AI AT THE WHEEL:
THE EFFECTIVENESS OF AUTONOMOUS VEHICLE
LEVEL 1 SAFETY FEATURES

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Abstract. Automakers' recent introduction of safety technologies based on artificial intelligence raise longstanding questions of whether they improve safety and whether the government should mandate their adoption in all new vehicles. We address those issues using a trim-level dataset of automobiles, which appears to be the first of its kind. We find that the safety technologies reduce the accident rate by 20-30% and the probability of a fatal accident roughly 75%. Notwithstanding those considerable benefits, we discourage government's intervention to mandate the safety technologies for new vehicles without a better understanding of the market forces that have contributed to their adoption.

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1. Introduction

The automobile industry has long been criticized for paying inadequate attention to motorists' safety and for complaining that safety does not sell. However, since Ford Motor Company mass produced the Model T more than a century ago, the automobile industry also has made significant safety improvements, including the introduction of automatic windshield wipers, shatterproof glass, headlights, improved braking, advances in body structure, collapsible steering columns, and occupant safety devices.

Government policies also have sought to improve automobile safety by requiring motorists to have a valid driver's license, prohibiting driving under the influence of alcohol or drugs, setting and enforcing speed limits, and requiring vehicles to satisfy National Highway Traffic Safety Administration (NHTSA) safety standards. In some cases, federal regulators have mandated that certain new safety improvements be installed in all new vehicles, such as collapsible steering columns, seat belts, and dual front seat airbags, while states have passed mandatory seat belt use laws.[1]

A long line of research, however, has questioned both the justification for and effectiveness of government automobile safety policies because market forces may be efficiently promoting safety and because drivers may adjust their behavior when a new safety technology is installed in their vehicle. For example, Thaler and Rosen (1976) and Mannering and Winston (1987) found that although federal law in 1968 required seat belts to be installed in all vehicles except buses, many motorists eschewed the safety benefits of seat belts based on a rational cost-benefit assessment of the time and bother costs to fasten seat belts and their effect on reducing the probability of a fatal accident. Lave and Weber (1970), Peltzman (1975), and Wilde (1976) argued that even when seat belts were used, motorists reduced their technological effectiveness by driving faster to reduce travel time, thereby maintaining their exposure to accident risk. Winston, Maheshri, and Mannering (2006) found that motorists' increase in risky driving behavior appeared to offset the initial effectiveness of airbags, which were mandated in 1998.

Recently, automakers have introduced safety technologies based on artificial intelligence that are a critical step towards fully autonomous vehicles. As discussed in Winston and Karpilow (2020), the Society of Automotive Engineers has created a widely accepted scale of vehicle autonomy ranging from level 0 (no autonomy) to level 5 (fully automated operations with cars not

[1] Government highway expenditures also have been used to improve the safety of the road system.

equipped with a steering wheel or pedals because they can perform the entire trip without human input). Beginning with level 1, hereafter L1, known as driver assistance, automakers are gradually installing autonomous safety features in vehicles with higher levels of trim.[2] For our purposes, we define a suite of L1 safety features as those that assist in both the forward dimension (e.g., automatic emergency braking or adaptive cruise control), and the lateral dimension (e.g., lane departure warning or blind spot collision prevention).[3]

As shown in figure 1, automakers have steadily introduced a suite of L1 safety features in more vehicles beginning in the late 2000s. Those features were standard for some vehicle makes and models, optional for other makes and models, and unavailable for the remaining makes and models. L1 safety features distinguish themselves from other automobile safety features because they assist the driver by making their own decisions in response to safety threats in real highway travel settings, such as automatically braking to avoid a collision. Hence, those features afford a greater degree of substitutability for driver attention than other safety features do. In addition, unlike safety features such as seat belts and airbags, which required government intervention before they were installed in all vehicles and were used by most motorists, L1 safety features have thus far been voluntarily installed in vehicles by automakers and selected by motorists through their choice of vehicle.

The recent adoption of L1 safety features motivates our interest here in assessing whether they are effective at reducing accident risk in practice—that is, after accounting for all behavioral responses of drivers to the installation of those features in their vehicles. Our assessment is further motivated by NHTSA's apparent dissatisfaction with the progress of motorists' adoption of L1 safety features in their vehicle choices. In a 2023 announcement, NHTSA proposed requiring all new passenger cars and light trucks to be equipped with automatic emergency braking systems, an important component of L1 safety features, with the requirement going into effect three years after the rule is adopted.[4] It is therefore also of interest to shed light on whether NHTSA's proposed requirement is justified.

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[2] A vehicle's trim includes powertrain options, aesthetic features, and comfort amenities as well as safety technology.

