PRELIMINARY ESTIMATES OF TARGET CRASH POPULATIONS FOR CONCEPT AUTOMATED VEHICLE FUNCTIONS

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ABSTRACT

This paper presents preliminary estimates of the target crash populations that could be addressed by automated light vehicles. These estimates are derived from a method that identifies automated vehicle functions, their automation levels, and operational characteristics; maps this information to five layers of crash information including crash location, pre-crash scenario, driving conditions, travel speed, and driver condition; and then queries the General Estimates System and Fatality Analysis Reporting System crash databases. This paper focuses on automated vehicle functions at automation levels 2 through 4 as defined by the National Highway Traffic Safety Administration. This paper also details an approach to account for levels 0 and 1 automated vehicle functions and their applicable safety benefits when estimating target crash populations for automated vehicle functions at levels 2 through 4. Target crash populations are quantified in terms of the annual frequency of all crashes, fatal-only crashes, and comprehensive costs broken down by level of automation. The L2-L4 concept automated vehicle functions address single-vehicle crashes such as road departure, pedestrian, and animal crashes; and multi-vehicle crashes such as rear-end, lane-change, opposite-direction, and intersection-crossing-path crashes.

INTRODUCTION

Automated vehicles have the potential to reduce motor vehicle crashes and mitigate the severity of injuries by performing driving controls effectively without the constraint of driver inputs. The target crash populations (TCPs) that could be addressed by automated vehicles depend on their specific functions, level of automation, and operational conditions.

This paper presents preliminary estimates of TCPs for automated vehicles based on a methodology that maps concept automated vehicle functions to national crash data [1]. This analysis considers automation levels as defined by the National Highway Traffic Safety Administration (NHTSA). It should be noted that a follow-on analysis is currently underway to update these preliminary TCP estimates using automation levels as defined by the Society of Automotive Engineers (SAE).

Automation Levels

NHTSA has defined the following five levels of automation that are distinguished by the degree of shared control and monitoring authority between the driver and the vehicle [2].

NHTSA Level 0 ‑ No Automation (L0): this involves no automated functionality and accounts for crash warning systems.

NHTSA Level 1 ‑ Function-Specific Automation (L1): this involves one or multiple specific control functions operating independently from each other. The driver has overall control, and is solely responsible for safe operation, but can choose to cede limited authority over a primary control (e.g., adaptive cruise control). The vehicle can automatically assume limited authority over a primary control (e.g., electronic stability control), or can provide added control to aid the driver in certain normal driving or crash-imminent situations (e.g., automated emergency braking).

NHTSA Level 2 - Combined Function Automation (L2): driver cedes primary control of at least two primary control functions designed to work in unison in certain limited driving situations, but is still responsible for monitoring and safe operation of the vehicle. The driver is expected to be available at all times to control the vehicle.

NHTSA Level 3 - Limited Self-Driving Automation (L3): driver can cede full control and monitoring authority of all safety-critical functions under certain traffic and environmental conditions. The driver is expected to be available for occasional control of the vehicle.

NHTSA Level 4 - Full Self-Driving Automation (L4): driver provides navigation input but is not expected to be available for control of the vehicle. The vehicle is designed to safely perform all safety-critical driving functions and monitor roadway conditions for an entire trip.

Variations in Automation Level Definitions

The SAE has developed definitions and a methodology to determine the various levels of automation [3]. Even though the TCP results presented in this paper are based on the NHTSA definitions, the same methodology can be applied to revise the TCP estimates using the SAE definitions. Table 1 shows the relationship between the levels of automation as defined by NHTSA and SAE.

Table 1.
Comparison of Automation Level Definitions between NHTSA and SAE

Automation Level Conversions NHTSA → SAE			
NHTSA		SAE	
L0	No Automation	L0	No Automation
L1	Function-Specific Automation	L1	Driver Assistance
L2	Combined Function Automation	L2	Partial Automation
L3	Limited Self-Driving Automation	L3 L4 L5	Conditional, High, Full Automation
L4	Full Self-Driving Automation	L4 L5	High, Full Automation

Research Focus

This paper is focused on estimating the TCPs for NHTSA L2-L4 automation levels in light vehicles (e.g., passenger cars, vans and minivans, sport utility vehicles, and pickup trucks with gross vehicle weight rating less than or equal to 10,000 pounds). It describes and exercises a method to determine the TCPs that could be addressed by L2-L4 levels in general, and the incremental TCPs that could not be addressed by crash avoidance applications or L0-L1 levels. Using NHTSA's General Estimates System (GES) and Fatality Analysis Reporting System (FARS) crash databases, the application of this method yields TCP estimates in terms of the annual frequency of all target crashes, fatal-only crashes, and comprehensive costs.

