean is unchanged) and may overpredict relative crash rate in the latter.

Potential Safety Benefits due to Reduced Travel Speeds

This discretized exponential model described in Elvik (2019) was applied to study potential changes in crash risk due to a speed limit compliant vehicle fleet rather than the current human driver fleet. While human drivers have a free-flow speed distribution that is normally distributed, speed limit compliant vehicles have a left-skewed speed distribution that is truncated near the speed limit of the road. For the purposes of the Elvik model, the current human driver speed distribution represents the original speed distribution while the ADS-equipped vehicle speed distribution represents the treatment distribution, serving as a proxy for the condition where all vehicles comply with roadway speed limits.

The mean and standard deviation of the observed speeds of opposite direction vehicles were used to compute the lower and upper limits of the intervals between -3 and 3 standard deviations with widths of 0.5 standard deviations. Because the "before treatment" speed distribution was an observational sample of human speed distributions, the data may not exactly meet a normal distribution. Therefore, the area under the normal curve described in Equation 3 may not match the observed percentage of observations falling within the interval. Using Equation 3 to estimate (P) in this experimental setup and computing a relative crash proportion will result in an effect from both the shift in distribution associated with speed limit compliance as well as the difference between the original human speed distribution and a normal approximation of the distribution. As a result, instead of computing P using Equation 3, P was estimated as the proportion of the sampled human speed distribution. The speed limit compliant vehicle fleet travel speeds (ADS vehicles traveling on the same road segments) were used as the "after treatment" distribution. The percent of this sample falling in intervals of the original human observed speed was calculated as P'.

The reduction in the fatality rate estimated by the discretized exponential model may then be used in conjunction with observed fatality counts to estimate the number of lives saved through speed limit compliance. Observed fatality counts for the Phoenix metro area and San Francisco were estimated using NHTSA's Fatality Analysis Reporting System (FARS), a nationwide census regarding fatal injuries suffered in motor vehicle crashes annually (inclusive of vulnerable road users). The FARS database was queried for persons who sustained fatal injuries in traffic collisions that occurred on roadways with speed limits of 25, 30, 35, or 45 mph in Maricopa County (Phoenix metro) and 25 or 30 mph in San Francisco County. Analysis was limited to the most recent two years (2021 and 2022), with the results averaged across years to produce an estimate for annual fatalities.

In an effort to normalize the injury and fatality counts, data from the Highway Performance Monitoring System (HPMS) from 2022 were leveraged to report estimates of annual vehicle miles traveled (VMT) for Maricopa County (Arizona) and the city of San Francisco, bucketed by roadway speed limit. Overseen by the Federal Highway Administration, HPMS is compiled, processed, and verified by a cooperation of local, state, and federal agencies. For both geographic areas, the default speed limit for roadways if there is no posted speed limit is 25 mph. Accordingly, instances in the HPMS data of roadways with 0 mph speed limits were set to 25 mph. Using the event count data from FARS in conjunction with the mileage data allows for rates estimation of fatalities. HPMS data may not reliably collect local road information, so mileage and fatalities from these roadways were excluded from rates-based analysis.

RESULTS

Observed Speeds

Figure 2 shows the distribution of observed travel speeds for vehicles traveling in the opposite direction and the speed limit-compliant fleet by posted speed limit and location. On average, the speed limit-compliant fleet traveled at lower speeds than human-driven vehicles, with a higher concentration of speed observations at or near the speed limit (Figure 2, Table 2). During this period, the ADS-equipped vehicle fleet traveled more often in the Phoenix metro area than in San Francisco, so there are accordingly more observations there (Table 2). These observations represent vehicle average speed on a given roadway segment, which is consistent with previous research in this area [Vadeby, 2023].

Crash Risk Reduction due to Lower Travel Speeds

Table 3 shows an example analysis for the reduction in fatal crashes using the discretized exponential model of Elvik (2019) for 30 mph speed limit roads in San Francisco. The relative fatality rate is computed using Equation 4 with a coefficient of 0.08 [Elvik et al., 2019]. Note that the speed values in Table 3 are presented in miles per hour (mph), and were converted to kilometers per hour (kph) for use in Equation 4 with coefficients presented in Elvik et al.