[3] According to the National Highway Traffic Safety Administration (NHTSA), a vehicle has level 1 driver assistance if it has systems that can perform either steering or acceleration/braking. In other words, driver input is necessary for at least one dimension of travel at any time. Our definition is consistent with NHTSA's definition in this regard. https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

[4] Under the proposed rule, all new vehicles would be required to have a version of automatic emergency braking that is "much more effective at much higher speeds." Specifically, all cars would need to be able to stop and avoid contact with a vehicle in front of them when traveling up to 62mph. Additionally, vehicles traveling as fast as 37mph would

We conduct a causal assessment of the effectiveness of L1 safety features in reducing the probabilities of motorists being involved in all types of accidents, which improves upon previous work by exploiting a novel source of plausibly exogenous variation in the availability of L1 safety features that allows us to address several endogeneity issues that are inherent to assessing the technological performance of vehicle safety features. We do so by constructing a novel panel dataset of the accident histories of a large, representative sample of roughly 800,000 vehicles whose owners lived in the seventeen largest counties in Texas from 2000 to 2019. Importantly, we classify vehicles at the model year-make-model-trim level, which enables us, to the best of our knowledge, to be the first to conduct an analysis of automobile safety using a trim-level dataset. By combining the panel of vehicle accident histories with detailed information about the safety features of specific vehicles from auto manufacturers, we leverage for identification the fact that L1 safety features became available at different times for different trim levels (even within vehicles of the same make and model).[5]

We find that even after accounting for drivers' behavioral responses, L1 safety features are highly effective at improving automobile safety as they reduce the rate of all accidents by 20-30% and the probability of a fatal accident roughly 75%. The efficacy of L1 safety features is greater than the efficacy of other safety features, such as seat belts and air bags, which cannot prevent a driver from getting into an accident. Accordingly, L1 safety features are notably more effective than seatbelts and airbags in reducing the probability of a motorist being involved in a fatal accident.[6]

Given the efficacy of L1 safety features and the fact that the federal government has mandated the installation of seat belts and air bags in all vehicles after they were introduced, it is natural to ask whether the federal government should mandate the installation of L1 safety features in all vehicles to further reduce the private and social costs of accidents. We caution against such a policy until more evidence becomes available that can refute the circumstantial evidence that we present, including that motorists are informed about L1 safety features' benefits given that, on average, they appear to be willing to pay for their significant installation costs, access to

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need to come to a complete stop to avoid hitting pedestrians and the braking systems also would be required to detect pedestrians and cyclists at night.

[5] Wåhlberg and Dorn (2023) assess the effectiveness of vehicle electronic stability control (ESC) on fatal crash rates, but they do not compare cars' safety performance with and without ESC.

[6] See https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811882.pdf and https://injuryfacts.nsc.org/motor-vehicle/occupant-protection/seat-belts

autonomous safety features is equitable and not affected by supply-side distortions, and the external benefits of mandating L1 safety features in all cars are unlikely to significantly increase the overall benefits of L1 safety features, while such a mandate would create a sizable welfare cost to motorists who are forced to bear an installation cost of L1 safety features that exceeds their private valuation of those safety features' benefits.

2. Estimating the Efficacy of L1 Safety Features

The staggered rollout of the availability of L1 autonomous safety features over time and across different automobile makes, models and trims generates temporal and cross-sectional variation in registered vehicles' safety features that enables us to identify the causal effect of L1 safety features on accident risk. In most safety analyses, a vehicle type in a given model year, which we index by i, is defined as a combination of make and model. However, within a make-model combination in our analysis, some vehicles (for example, luxury editions) may have L1 safety features and others (for example, standard editions) may not. We therefore expand the definition of vehicle type as a combination of make, model and trim, where trim levels are indexed separately by j as defined in the data section.

Crucial to our analysis is that the availability of L1 safety features for a given vehicle make and model may vary over time because L1 safety features are not available in earlier model years of some vehicles, but they are available in later model years. At the same time, some vehicle makes and models may never have L1 safety features available during our sample period. Let y index the model year of a given vehicle type. Note the model year for vehicles manufactured up to June 2022 will be 2022, but the model year for any of the vehicles in our sample manufactured from July through December in each year (for example, 2015) can be advertised as the next model year (for example, 2016). Thus, our treatment, the availability of L1 safety features, denoted by the dummy variable S_{yij}, varies at the model year, make-model, and trim level.

For each vehicle in each calendar year of our sample, we observe the vehicle's model year, type (make-model), whether it was involved in an accident, and if so, the accident severity (ranging from property damage only to a fatal accident). Let t, the calendar year, which will generally differ from the model year, index a specific year in a vehicle's accident history. Because we are interested in the effect of a treatment that occurs at the vehicle level, we aggregate accident outcomes to the model year-type-calendar year level. Let A_{yijt} denote the total number of accidents of a given type that vehicles yij had in year t. Alternatively, we can let A_{yijt} denote the accident rate (i.e., the total number of accidents of a given type that vehicles yij had in year t per total vehicle miles travelled by all vehicles yij in year t).