Future research would provide potential safety benefits for automated vehicles by multiplying the TCP values with estimates of the crash avoidance effectiveness of various automated vehicle functions. These crash avoidance effectiveness estimates need to be derived from research studies and field operational tests that collect and analyze driver-vehicle-roadway performance data for various automated vehicle systems.

Previous Research

NHTSA has conducted a crash causal study that analyzed 5,471 passenger vehicle crashes within the United States between 2005 and 2007. This analysis determined the pre-crash events and critical factors related to the actions that led to a crash [4]. Results from this study suggest that human error is the critical reason for 93% of crashes. Human errors were categorized into recognition (e.g., inattentive, distracted), decision (e.g., too fast, gap misjudgment), performance (e.g., overcompensation, poor control), and non-performance (e.g., sleepy, ill) errors. Thus, automated vehicles at all levels of automation could potentially address a part of these crashes by supporting driver attention and response, and providing automatic vehicle control in both normal driving tasks and crash-imminent situations [5].

By compensating for driver error, many presentations and articles viewed the 93% of crashes as a preliminary estimate for the potential TCPs of automated vehicles. This general estimate is made independent of the prospective automated vehicle functions and their automation levels (i.e., L2-L4), and does not account for the crashes that would be avoided with crash avoidance systems and other motor vehicle safety applications (i.e., L0-L1). For example, forward crash warning (FCW) systems (i.e., L0) alert drivers to a potential crash with a slower or stopped lead vehicle. Rear-end crashes are the TCP for FCW within the operational conditions of the system. On the other hand, an L2 automated car-following function, which controls the headway to lead vehicles and keeps the vehicle within the travel lane, would also target rear-end crashes mostly on highways. Hence, the analysis in this paper seeks to refine this general TCP estimate (93% of crashes) by identifying TCPs for individual automated vehicle functions and levels of automation, finding target crash overlaps among automated vehicle functions, and accounting for incremental target crashes between L0-L4 automation levels.

APPROACH

This analysis follows a three-step approach:

1. *Identify automated vehicle functions, their automation levels, and operational characteristics*: this step identifies and describes the concepts of operation for prospective L2-L4 automated vehicle functions as reported in literature. Analogous examination into L0 and L1 systems of interest that may share TCPs with higher levels of automated vehicle functions was also conducted. The analysis only considers the L0 and L1 functions that have been implemented or tested as prototype or production systems in light vehicles.
2. *Map this information to five layers of crash information including crash location, pre-crash scenario, driving conditions, travel speed, and driver condition*: this step seeks to map the automated vehicle functions and their operational conditions to the crash information where they may apply. The applicability to crash information is dependent on the operational capabilities of each automated vehicle function and the availability of pertinent information. Key crash information includes: pre-crash scenarios and their characteristics, crash contributing factors of the driving environment and vehicle, and detailed crash causes associated with the driver.
3. *Query and estimate TCPs from national crash databases*: based on results from steps 1-2, this step queries the GES and FARS crash databases and analyzes the data to yield the annual numbers of all police-reported and fatal-only crashes, and the comprehensive economic costs based on the numbers of injured persons and their injury levels, which could be addressed by L0-L4 functions individually and incrementally. This is accomplished by accounting for potential safety benefits as estimated from previous benefits studies addressing foundational L0-L1 crash avoidance technologies, then aggregating the results of the individual L0-L4 functions to the respective level of automation. The results of this analysis provide realistic incremental TCPs and thus can be used as basis for subsequent safety benefit estimates for automated vehicle functions.

AUTOMATED VEHICLE FUNCTIONS

L2-L4 automated vehicle functions [6]:

- Can aid in driver vigilance; e.g., watch for forward collision or ensure vehicle heading.
- Can decrease total driver workload and mitigate driver fatigue.
- Monitor the driving environment at a constant level of alertness, which may eliminate small driver errors such as steering reversal.
- May offer some protection from distraction.
- May correct or prevent poor decisions of novice drivers.

Thus, automated vehicle functions may address crashes in any pre-crash scenario caused by driver physiological impairment or driving task errors including driver recognition, decision, and action. This paper considered a list of concept automated vehicle functions as described below [7] [8]. This list reflects the available information at the time of the analysis. Functions were considered for analysis based on the availability of detailed operation design domain, vehicle operations, and effectiveness estimates (for L0 and L1 functions only). Many other systems were also identified; however, these concepts were not incorporated into the analysis due to the lack of information.