(2019). As was observed in Figure 2, there is reduction in fatal crash risk due to less probability mass above the speed limit in the intervals from 0.5 to 3.0 standard deviations and below the speed limit in the intervals -3.0 to -1.0 standard deviations. This reduction in risk is counterbalanced by an increase in contribution to the fatal crash risk near the mean in the intervals between -0.5 and 0.5 standard deviations. Summing the original fatality contribution and new fatality contribution columns individually as outlined in Equation 6 yields the aggregate effect of speed limit compliance on fatalities. Overall, this analysis shows a potential 34.1% reduction in the number of fatal crashes if roadway speed limits were complied with. Using a coefficient of 0.06 for serious injury collisions and 0.04 for slight injury collisions, the potential reduction was 23.4% and 13.8%, respectively [Elvik, 2019]. These smaller safety benefits for lower severity injuries are anticipated, given that changes in speed would be less likely to have an effect on injuries which can occur at lower speeds.

This analysis was similarly completed for other speed limit roadways in Phoenix and San Francisco. Given the higher mean speeds and standard deviations observed in Phoenix (Table 2), there is greater potential for injury and fatality reduction there relative to San Francisco were the current human driving fleet to become compliant with roadway speed limits (Figure 3). The effect is largest for 30 mph roadways in both Phoenix and San Francisco. On these roadways, other agents were observed to be traveling above the speed limit approximately 38% of the time in San Francisco and approximately 49% in Phoenix, with more than 12% traveling 5 mph above the speed limit in San Francisco and more than 23% traveling 5 mph above the speed limit in Phoenix. Speeding was reported as a factor in FARS for 36% of fatal collisions in San Francisco and 28% of Phoenix metro area fatal collisions.

Estimating Aggregate Reductions in Traffic Fatalities

With the aggregate fatality and injury reduction associated with speed limit compliance computed, real-world data can be leveraged to estimate the magnitude of this effect. While San Francisco has fewer fatalities than the Phoenix metro area, the fatality rate is actually higher given the lower driving mileage (Table 4). Across the roadway speed limits in the locations considered in this study, complying with the roadway speed limit over the current driving population was estimated to result in approximately 82 lives saved annually. After removing fatal collisions (3.1% of collisions) and mileage (11.6% of miles) from local roadways, the overall reduced fatality rate, computed based on weighting the individual roadway speed limit bin fatality rates by the annual vehicles mile traveled, for the Phoenix metro area was 0.0117 per million miles; while in San Francisco, it was 0.0154 per million miles. These represent reductions of 0.0051 and 0.0061 fatalities per million miles in Phoenix and San Francisco, respectively. In other words, complying with the roadway speed limit on these roadways in the Phoenix metro area and San Francisco would be expected to save one life for every 196 million miles of driving and 164 million miles of driving, respectively.

As an additional demonstration, the driving mix of the speed compliant vehicle fleet (ADS observations in Table 2) could be used in conjunction with the known human driving fatality rates (0.0168 fatalities per million miles in Phoenix and 0.0215 in San Francisco) and the reported driving mileage of the Waymo service through the end of

September 2024 (20.823 million miles in the Phoenix metro area and 10.209 million miles in San Francisco) to estimate expected fatality observations [Waymo 2024]. Aggregating these data results in an expected fatalities count of 0.58 over the 31 million miles of driving. Put another way, a single traffic fatality would be expected to occur after 53.7 million miles of driving for human drivers driving the same mix of roadways in the Phoenix metro area and San Francisco as Waymo. This simplified approach is merely meant to demonstrate potential calculations available via this methodology and does not take into account 1) any changes in Waymo driving mix over the course of its service; 2) any miles on other, higher speed roadways (i.e., all mileage is mapped to those speed limit bins in Table 2); and 3) changes in the fatal crash involvement due to factors other than modeled by the exponential model due to speed limit compliance. As additional data become available (e.g., high speed roadways, other geographic areas, or ADS services), this same methodology may be employed to estimate safety benefits due to speed limit compliance.