Our panel is distinctive because it contains two different temporal dimensions, model year y and calendar year t. Although the outcome varies over the calendar year dimension, the treatment varies only over the model year dimension y—older models of a vehicle type that were untreated remain untreated even if newer models of that type are treated. Hence, a different treatment variable may be observed at a given $t \geq y$. We exploit the variation in the treatment variable across trim levels, model years and calendar years to identify the causal effect of L1 safety features on accidents. Operationally, we use the calendar year as our main temporal dimension, and we identify the treatment effect using calendar year and make-model-model year fixed effects.[7]

In table 1, we illustrate the organization of our data for a single vehicle type, the Acura MDX, using the calendar year as the primary temporal dimension for the sample period of 2000 to 2019. This vehicle has three trim levels that we denote as Low (L), Medium (M), and High (H), each characterizing the period that they were equipped with L1 safety attributes. Vehicles with a low trim level were never equipped with L1 safety features during our sample period; vehicles with a medium trim level were equipped with L1 safety features in model year 2018 but not before that calendar year; and vehicles with a high trim level were equipped with L1 safety features in 2015 but not before that calendar year. The three different trim levels of Acura MDX's on the road during our sample period enable us to define our treated vehicles as Acura MDX's of high (and/or medium) trim levels that include L1 safety features. Our untreated or control vehicles are Acura MDX's that did not include L1 safety features.[8]

[7] One might intuit that a difference-in-differences (DID) estimator is appropriate for our analysis. However, note that our data structure is not consistent with a difference-in-differences design because the untreated vehicles remain untreated even after vehicles of a similar trim level are treated. Using the example shown below in table 1, when the H trim level is treated in 2015, all H vehicles on the road are not treated, only those from model year 2015 and future model years are treated. Generally, treatment in a DID design would be consistent within the ijt dimension, while the treatment in our data structure is not consistent in that dimension.

[8] Because our estimates could be affected by unrelated variation in the safety of different trim levels of never-treated vehicles, we report estimation results with and without never-treated vehicles.

Specification

We specify our empirical model of accidents A_{yijt} as:

$$A_{yijt} = \beta\, \boldsymbol{S_{yijt}} + \lambda_{yi} + \lambda_t + \epsilon_{yijt} \quad (1),$$

where $\boldsymbol{S_{yijt}}$ is a dummy variable equal to one if L1 safety features were available on vehicles yij in year t and zero otherwise; λ_{yi} are model year-make-model fixed effects; λ_t are calendar year fixed effects; and ϵ_{yijt} is an error term. Because our assessment is based on vehicles, L1 safety features could be available on any vehicle as either standard equipment or purchased through an optional package.[9]

The parameter β can be interpreted as the causal effect of the availability of L1 safety features on selected vehicles on the total number of accidents if $cov(S_{yijt}, \epsilon_{yijt} | \lambda_{yi}, \lambda_t) = 0$. That is, any unobserved determinants of accidents (or the accident rate) in a given calendar year that are correlated with whether a vehicle has L1 safety features in that calendar year should be constant within the model year-make-model or the calendar year.

Drawing on the early experience with autonomous vehicles in controlled testing environments, the Insurance Institute for Highway Safety[10] and the Virginia Tech Transportation Institute (Blanco and others (2016)) found that autonomous vehicles were involved in fewer and less severe crashes than human-driven vehicles and that features such as lane departure and blind spot warnings reduced accident risk. Those findings and the fact that our construction of the L1 dummy variable is based on a full suite of safety features installed in a vehicle suggest that β should have a negative sign.

Sources of Bias

There are three potential sources of bias in our specification. The main potential source of bias stems from the fact that a driver's *self-selection* into treatment may be non-random because their L1 adoption decision may be correlated to their intrinsic safety on the road. If, for example,

[9] Data on specific vehicles with L1 safety features that were purchased as an optional package are not available.
[10] Insurance Institute for Highway Safety (IIHS) and Highway Loss Data Institute (HLDI), "Lane Departure Warning, Blind Spot Detection Help Drivers Avoid Trouble," IIHS/HLDI, August 13, 2017, http://www.iihs.org/iihs/news/desktopnews/stay-within-the-lines-lane-departure-warning-blind-spot-detection-help-drivers-avoid-trouble.

safer drivers were more likely to adopt L1 safety features than riskier drivers, then our estimates of β would be biased upwards. Conversely, our estimates of β would be biased downward if riskier drivers were more likely to adopt L1 safety features than safer drivers. The latter behavior would be more relevant in the case of a safety feature, such as L1, which could compensate for a driver's riskiness, instead of a safety feature, such as airbags, which does not compensate for a driver's riskiness but engages *after* a vehicle is involved in a collision.

In either case, our identification strategy mitigates this source of bias. By classifying our vehicles at the model year-make-model-trim level, we compare the safety outcomes of drivers who purchase the same model year, make, and model of vehicle. Hence, the only selection bias that might arise would be due to differences in drivers' intrinsic safety that are correlated with the decision to purchase a specific trim level of the same model year, make, and model of vehicle. But as noted, a vehicle's trim includes notable non-safety features and amenities as well as safety technology; thus, any selection bias should be small. We present evidence below of heterogeneous treatment effects across vehicle types that suggests that our estimates of the effects of L1 safety features are, if anything, conservative.