L2 Automated Vehicle Functions

Level 2 concept functions considered in the analysis include the following applications:

Adaptive Cruise Control (ACC) with Lane Keeping, Lane Change, and/or Merge: these functions keep the vehicle in its intended lane of travel (i.e., lane keeping) and at a desired headway to the lead vehicle or, if no lead vehicle is present, maintain a constant speed (i.e., ACC). They also support the driver in passing maneuvers where the vehicle automatically proceeds to change lanes after the driver approves each maneuver separately (e.g., by actuation of a button). Moreover, they allow other vehicles to merge onto the roadway. These functions perform on highways at travel speeds up to 130 km/h (~ 81 mph).

Traffic Jam Assist: this function performs car-following (i.e., longitudinal control) and lane keeping (i.e., lateral control) on highways at slow speeds. It supports the driver with monotonous driving in traffic jams on highways at speeds of up to 60 km/h (~ 37 mph). This function follows a lead vehicle at a safe distance and keeps the host vehicle in the center of the lane. The function is only available if slow-moving vehicles are detected in front. The driver monitors the system constantly and intervenes if required (e.g., if the vehicle is going to exit the highway at an exit or interchange, a vehicle needs to merge into traffic, or the traffic jam situation ends).

Automated Roadwork (or construction zone) Assistance: this function navigates the vehicle through a work zone at limited speeds. It supports the driver while driving in construction zones on highways by adjusting the velocity according to the speed limit and traffic flow. Furthermore, it applies a course corrective steering momentum if the driver is steering too close to vehicles in the adjacent lane, or too close to the edge of the lane (e.g., guardrails, road barriers and/or traffic cones).

Automated Parking: this function provides parking assistance with automatic steering and accelerating/ braking maneuvers with the driver located in the driver's seat monitoring the system and environment.

L3 Automated Vehicle Functions

Level 3 concept functions considered in the analysis include the following applications:

Automated Highway Driving: this function performs ACC with lane keeping, lane change, and merge as in Level 2 but it allows the driver to turn his attention away from the driving task. In addition to allowing other vehicles to merge, this function allows the host vehicle to automatically merge onto and exit the highway. However, the driver is in position to resume control with a suitable lead time if a takeover request from the system occurs.

Coordinated Convoy: this function controls the longitudinal and lateral dynamic aspects of the vehicle on highways at all speeds including entering and leaving the convoy. It is similar to Automated Highway Driving except that participating vehicles also exchange additional critical information such as their speeds and headways to other vehicles in the convoy. This critical information must be exchanged quickly and accurately. One way this may be implemented is through low-latency wireless communications. Convoying could enable shorter time headways between vehicles within the convoy on a highway for purposes of potentially reducing fuel consumption by slipstream driving and increasing road throughput capacities. Convoy members might be passenger cars and/or trucks. The driver of a following vehicle in the convoy may be able to divert his own attention from the driving task in the specific scenario of a convoy on a highway. However, the driver is in position to resume control with a suitable lead time if a takeover request from the system occurs.

Emergency Stopping Assistant: this function operates on highways. It can detect when the vehicle's driver is incapacitated and can safely maneuver the vehicle to park on the side of the road.

Automated Parking: this function maneuvers the vehicle in large or narrow parking spaces with the driver out of the vehicle initiating and stopping, if required, the parking maneuver by remote control.

L4 Automated Vehicle Functions

Level 4 concept functions considered in the analysis include the following applications:

Automated Urban Shuttle: it performs automated functions that operate in designated city streets and is functional at relatively slow speeds in designated zones including city streets and campuses. It accomplishes the complete dynamic driving task from origin to destination in a prescribed and limited urban environment. Its maximum speed may be limited to 40 km/h (~ 25 mph). The dynamic driving task consists of all the real-time functions required to operate a vehicle in on-road traffic such as obstacle detection, event response, and maneuver planning. Navigation or route planning is excluded.

Automated Universal Shuttle: it performs automated functions that operate in all traffic ways (e.g., urban roads, rural roads, highways etc.) with maximum speed up to 130 km/h (~ 80 mph). Since there are no limitations concerning scenarios or environment for most of the drivers, the automated universal shuttle would be an equivalent replacement for today's vehicles.

Emergency Stopping Assistant: this function operates on all roads. It detects when its driver is incapacitated and safely maneuvers the vehicle to park on the side of the road.

Automated Parking: it fully controls the parking of a motor vehicle by providing valet parking where the vehicle automatically enters and maneuvers in the parking garage, detects and avoids obstacles, searches for, and maneuvers into the parking space.

L0 and L1 Automated Vehicle Functions

Level 0 and level 1 concept functions considered in the analysis include the following applications:

Alcohol Detection Technology: it warns the driver of limited vehicle operation if above-limit alcohol levels are detected for the driver.

Back-Up System: it warns the driver of objects and persons when backing up.