DISCUSSION

This study leveraged vehicle speed distribution data as measured by a fleet of autonomous ride-hailing vehicles in conjunction with the most current relationships between vehicle speed distributions and aggregate traffic fatalities and injuries to estimate the potential safety benefits associated with ADS-equipped vehicles and their compliance with roadway speed limits. Aggregate vehicle fleet compliance with roadway speed limits on surface streets in San Francisco and the Phoenix metro area was estimated to result in saving 82 lives annually. This would represent a 30% reduction for fatalities on these lower speed roadways in these areas and highlights the impact of speed limit compliance on fatality prevention for all road users, particularly for VRUs who represent the majority of fatalities in these two urban areas and many others around the U.S.

Comparison to Previous Work

The data used by Elvik (2019) to illustrate his framework for speed-based reductions in collisions and fatalities was taken from studies performed in Australia in the late 1990s investigating the effect of traffic speed on collision outcomes [Kloeden et al., 1997, 2001]. Using a relative risk-based approach, they estimated fatality reductions of approximately 46% for collisions on urban roadways with 60 kph speed limits and approximately 29% on rural roadways with speed limits up to 110 kph associated with all speeding vehicles having their travel speed reduced to the roadway speed limit [Kloeden et al., 1997, 2001]. In Elvik (2019), various analyses associated with different reductions in travel speed using the Kloeden et al. (2001) data were carried out and showed results consistent with the initial analysis, though using the updated exponential model. An overall leftward shift in the speed distribution was associated with the largest reduction in fatalities while compressing the upper end of the speed distribution had the next largest impact. As presented here, the increased concentration of the speed distribution toward the speed limit associated with a speed limit compliant vehicle fleet would reflect both of these changes in part, while also decreasing the variance of the speed distribution. As shown in Table 3, there is an increase in fatalities associated with an increase in speed among the lower speed data; this increase is offset though by decreases in speeding behavior over the roadway speed limit. Given that the higher speed data contributes more to fatal outcomes, the net benefit is intuitively positive (i.e., fatality reduction) for increased roadway speed limit compliance.

In a similar analysis to that presented here, researchers at VTI investigated the effect of geo-fence-based speed limiting on travel speeds [Nygårdhs et al., 2023]. As was reported here, the speed distribution shifts closer toward the speed limit with increasing penetration of speed limit-compliant vehicles. Statistically-significant reductions in 85th percentile speed were estimated for penetration rates as low as 10%, though achieving a 85th percentile close to the speed limit were associated with greater than 70% vehicle fleet penetration. They also noted that a higher penetration rate was needed for lower speed roadways than higher speed roadways, consistent with one of the underlying assumptions of Elvik's framework: that higher speeds are associated with higher collision, and thus injury and fatality, risk [Elvik, 2019; Aarts and Van Schagen, 2006]. Higher speed roadways were represented in approximately 52% of fatal collisions in the Phoenix metro area and San Francisco in FARS. These were not included in the present study (40 mph and 50+ mph speed limit roadways). Thus, the safety benefits analysis presented herein undercounts the total potential for speed compliance benefits across all roadways in these geos.

Using the same exponential model employed in this study, Vadeby (2023) estimated the number of lives that could be saved in Sweden through compliance with roadway speed limits. This was achieved by assuming that all vehicles traveling above the speed limit would travel at the roadway speed limit, with no changes to the speed behavior for vehicles already complying with roadway speed limits. This approach resulted in an estimated 51 lives saved annually, a 20% reduction in the total number of traffic fatalities in Sweden. The difference in reduction percentage from the present study can be attributed to methodological differences: Vadeby (2023) used the change in mean speed only to estimate the effect while the present study used changes across the entire speed distribution. Vadeby (2023) concluded that the largest effect was observed on higher speed (70-90 kph) rural roadways. This work highlights the importance of speed on fatal traffic outcomes.

Speed Effects

The results from the present study highlight the potential safety benefits associated with reductions in speed associated with speed limit compliance. These results were presented at the aggregate level. As an extension of this, it is important to consider the extent to which travel speeds are presently affected by roadway speed limits and public perception, as well as the effect speeding has on injury risk on an event level.