A second potential source of bias stems from the fact that the adoption of L1 safety features might change a driver's behavior on the road. For example, a driver with L1 safety features might take more risks while driving, like texting and paying less attention to traffic conditions, which would offset the safety benefits of L1 technology. However, given our interest in estimating the effect of L1 safety features on automobile safety in actual driving conditions instead of the controlled environments typically studied by engineers, it is appropriate for any change in drivers' behavior in response to the adoption of L1 safety features to be incorporated in our estimate of β^1. Although we assess the technological effectiveness of L1 safety features accounting for drivers' behavioral responses, we offer suggestive evidence below on the nature of those responses based on estimates of the heterogeneous effects of L1 safety features by vehicle characteristics and by the riskiness of drivers who are most likely to select vehicles with those characteristics.

The third potential source of bias, which to the best of our knowledge has not received attention in the safety literature, stems from *contamination* of the control group. Specifically, given that treated and untreated vehicles are likely to be periodically involved in accidents with each other, any safety improvement in the treated vehicles, for example, due to the adoption of L1 safety features, also may improve the safety of untreated vehicles. Thus, an estimate of the effectiveness of L1 safety features—or any other safety features—would be biased downward because it does not account for the positive spillover of safety accruing to vehicles that are not equipped with those safety features.

Although all observational analyses of accident data that are generated when treated and untreated vehicles share the same roadways will be susceptible to contamination bias, the bias is mitigated in our analysis for two reasons. First, many of the vehicles (new and used) on the road during our sample period did not have L1 safety features available as an option at the time of manufacture.[11] Second, nearly 50% of the fatal accidents in our sample were single-vehicle accidents.

3. Data

We constructed a comprehensive dataset of Texas households to conduct our estimation of the efficacy of L1 safety features. For the period covering 2010 to 2020, we obtained from AIB, Incorporated a sample of Texas households living in the seventeen counties that comprise the Houston-Galveston-Brazoria, Dallas-Fort Worth, Austin, and El Paso areas. The model year, make, and model of all the automobiles the households owned were included in the sample.

We decoded the Vehicle Identification Number (VIN) of all the vehicles in our sample using a commercially available VIN decoder to obtain this information. The decoder also identified all our vehicles to the trim level, which represent different versions of the same vehicle make and model that have different features. The decoder is essential to our analysis because it provides information at the level where we observe variations in the availability of L1 safety features for vehicle makes and models.[12] We then obtained detailed information on the autonomous safety features available for different vehicle trims in a given model year directly from the auto manufacturers. By combining this information, we were able to classify manufacturer trims into high, medium, and low levels on the basis of a common history of L1 availability.[13]

Finally, we matched all of the vehicles in our sample with the Texas Department of Safety's Police Accident Reports by VIN, which enabled us to merge each vehicle's complete accident

[11] Slightly more than 25% of all the vehicles in our sample have L1 safety features.
[12] Using the example in table 1, the Acura MDX high level trim is called the Type S Advance, which made L1 safety features available in model year 2015. The low level is the base trim, which has not made L1 safety features available.
[13] Our construction of the data also allowed us to replicate our analysis under different definitions of L1 safety features. Generally, our results were unchanged.

history and the severity, if any, of the accidents it experienced. In addition, we obtained reliable measures of annual miles traveled of each vehicle based on odometer readings from the Texas Commission on Environmental Quality.

4. Estimation Results

We present the estimation results of the effect of the availability of L1 safety features on total accidents and the accident rate in table 2. We report both ordinary least squares (OLS) estimates and maximum likelihood Poisson regression estimates as in previous safety research because accidents take on (small) nonnegative integer values. By exponentiating the parameters in equation (1), we obtain Incidence Risk Ratios (IRRs), which we present for the Poisson regression model to facilitate interpretation of our findings. An IRR greater than 1 corresponds to a positive relationship to vehicle accidents and the accident rate, and an IRR less than 1 corresponds to a negative relationship to vehicle accidents and the accident rate. For instance, an IRR of 1.10 indicates that a unit increase in the variable corresponds to a 10% increase in accidents, and an IRR of 0.9 indicates that a unit increase in the variable corresponds to a 10% decrease in accidents.