Blind Spot Warning/Lane Change Warning (BSW/LCW): it alerts drivers to the presence of vehicles approaching or in their blind spot in the adjacent lane.

Drowsy Detection System: it warns the fatigued driver and prevents the driver from falling asleep momentarily.

FCW: it warns drivers of stopped, decelerating, or slower vehicles ahead.

Intersection Movement Assist (IMA): it warns drivers of vehicles approaching from a lateral direction at an intersection or road junction. This function may include a warning to drivers who are about to violate and run the red light or stop sign at intersections.

Left Turn Assist (LTA): it warns drivers to the presence of oncoming, opposite-direction vehicles when attempting a left turn at an intersection or road junction.

Road Departure Crash Warning (RDCW): it warns drivers of unintentional lane departure or when approaching a curve at unsafe speeds.

ACC and Cooperative ACC (CACC): it supports the driver in longitudinal speed control by maintaining a constant headway to a lead vehicle directly in front or maintaining a constant speed set by the driver if no lead vehicle is present.

Automated Emergency Braking (AEB): it supports the driver in imminent crash situations by automatically applying maximum braking level (i.e., longitudinal control) in an attempt to avoid a collision or reduce the resulting impact speed.

Automated Parking with Automated Steering Control Only: it provides the driver with lateral control of the vehicle in parking situations, while the driver maintains acceleration, brake, and speed control (i.e., longitudinal control).

Automated Roadwork Assistance with Automated Lateral Control Only: it supports the driver in clearly defined roadwork areas by providing lateral control to navigate narrow lanes constrained by adjacent vehicles, road barriers, guard rails, and/or traffic cones.

Electronic Stability Control (ESC): it aids in situations where the driver may be losing steering control or the vehicle may be losing traction by automatically applying the brakes (i.e., longitudinal control) to individual wheels to regain control of the vehicle.

Ignition Interlock: it prevents a driver from operating the vehicle if the driver has been drinking alcohol. All States have enacted legislation requiring or permitting the use of breath-alcohol ignition interlock devices for repeat driving-while-intoxicated drivers to prevent alcohol-impaired driving.

Pedestrian Crash Avoidance and Mitigation (PCAM): it supports the driver by applying automatic braking (i.e., longitudinal control) in imminent crash situations with a pedestrian in attempt to avoid the crash or reduce impact speeds.

Table 4 in the appendix summarizes the list of concept automated functions identified and obtainable operational condition information. This information reflects details available from the literature at the time of this analysis (e.g., maximum speeds). This paper assumes that each automated vehicle function will mature in a timely manner and uses the intended operational capabilities when estimating the TCPs (e.g., Coordinated Convoy was only tested at a speed of 56 mph (85 km/h) and gaps of 5-15 meters, but platooning would plausibly occur at higher highway speeds).

Some automated vehicle functions (e.g., Highway Driving and Automatic Parking) transcend multiple levels of automation. These functions may be designed for minimal or full automation at the discretion of the manufacturer. An automatic parking feature may only control lateral motion when parallel parking or can allow the driver to leave the vehicle and have the vehicle park itself. The information obtained from this analysis was compared to variables in the GES and FARS crash databases to develop a mapping system that enables the correlation of automated vehicle functions to historical crash information.

MAPPING AUTOMATED FUNCTIONS TO CRASH DATA

For specific automated vehicle functions, it is important to determine their applicable crash characteristics. Figure 1 illustrates the process used to map the specific automated vehicle functions to the crash data. This process correlates automated vehicle functions and their capabilities to the crash information available. The following key crash characteristics help to decide on the applicability of automated vehicle functions: crash location, pre-crash scenario, driving environmental conditions, vehicle travel speed, and driver condition.

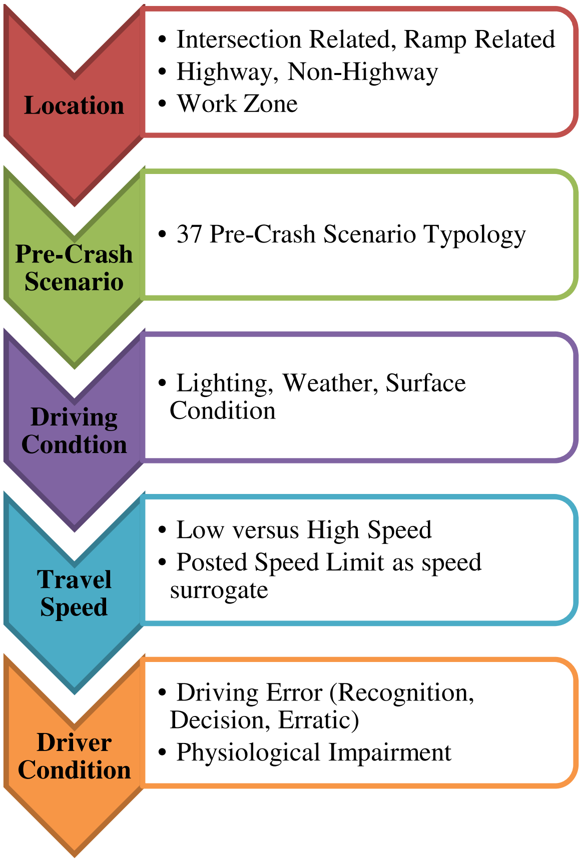

Figure 1. Breakdown Process to Correlate Automated Vehicle Functions to Crash Data.