Effect of Speed Limit Changes: Changes to roadway speed limits have long been associated with changes in observed vehicle travel speeds, as well as collision injury and fatalities. Following the national repeal in 1995 of a national speed limit maximum, U.S. states began to raise maximum speed limits for various roadways. By way of example, in the year following a speed limit change from 55 mph to 70 mph on three urban freeways in Texas, approximately 50% of passenger vehicles were traveling over 70 mph, compared to only 15% the year prior [Retting and Greene, 1997]. As it relates to traffic fatalities, a study completed by the Insurance Institute for Highway Safety investigated the effect of a 5 mph increase in a state's maximum speed limit over a 15-year period (1993-2017) and observed an 8% increase in fatality rate on interstates and freeways and a 3% increase on all other roadways [Farmer, 2019]. Further, several studies investigating speed limit change effects have noted that the 85th percentile speed, a metric often used by traffic engineers in setting speed limits, increases with an increase in roadway speed limit. In other words, the increased speed limit results in a new, and often higher, prevailing roadway speed [Najjar et al., 2000; Retting and Greene, 1997; Retting and Teoh, 2008]. This phenomenon was observed in this data sample as well, where the 85th percentile speeds for other vehicles exceeded the roadway speed limit by an average of 5.1 mph.

Driver Attitudes on Speeding: As observed in this study, between 10% and 23% of human drivers traveled more than 5 mph over the speed limit across all surface streets considered in this analysis, with 2% to 8% traveling more than 10 mph over the speed limit. According to the most recent information from 2022 from the American Automobile Association (AAA) as part of their annual Traffic Safety Culture Index survey, nearly half of respondents reported driving more than 15 mph over the speed limit on a freeway within the last 30 days, and approximately 35% reported driving more than 10 mph over the speed limit on a residential street within the last 30 days [AAA Foundation for Traffic Safety, 2023]. It is noteworthy to consider this in conjunction with the fact that only 61% of respondents perceived traveling 10 mph over the speed limit on residential streets as very or extremely dangerous [AAA Foundation for Traffic Safety, 2023].

Effect of Speeding on Injury Risk: In light of these observations, let us consider three scenarios to illustrate the effect of speeding on serious injury risk (Maximum Abbreviated Injury Scale score of 3 or higher [MAIS3+]): 1) a head-on collision between two passenger vehicles on a two-way, undivided residential street, 2) a frontal collision between a passenger vehicle and a pedestrian, and 3) a frontal collision between a passenger vehicle and a bicyclist, all occurring on roadways with a speed limit of 30 mph (48 kph). With both vehicles traveling at the speed limit, the serious injury risk (MAIS3+) associated with this collision is 9%. If one of these vehicles is traveling 10 mph (16 kph) over the speed limit, the closing speed has increased by 17% but risk has more than doubled, up to 18%. If both vehicles were traveling 10 mph (16 kph) over the speed limit at the time of collision, the 33% increase in closing speed results in a nearly four-fold increase in risk relative to the baseline collision, 32% risk of injury at the MAIS3+ severity level [McMurry et al., 2021]. Given their lack of protection, vulnerable road users are at even higher risk of serious injury in the event of collision with a speeding vehicle. A pedestrian struck by a vehicle traveling at 40 mph (64 kph) on a 30-mph roadway faces a 45% risk of serious injury, compared to 22% when struck by a vehicle following the roadway speed limit [Schubert et al., 2023]. Similarly, a cyclist faces a 22% risk of serious injury, compared to 9%, in the same impact conditions [Schubert et al., 2024]. These disproportionate increases in injury risk for speed increases associated with noncompliance with roadway speed limits additionally highlight the potential for speed limit compliance to reduce injury outcomes. Compliance with roadway speed limits, which serves to reduce the total energy available in the event a collision occurs, represents a key way to contribute to a Safe System and mitigate the potential for serious and fatal injury outcomes. As outlined in the introduction, speed limit compliance may be achieved in a myriad of ways, including new technologies, law enforcement, and roadway infrastructure changes.