We find that the availability of L1 safety features reduces both the number of accidents and vehicle accident rates, and the effects are statistically and economically significant. The estimates of the L1 safety features' effects on the accident rate are smaller than their effects on total accidents, which is consistent with drivers responding to the availability of L1 safety attributes by driving more miles. The table also shows that we obtain similar results for specifications with and without never-treated vehicles, which suggests that our findings are not an artifact of unrelated variation in safety between different trim levels of never-treated vehicles. Finally, the availability of the L1 safety attributes reduces the accident rate approximately 25%, which is a large effect.[14]

Figure 2 shows the heterogeneous effects that L1 safety features have on vehicles' accident safety by vehicle weight, price (MSRP), type, and make. Generally, it appears that the L1 safety features have the largest effects on vehicles where they can provide the greatest improvement in

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[14] For sensitivity purposes, we also specified the main temporal dimension in our analysis to be the model year as opposed to calendar year. Thus, we could use a difference-in-differences (DID) econometric design because our treatment variable is consistent within vehicle make, model, trim, and calendar year. We then estimated an event study of the effect of L1 safety attributes on accidents and we obtained similar findings on the effect of the L1 safety attributes as in our preferred, and more appropriate, approach.

safety. That is, they are more effective in cars than in SUVs and trucks; in lighter vehicles than in heavier vehicles; in less expensive vehicles than in more expensive vehicles; and in Japanese brands than in American and European brands, which may reflect a pure technological effect of L1 safety features.

Those findings indicate that our identification strategy mitigates the bias attributable to the safest drivers selecting the safest makes and models with L1 safety features. If our results mostly reflected that source of bias, we would have been unlikely to find that L1 safety features had their largest effects for cars, lighter vehicles, and less expensive vehicles, which are generally *less* safe in an accident than their counterparts. Given that is reasonable to expect that the riskiest drivers tend to select vehicles that are less safe, it is likely, if anything, that our estimates of the effect of L1 safety features on automobile safety are biased downward given the evidence that, all else constant, risky drivers are more likely than safer drivers to be involved in an accident while driving a vehicle with L1 safety features.

Figure 3 provides additional evidence against selection bias by showing that over time the safest drivers did not necessarily switch to vehicles that had L1 safety attributes. Instead, the crash rate of all drivers who eventually switched to a vehicle with L1 safety attributes was quite similar over time. The crash rate of drivers who never switched to a vehicle with L1 safety attributes was generally greater over time than the crash rate of drivers who switched to a vehicle with L1 safety attributes, but those drivers account for a modest share of drivers in our sample.

Appendix table 1 in the online appendix presents evidence that the availability of L1 safety features also reduces fatalities and that the quantitative effect, roughly a 75% reduction in the fatal accident rate (see columns (6) and (8)), is very large. Of course, the fatal accident rate itself is very small, with a mean of 0.0002 fatalities per 100,000 miles shown in the table, so the absolute reduction in the fatal accident rate is small. We also find that the availability of L1 safety features reduces total fatalities nearly 50% (see column 2).[15] It is likely that we were unable to obtain statistically significant effects of L1 safety features on the total number of fatalities for specifications without vehicles that were never treated because fatal accidents are quite infrequent,

[15] It is premature to perform a "reality check" of the efficacy of L1 safety features by isolating their effect on the nation's automobile fatalities over time because the share of vehicles in the total US vehicle fleet with L1 safety features is still small and because of the difficulty of controlling for various episodic influences on the nation's automobile fatalities. For example, Maheshri and Winston (2024) find that during the pandemic, automobile fatalities increased in metropolitan areas that were highly congested before the pandemic but that experienced an erosion of congestion during the pandemic because of an apparent increase in the share of risky drivers on the road.

which results in relatively little variation in fatality counts across narrow make-model-trim-calendar year groupings.

5. Assessing the Case for Mandating Autonomous Safety Features in New Automobiles

Our analysis can be used to guide policymakers considering mandates for autonomous safety features in new automobiles. There are three primary justifications for such a mandate: (1) There is a large potential external benefit to people besides the driver from those features, which causes privately optimal and socially optimal vehicle decisions to diverge. (2) Individuals are unaware of the benefits (or costs) associated with the choice to include autonomous safety features in their vehicles; thus, they make themselves worse off by undervaluing those features. (3) Access to autonomous safety features is inequitable because of, say, price discrimination through bundling or other supply-side distortions.

Our analysis suggests that although L1 safety features are extremely effective, it is unlikely that any of the preceding conditions to justify mandating them are met. Of course, it is understandable that policymakers want all motorists and possibly other people to benefit from the most effective automobile safety features to date[16], as supported by ours' and others' findings.[17] However, the available evidence does not support policymakers mandating those safety features.

Estimating the external benefits of an automobile safety feature is a challenging empirical problem because it is difficult to determine whether a safety feature could have prevented other people besides the driver from being injured or killed in an accident. Thus, to the best of our knowledge, estimates of such benefits are not available in the literature. It is beyond the scope of this analysis to attempt to develop a methodology and to collect appropriate data to estimate the external of benefits of L1 safety features, but contextual evidence suggests that an estimate of those benefits would not significantly increase the large benefits we have already estimated for L1 safety features.

An implication of the fact that L1 safety features are much stronger substitutes for driver attention than other automobile safety features is that a large share of the overall benefits of L1

[16] We have pointed out that seat belts and air bags cannot prevent a driver from getting into an accident, and we reported evidence in footnote 6 that those safety devices reduce the probability of a fatal accident less than L1 safety attributes reduce that probability.