Location

The location of a crash easily identifies the applicability of an automated vehicle function to a crash. For example, an L0 IMA warning would only be issued at an intersection, L1 automated roadwork assistance function would only activate in a dedicated work zone, or L2 Highway Driving would be limited to highways. Furthermore, the general location of the crash within the crash data can be obtained from variables in the GES and FARS crash databases (e.g., dedicated work zone, non-junction, intersection, entrance/exit ramp, etc.).

Pre-Crash Scenario

The pre-crash scenarios depict specific vehicle movements and dynamics as well as the critical event occurring immediately prior to the crash [9]. Some L0-L1 automated vehicle functions are primarily designed to prevent specific pre-crash scenarios (although secondary pre-crash scenarios may benefit from the same function). For example, an L0 FCW function is designed to prevent rear-end crashes and an L1 PCAM function is designed to prevent pedestrian crashes. Some L2-L4 automated vehicle functions indirectly address specific pre-crash scenarios based on the vehicle maneuvers that are automatically performed. For example, L2 ACC with Lane Centering would prevent rear-end, drifting, and road departure crashes.

By mapping the operational roadway of an automated function to the location of a crash, the pre-crash scenarios are naturally filtered out (e.g., crossing-path crashes don’t occur on a highway for Highway Driving functions). The pre-crash scenarios are derived from various pre-crash event variables within the GES and FARS databases.

Based on the applicable list of pre-crash scenarios, it was determined that the *No Driver* (e.g., operating without proper driver input), *Non-Collision* (e.g., engine fire), and *Vehicle Failure* (e.g., tire blowout) pre-crash scenarios could not be addressed by the identified automated vehicle functions. These incidents are not directly tied to driving tasks and are irregular and extreme circumstances.

Driving Condition

The driving condition seeks to identify the environment in which the crash occurred. The environment is simplified to lighting, atmospheric conditions, and roadway surface conditions. All these conditions are readily available within GES and FARS databases. The described breakdown maps automated vehicle functions to crash data regardless of the technology used. However, it is possible that some technologies may be limited or suppressed in severe driving conditions. For example, a camera-based L2 ACC with lane keeping may not be available for operation on snow-covered roadways or an L3 Coordinated Convoy may not operate at high speeds on wet or slippery roadway surfaces. When projecting the potential safety benefits in the future, driving conditions are crucial to estimating the crash avoidance effectiveness of these automated vehicle functions.

Travel Speed

Some automated vehicle functions are active at certain speeds. For example, an L1 PCAM function may not operate at speeds above 45 mph (72 km/h) or an L2 ACC with lane keeping may not work at speeds less than a typical highway speed (~50 mph or 80 km/h). Although travel speed is not as readily available or accurate in the crash data, this information can be deduced from other variables in the GES and FARS databases. For instance, it can be assumed that the driver is traveling at the speed limit if the travel speed is not a contributing factor to the crash (GES and FARS variable) on a roadway with certain posted speed limit (GES and FARS variable). On the other hand, if speed were referenced as a crash contributing factor, then it is assumed that the driver would be traveling at least +10 mph (16 km/h) over the speed limit. This analysis considers the 45 mph (72 km/h) travel speed as the threshold between "low" and "high" speed categories.

Driver Condition

Ideally, if full automation (L4) were to replace the driver in all motor vehicles then all crashes caused by the driver would be avoided given that the automated functions perform driving tasks without driver input and would do so without making any mistakes. Driver conditions were broken down into actions and physiological impairments, and were classified into seven distinct categories based on the available GES and FARS driver information:

1. Recognition errors such as inattention, looked but did not see, and obstructed vision.
2. Decision errors such as tailgating, unsafe passing, gap/velocity misjudgment, excessive speed, and trying to beat yellow light or other vehicle.
3. Erratic actions such as failure to control vehicle, prior evasive maneuver, deliberate violation of traffic control device, and willful unsafe driving act.
4. Impaired/ under influence of alcohol, drugs, or medication.
5. Drowsiness from fatigue or being asleep.
6. Physical impairment from illness, blackout, or disability.
7. Not cited with no information to suggest any erroneous action or physiological impairment from the police report.