Limitations

There are several limitations to note regarding this study. Firstly, there is measurement error associated with the estimated speeds for opposing travel in this study. Average error within the range investigated in this study was observed to be quite low, with 90th percentile error of less than 1.0 mph. Additionally, the speed-limit-compliant vehicle fleet does not follow a normal distribution, as outlined in the Elvik framework, and it is not apparent what the exact distribution for a speed limit-compliant fleet may look like; nonetheless, previous research [Elvik 2019; Vadeby 2023] modeled a similar effect as that employed in this study. Furthermore, the low speed tail in the driving distribution contributes little to the aggregate fatality rate, so the effect of modeling the speed limit-compliant fleet as was done in the present study is not anticipated to affect the fatality reduction estimates considerably. It should also be noted that the potential safety benefit analysis did not consider event-specific context and evaluated the aggregate effect of speed limit compliance on injury and fatality reduction. This study assumed static speed limits, and there exists the potential for discrepancies in both the HPMS and ADS-equipped vehicle mileage due to speed limit changes. Lastly, it should be noted that the speed sample in this study was one of convenience from two days of driving. Seasonal variability in driving mix/mileage, as well as the data sample used and potential variation due to weather, may have an effect on the results of this analysis. That being said, the observed speed distributions reported in this study are consistent with previous observations within slightly different geographic zones from a prior year and time of year [Waymo 2023].

Conclusions

Safer Speeds represents one part of the Vision Zero and Safe System Approach that may be employed to eliminate traffic fatalities and serious injuries. Using novel data from an ADS-equipped vehicle fleet to estimate the travel speed distribution of both the current human driven and a speed limit compliant fleet, in conjunction with the Elvik speed framework, the results from this study indicate the potential for saving 82 lives annually on surface streets in San Francisco (7 lives) and the Phoenix metro area (75 lives) simply through compliance with roadway speed limits. The disproportionate relationship between increased speed and increases in injury risk highlights the tremendous opportunity to reduce serious and fatal outcomes through speed limit compliance.

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TABLES AND FIGURES

Table 1. Average lane segment speed thresholds used to determine high level of service (HLOS)

Speed Limit (mph)	Average Lane Segment Speed Threshold (mph)
25	17
30	20
35	23
45	30

Table 2. Mean and standard deviation of observed vehicle free-flow travel speeds

Location	Speed Limit (mph)	Vehicle Type	Vehicle Speed Observations	Mean Speed (mph)	Standard Deviation (mph)
Phoenix Metro	25	Human-driven	18,934	23.4	5.8
		ADS	128, 320	22.2	2.6
	30	Human-driven	27,656	29.9	7.1
		ADS	80,181	27.6	2.8
	35	Human-driven	216,736	34.2	7.3
		ADS	435,799	33.0	3.2
	45	Human-driven	154,686	41.9	7.3
		ADS	317,117	42.1	4.0
San Francisco	25	Human-driven	28,771	22.9	5.5
		ADS	589,963	22.1	2.5
	30	Human-driven	7,826	28.1	6.0
		ADS	84,457	26.6	2.9

Table 3. Example fatal crash reduction analysis for speed limit compliant vehicle fleet for 30 mph roads in San Francisco

Interval (standard deviations)	Mean Speed (mph)	Original Distribution Share	New Share	Relative Fatality Rate	Original Fatality Contribution	New Fatality Contribution	Contribution Reduction
2.5 to 3.0	44.8	0.9%	0.0%	8.506	0.073	0.0	0.073
2.0 to 2.5	41.7	1.5%	0.0%	5.764	0.086	0.0	0.086
1.5 to 2.0	38.7	3.6%	0.0%	3.905	0.141	0.0	0.141
1.0 to 1.5	35.7	7.6%	0.0%	2.646	0.200	0.0	0.200
0.5 to 1.0	32.7	13.3%	0.0%	1.793	0.239	0.0	0.239
0.0 to 0.5	29.6	19.3%	34.9%	1.215	0.234	0.425	-0.190
-0.5 to 0.0	26.6	20.8%	32.4%	0.823	0.171	0.266	-0.095
-1.0 to -0.5	23.6	17.3%	20.6%	0.558	0.096	0.115	-0.019
-1.5 to -1.0	20.6	10.6%	12.1%	0.378	0.040	0.046	-0.005
-2.0 to -1.5	17.5	3.3%	0.0%	0.256	0.008	0.0	0.008
-2.5 to -2.0	14.5	0.9%	0.0%	0.174	0.002	0.0	0.002
-3.0 to -2.5	11.5	1.0%	0.0%	0.118	0.001	0.0	0.001