[17] Reviews of studies of autonomous safety features by Wang et al. (2020) and by the Foundation for Traffic Safety (FTS) in its Research Brief provide evidence on the effectiveness of those features, although they do not control for behavioral offset effects as we do here.

safety features are likely to be internalized by drivers. We also stress that our estimates of the L1 safety features' effect on fatal accidents include the potential external benefits of fatality reduction that are associated with those safety features because the dependent variable in our analysis is specified as the probability of a fatal accident, where the fatality could occur in any vehicle involved—that is, our estimates capture the effect of L1 safety features on fatalities involving non-L1 equipped vehicles. Generally, the cost of fatal accidents greatly exceeds the cost of nonfatal accidents. The scope of external benefits of L1 safety features is further limited because roughly one-third of all accidents and one-half of fatal accidents are single vehicle crashes, and 5% of multivehicle accidents involve only vehicles that are equipped with L1 safety features.

It also is likely that consumers are well-informed about L1 safety features' effectiveness. To see this, note that the probability of a person dying in car crash during their lifetime is roughly 1.0%.[18] If a person owns roughly six cars during their lifetime[19], the probability of dying in one of those cars is 0.166%. Based on our estimates in appendix table 1, the probability of dying in those cars is reduced 50%, or becomes 0.083%, if they are equipped with L1 safety features. Finally, consistent with US Department of Transportation Guidelines during our sample period, assume the value of life for a person is \$6 million[20], which implies that a person is willing to pay \$60,000 to reduce the probability of dying in a fatal car accident by 1%. Thus, on average, motorists should be willing to pay \$4980 (\$60,000 · 0.083) for L1 safety attributes to be installed in their vehicle, which exceeds the \$4248 cost of installing basic L1 safety features.[21]

Of course, under alternative plausible assumptions, one could calculate a willingness to pay of as much as \$7000 for advanced L1 safety features or less than the \$4200 cost of installing basic L1 safety features. However, making those assumptions does not effectively cast doubt on whether consumers are informed about the effectiveness of those safety features. Instead, they underscore the importance of recognizing that focusing on the average willingness to pay (WTP) masks motorists' heterogeneity. Indeed, our finding that L1 safety features have heterogeneous effects on the accident rate in accordance with different types of vehicles suggests by implication that the different types of people who own those different types of vehicles are likely to vary in their WTP for L1 safety features. It also appears, in general, that consumers are able to discern

[18] https://www.curcio-law.com/blog/odds-of-dying-in-a-car-crash/.
[19] https://www.usedvwaudi.com/blog/2017/11/16/how-many-cars-will-you-go-through-in-one-lifetime.
[20] https://www.theglobalist.com/the-cost-of-a-human-life-statistically-speaking/.
[21] https://www.sbdautomotive.com/post/collision-avoidance-saves-lives-vpp

the considerable benefits of L1 safety features to a reasonable degree and that automakers have steadily increased the availability of those safety features on more vehicles because they are able to price them in a manner consistent with their safety benefits, installation costs, and consumers' WTP.

The remaining justification for mandating the installation of L1 safety features on all cars is that access to them is limited by supply-side constraints. However, as shown previously in figure 1, the availability of L1 safety features has notably increased over time. In addition, appendix figure 1 in the online appendix shows the distributions of manufacturers' suggested retail prices for all L1 equipped and non-L1 equipped vehicles in our sample in 2019. The figure shows that the supports of those distributions are nearly identical. Thus, L1 safety features are generally available at all price points for new vehicles, and consumers can choose from either L1 equipped or non-L1 equipped vehicles at all price points.

6. Conclusion

Historically, the introduction of a new vehicle safety feature by automakers has been met with controversy over its technological effectiveness at reducing the probability of fatal and severe injuries, accounting for drivers' behavior, and whether a government intervention could enhance social welfare by making it required in all new vehicles.

We have addressed the first issue empirically in the context of automakers' introduction of L1 autonomous vehicle safety features and presented causal evidence that those features have improved automobile safety by significantly reducing the probability of fatal and nonfatal accidents. Our finding is important because it provides evidence of the benefits of vehicle automation, which could generate social welfare gains in the trillions of dollars from reductions in safety, congestion, and emissions externalities and from violent altercations from police stops when it evolves in future decades to Level 5 fully automated operations (Winston and Karpilow (2020), Winston, Yan, and Associates (2024)).

Turning to the second issue, automobile safety policies have not historically been guided by a careful assessment of the costs and benefits of the policy to all members of society. For example, Mannering and Winston (1995) found that, on average, motorists were willing to pay the average cost of installing air bags on their vehicles and that automakers were steadily installing airbags on those vehicles for which motorists were willing to pay the average cost of air bag installation. Nonetheless, in 1998, federal law required that all cars and light trucks sold in the United States have air bags on both sides of the front seat without carefully assessing whether such a requirement was justified on cost-benefit grounds.