Since the reported driver condition can be subjective depending on the combination of information provided in the crash data (e.g., drunk, inattentive, excessive speed) and that extensive human factors testing may be necessary to fully understand the capabilities of these automated vehicle functions as they relate to the driver, this analysis relegates the driver condition to the last layer of the breakdown.

Mapping Functions to Crash Variables

Table 5, in the appendix, lists the key variables in each of the five crash layers. Each concept automated vehicle function is mapped through these five layers by identifying applicable parameters, and aggregated results are used to identify the TCPs for the levels of automation. Many of the listed automated vehicle functions overlap on many variables. By applying this method, the analysis should first map each automated vehicle function individually and later aggregate the results so as to directly trace and account for the overlaps.

TARGET CRASH POPULATIONS

Results from the mapping provide preliminary TCP estimates of L2-L4 automated vehicle functions in terms of all light-vehicle (LV) crashes, fatal-only crashes, and comprehensive economic costs based on 2013 GES and FARS crash statistics. The societal costs of motor vehicle crashes that involved at least one LV in 2013 are[1]:

- 5,354,382 police-reported (PR) crashes of all severities,
- 24,074 fatal crashes, and
- $569,086,000,000 in comprehensive costs.

Economic costs are expressed in year 2010 economics, which include productivity losses, property damage, medical costs, rehabilitation costs, congestion costs, legal and court costs, emergency services such as medical, police, and fire services, insurance administration costs, and the costs to employers [10]. Values for more intangible consequences such as physical pain or lost quality-of-life are also incorporated in estimates of comprehensive costs.

Baseline Crash Population

By excluding the societal costs from the *No Driver*, *Non-Collision*, and *Vehicle Failure* crash types, this mapping analysis starts with the following baseline crash populations:

- 5,278,243 PR LV crashes of all severities (98.6% of all LV-initiated crashes),
- 23,607 fatal LV crashes (98.1% of all LV-initiated fatal crashes), and

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[1] The light vehicle was the initiator (i.e., following another vehicle, making a maneuver in the crash).

- $559,640,000,000 in comprehensive costs (98.3% of all LV-initiated crash costs).

The main focus of this paper is to determine the TCPs of L2-L4 automated vehicle functions. However, it is logical to consider L0 and L1 functions that are or will be simultaneously implemented in the LV fleet and will potentially provide considerable safety benefits. Mapping the operational conditions of L0 and L1 functions through the crash layer characteristics enables the estimation of their TCPs. The values of the crash avoidance/mitigation effectiveness parameter are obtained from publicly-available reports.

The TCPs of L2-L4 functions are reduced by the societal cost savings that would be accrued only by these L0 and L1 functions where applicable. Despite their anticipated safety benefits, this analysis does not account for any societal cost savings from L0/L1 functions, including alcohol detection, BSW/LCW, drowsy detection, AEB, automated parking, and automated roadwork assistance functions, since their effectiveness estimates are not cited in any publicly-available references. In doing so, it is acknowledged that this assumption may lead to larger TCPs for L2-L4 automated systems. If further research revealed that these technologies have non-zero effectiveness at addressing the crashes analyzed in this paper, then the TCPs for L2-L4 would be reduced by the safety benefits observed. It should be noted that the L4 Automated Universal Shuttle function is not accounted for in this analysis since it targets all the baseline crashes not saved by L0 and L1 functions.

The TCP estimates can then be characterized by the level of automation independently (i.e., not accounting for target crashes or safety benefits observed by other levels) and incrementally (i.e., accounting for residual crashes).

Target Crash Population Estimates

Independent of Other High Levels of Automation

Table 2 presents the results of the mapping analysis and data query of the 2013 GES and FARS crash databases in terms of societal cost measures. The TCP for each individual automated vehicle level is listed in the columns with the "Target" heading. The "Remainder" column refers to crashes and cost not saved by L0-L1 functions and not addressed by each individual L2-L4 automated vehicle level.

Table 2.
Target Crash Populations for Individual L2-L4 Automated Vehicle Levels

Level	Measure	L0/L1 Benefit	Target	Remainder
L2	All Crashes	53,832	**438,693**	4,785,718
	Fatal Crashes	132	**1,127**	22,348
	Cost ($ M)	$4,568	**$35,496**	$519,577
L3	All Crashes	57,781	**468,287**	4,752,175
	Fatal Crashes	429.3	**2,312**	20,866
	Cost ($ M)	$8,372	**$51,842**	$499,426
L4	All Crashes	527,668	**1,882,120**	2,868,456
	Fatal Crashes	2,662	**9,896**	11,049
	Cost ($ M)	$66,282	**$215,324**	$278,034
L2 – L4	All Crashes	581,472	**2,315,671**	2,381,099
	Fatal Crashes	2,792	**11,015**	9,800
	Cost ($ M)	$70,820	**$250,644**	$238,176

Figure 2 compares the TCP percentages in terms of three societal cost measures among the L2-L4 automated vehicle levels (Percentages are based on the total LV-initiated crash population). By accounting for the safety benefits from L0 and L1 functions, the L4 automated vehicle level could address the most crashes while the L2 and L3 automated vehicle levels individually target below 10% of the LV crash societal cost.