Table 4. Estimated aggregate reduction in traffic fatalities

Location	Speed Limit (mph)	Observed Fatal Collisions (2-year average)	Annual VMT (Mmi)	Fatality Reduction	Lives Saved
Phoenix Metro	25	29.5	2,956	32%	9.3
	30	7.5	1,206	43%	3.2
	35	53.5	2,890	34%	18.3
	45	156	9,319	29%	44.5
San Francisco	25	22	944	28%	6.1
	30	2.5	95	34%	0.9

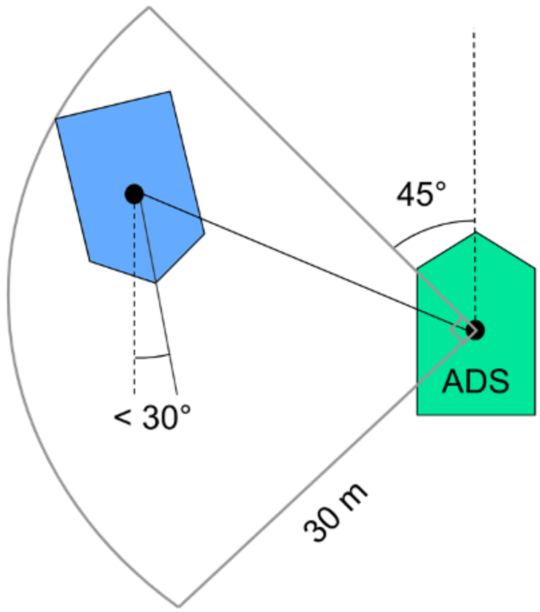

Figure 1. Relative distance and heading requirements for other vehicles traveling in the opposite direction

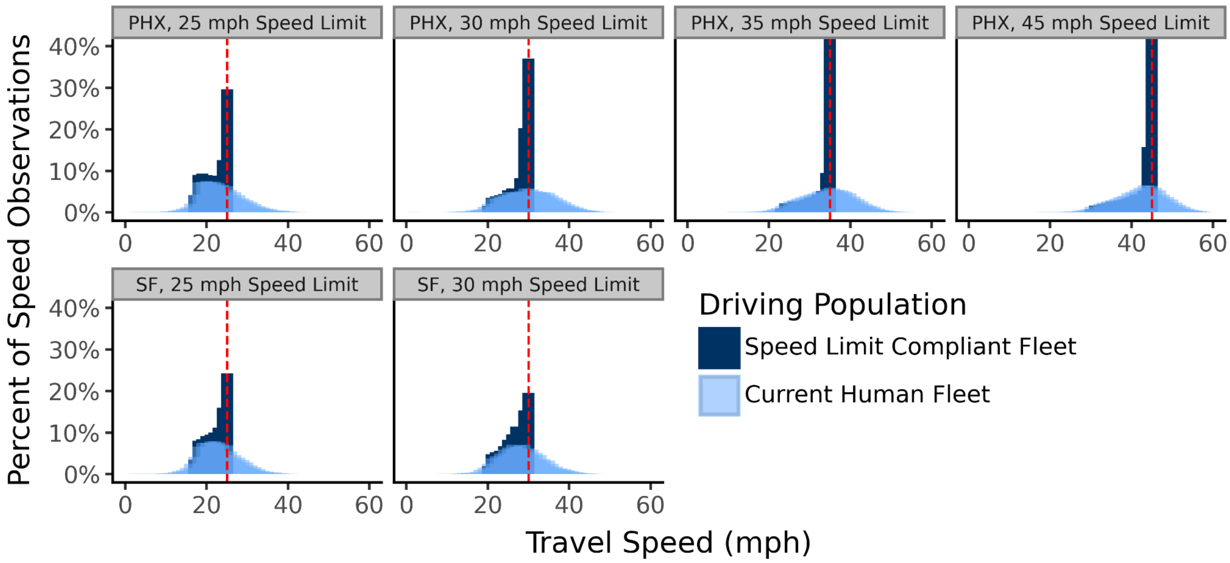

Figure 2. Distribution of vehicle travel speeds by speed limit and location, Vertical dashed lines represent the roadway speed limit. Percentage of observations for speed limit compliant fleet exceeds 40% at speed limit for 35 mph and 45 mph roadways in Phoenix metro area.