The speed with which L1 automobile safety features have been introduced is notable and our findings strongly indicate that motorists have been benefiting from their effectiveness in improving safety. Notwithstanding those considerable benefits, our analysis casts doubt that government's intervention in the market's adoption of L1 safety features by mandating them for all vehicles would enhance social welfare. We conclude that such a policy should not implemented without a better understanding of the efficacy of the market forces that have contributed to the adoption of those safety features.

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Table 1. Example of Data Structure for the Acura MDX

Treated Vehicles			2015 H	2015-2016 H	2015-2017 H	2018 M 2015-2018 H	2018-2019 M 2015-2019 H
Untreated Vehicles	2000-2013 L 2000-2013 M 2000-2013 H	2000-2014 L 2000-2014 M 2000-2014 H	2000-2015 L 2000-2015 M 2000-2014 H	2000-2016 L 2000-2016 M 2000-2014 H	2000-2017 L 2000-2017 M 2000-2014 H	2000-2018 L 2000-2017 M 2000-2014 H	2000-2019 L 2000-2017 M 2000-2014 H
Calendar Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**

Notes: There are three trim levels for the MDX: L, M and H. Trim level H received L1 safety features in model year 2015. Trim level M received L1 safety features in 2018

Table 2. Effect of L1 Safety Attributes on Total Accidents and Accident Rate

Dependent Variable	Total Accidents				Accident Rate			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L1 Safety Features Dummy	-1.10** (0.53)	0.62** (0.14)	-0.41** (0.16)	0.70*** (0.09)	-0.02*** (0.004)	0.77*** (0.06)	-0.02*** (0.01)	0.71*** (0.07)
Model Year-Make-Model FEs?	Y	Y	Y	Y	Y	Y	Y	Y
Calendar Year FEs?	Y	Y	Y	Y	Y	Y	Y	Y
Include Never Treated Vehicles?	Y	Y	N	N	Y	Y	N	N
	OLS	Poisson	OLS	Poisson	OLS	Poisson	OLS	Poisson
R2	0.05	0.68	0.66	0.62	0.10	0.07	0.10	0.07
N	38,292	33,263	11,397	9,325	37,346	31,668	10,972	8,597
Mean of Dep. Variable	3.09		2.10		0.04		0.04	

Notes: Accident Rate calculated as accidents per 100k VMT. Vehicles with accident rates greater than 1 are dropped (2.3% of observations). Heteroskedasticity robust standard errors clustered by model year-make-model-trim are presented in parentheses. Pseudo R2 presented for Poisson regressions. *** 99% significance, ** 95% significance.

Figure 1. Availability of L1 Safety Features Over Time

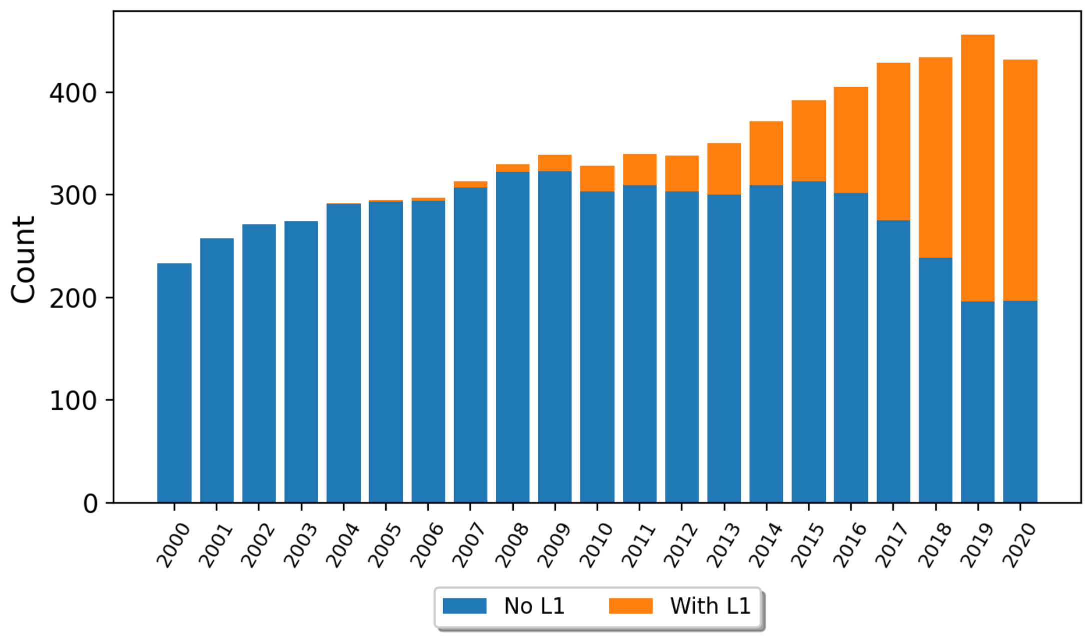


Figure 2. Heterogeneous Effects of L1 Safety Features on the Accident Rate (IRR)