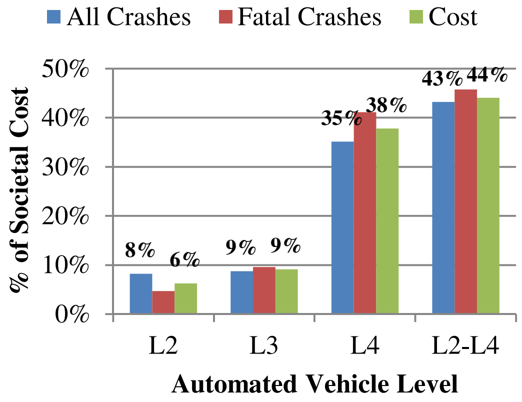

Figure 2. Proportions of Target Crash Populations Relative to Light-Vehicle Crash Societal Cost (excluding No Driver, Vehicle Failure, and Non-Collision Pre-Crash Scenarios).

Incremental to Other Levels of Automation

Table 3 presents statistics about the added TCPs from new functions and enhanced capability as automated vehicle levels progress from Level 2 to Level 3 and from Level 3 to Level 4. That is, this analysis assumes that Level 2 functions are 100% effective in preventing their target crashes before proceeding to estimate the incremental TCP for Level 3 functions. Similarly, Level 3 functions are 100% effective in preventing their target crashes before proceeding to estimate the incremental TCP for Level 4 functions. Compared to L2 TCPs, L3 functions yield about 10%

increase in all target crashes, double target fatal crashes, and address about 50% more of the target crash cost. Compared to L3 TCPs, L4 functions (excluding the automated universal shuttle) address about 4 times the number of all crashes, 7 times the number of fatal crashes, and 11 times the crash cost.

Table 3.
Incremental Target Crash Populations by Automated Vehicle Level

Automation Level	Total Numbers		
	All Crashes	Fatal Crashes	Costs ($ Millions)
L0/L1 Benefits	581,472	2,792	$ 70,820
L2	438,693	1,127	$ 35,496
L3	43,468	1,212	$ 17,346
L4	1,833,511	8,676	$ 197,801
Remainder	2,381,099	9,800	$ 238,176
Sub-Total	5,278,243	23,607	$ 559,640
Unaddressed ^	76,139	467	$ 9,446
Total	5,354,382	24,074	$ 569,086

Figure 3 illustrates the incremental contribution by each level of L2-L4 automated vehicle functions to the TCPs. Generally, the L4-level functions contribute to about 80% of all target crashes, target fatal crashes, and target comprehensive economic costs. Percentages are based on the target crash population addressed by L2-L4 automated vehicle functions, after discounting L0/L1 safety benefits.

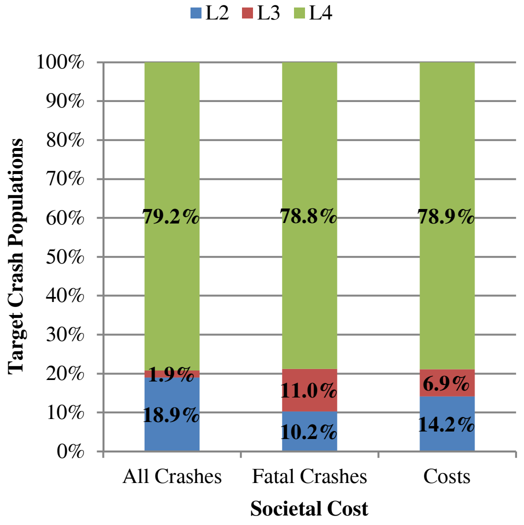

Figure 3. Proportions of Target Crash Populations Relative to Automated Vehicle Level.

Figure 4 shows the incremental contribution to avoiding the comprehensive societal cost figures by each automation level as defined by Table 3. Percentages are based on the total LV-initiated crash population. The aggregate L0 and L1 safety systems can provide a 12% safety benefit in terms of crash comprehensive costs. Higher levels of automation (L2-L4) can address 44% of the crash population (LV-initiated) in terms of crash comprehensive costs. Approximately 1.7% of costs cannot be addressed by any automated vehicle concept function (N*o Driver*, V*ehicle Failure*, and N*on-Collision* pre-crash scenarios). The remaining 41.9% of crash comprehensive costs cannot be addressed by any automated vehicle concept function defined in this paper.