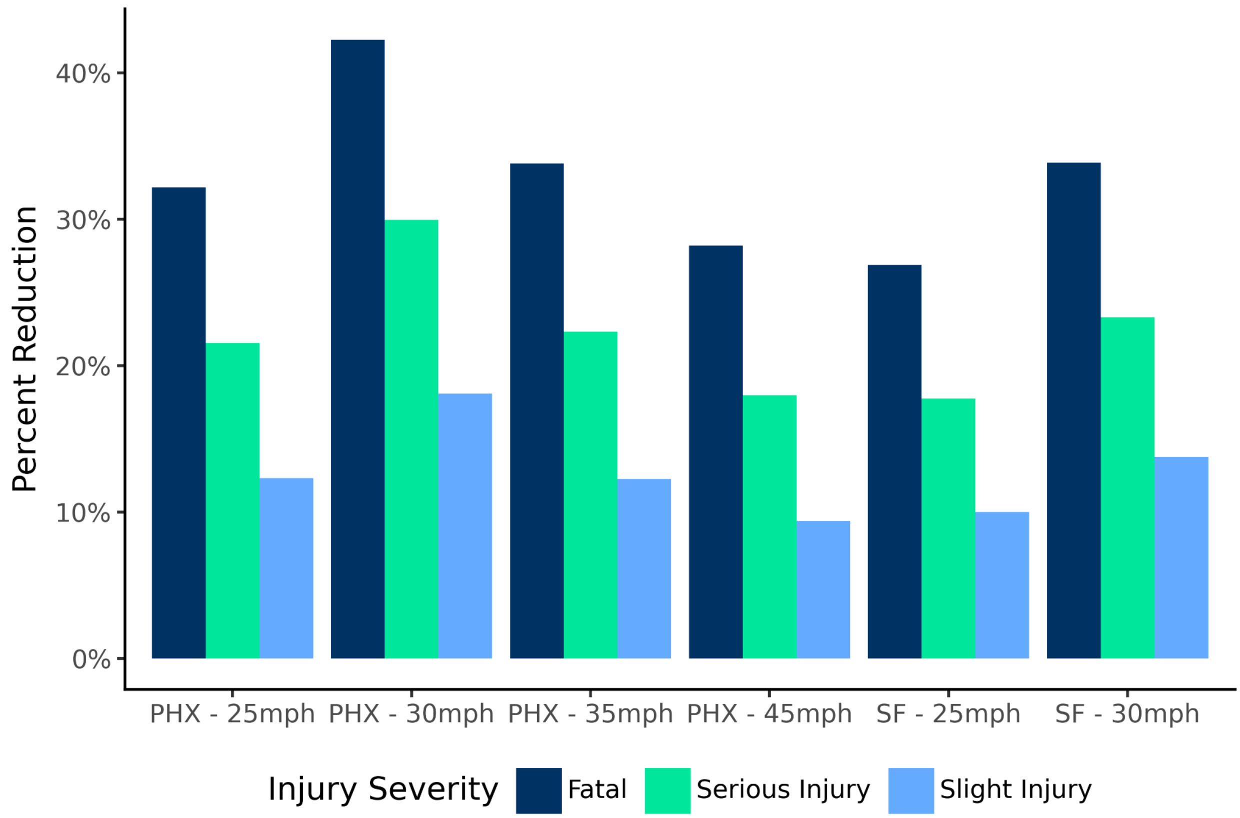

Figure 3. Potential reduction of fatal, serious injury, and slight injury crashes with a speed limit-compliant fleet for Phoenix and San Francisco by road speed limit.