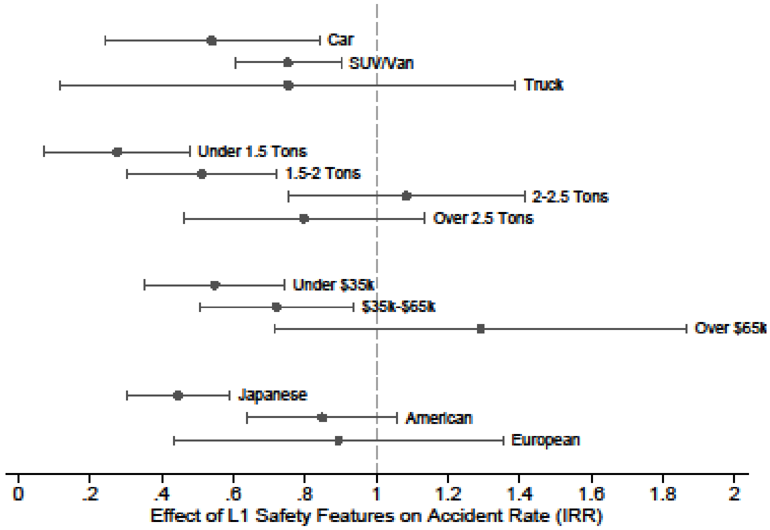
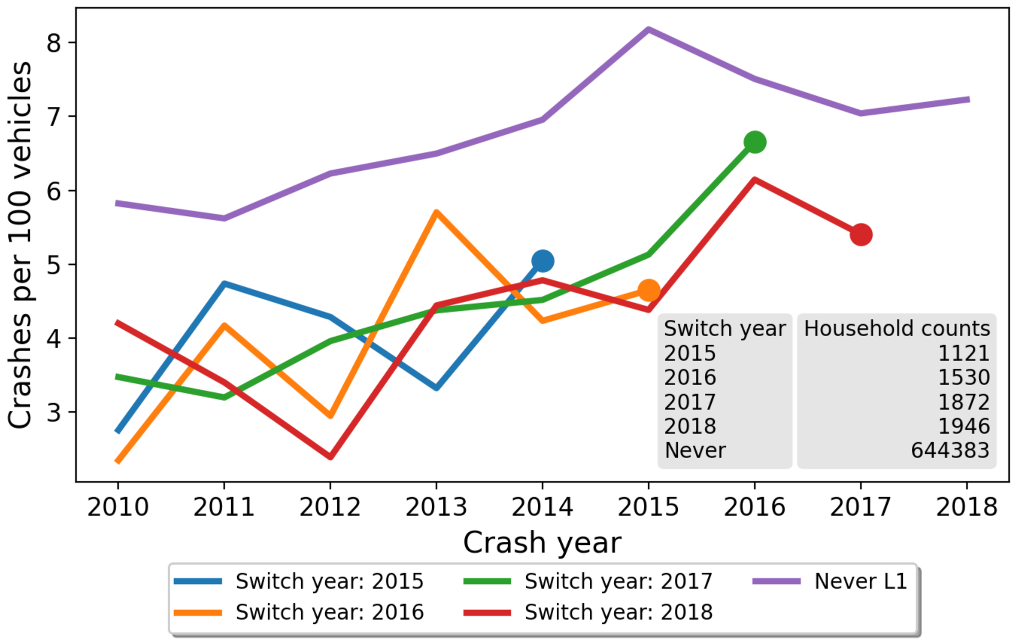


Figure 3. Crash Rate by Year and Household L1 Switch Year



Online Appendix

Appendix Table 1. Effect of L1 Safety Attributes on Fatal Accidents and the Accident Fatality Rate

Dependent Variable	Total Fatal Accidents				Fatal Accident Rate			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L1 Safety Features Dummy	-0.01* (0.004)	0.52* (0.19)	-0.004 (0.005)	0.60 (0.33)	-0.001** (0.0003)	0.22*** (0.12)	0.001*** (0.0004)	0.24 (0.21)
Model Year-Make-Model FEs?	Y	Y	Y	Y	Y	Y	Y	Y
Calendar Year FEs?	Y	Y	Y	Y	Y	Y	Y	Y
Include Never Treated Vehicles?	Y	Y	N	N	Y	Y	N	N
	OLS	Poisson	OLS	Poisson	OLS	Poisson	OLS	Poisson
R2	0.05	0.07	0.01	0.09	0.09	0.27	0.06	0.30
N	38,292	4,114	11,535	791	38,289	4,093	11,395	776
Mean of Dep. Variable	0.01		0.01		0.0002		0.0002	

Notes: Fatal Accident Rate calculated as fatal accidents per 100k VMT. Heteroskedasticity robust standard errors clustered by model year-make-model-trim are presented in parentheses. Pseudo R2 presented for Poisson regressions. *** 99% significance, ** 95% significance, * 90% significance.

Appendix Figure 1. Distributions of Prices for Vehicles With and Without L1 Safety Features