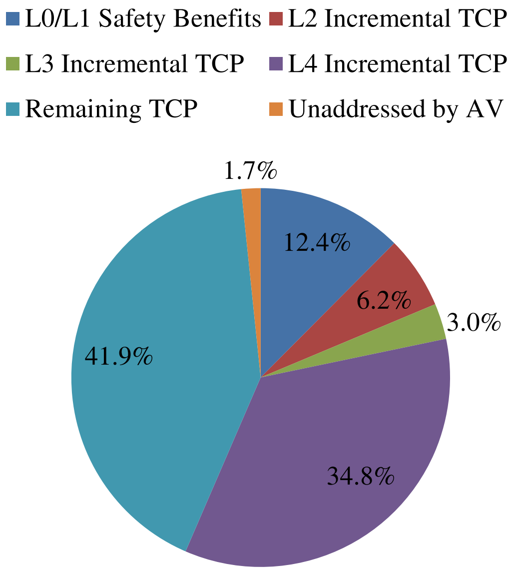

Figure 4. Incremental Proportion Target Crash Population for Comprehensive Costs Addressed by Automation Level.

CONCLUSION

This paper derived preliminary estimates (based on the best currently available information) of the TCPs for automated vehicle functions at NHTSA levels 2 through 4 while accounting for the potential safety benefits that could be accrued from the full deployment of select L0 and L1 functions. These estimates were determined based on a method that correlated specific automated vehicle functions to five layers of crash data. The method involved identifying specific automated vehicle functions with detailed operational conditions, mapping each automated vehicle function through five filters within the crash data, and querying the 2013 GES and FARS crash databases.

This paper estimated that an aggregated list of all considered L2-L4 automated vehicle functions (except Automated Universal Shuttle) would potentially address about 2,316,000 PR crashes, 11,000 fatal crashes, and 251 billion dollars in comprehensive costs annually after accounting for the documented safety benefits provided by L0 and L1 functions. When using an incremental method:

- The aggregated list of all considered L2 automated vehicle functions would potentially address about 439,000 PR crashes, 1,100 fatal crashes, and 35 billion dollars in comprehensive costs annually.
- The aggregate list of all considered L3 automated vehicle functions would potentially address an additional 43,000 PR crashes, 1,200 fatal crashes, and 17 billion dollars in comprehensive costs annually beyond L2.
- The aggregate list of all considered L4 automated vehicle functions (except automated universal shuttle) would potentially improve L2 and L3 TCPs by adding an additional 1,833,000 PR crashes, 8,700 fatal crashes, and 198 billion dollars in comprehensive costs annually.

The Automated Universal Shuttle was not considered in the L4 TCP estimates, as this function could target all baseline crashes not prevented by L0 and L1 functions regardless of location, environmental conditions, travel speed, or driver condition. Including this function, overall L4 functions would potentially address nearly all of the LV-initiated PR and fatal crashes.

The analysis in this paper was based on publicly-available information with a variety of uncertainties (e.g., types of technologies at each automation level, their capabilities, their effectiveness, etc.). The preliminary TCP estimates could be further refined as the assumptions made are validated and automated vehicle concepts and technologies improve and mature.

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APPENDIX

Table 4.
Summary of L0-L4 Automated Vehicle Functions.

Automation Level	Automated Vehicle Function	Operational Conditions	Roadways
L0	Alcohol Detection Technology	Drunk Driver	All Roads
	Back-Up System	Low Speeds	All Roads
	Drowsy Detection System	Drowsy Driver	All Roads
	Warning Systems (BSW/LCW, FCW, IMA, LTA, RDCW)	Speeds > 25 mph	All Roads
L1	ACC and Cooperative ACC	High Speeds	Highway
	Automated Emergency Braking	Imminent Crash	All Roads
	Automated Parking	Low Speeds	Urban
	Automated Roadwork Assistance	Low Speeds	Work Zone
	Electronic Stability Control	Loss of Control	All Roads
	Ignition Interlock	Drunk Driver	All Roads
	Pedestrian Crash Avoidance and Mitigation	Speeds < 45 mph	All Roads
L2	ACC w/Lane Centering	Speeds ≤ 100 mph	Highway
	ACC w/Lane Keeping and Lane Change	Speeds < 75 mph	Highway
	ACC w/Lane Keeping, Lane Change, and Merge	Speeds ≤ 81 mph	Highway
	Traffic Jam Assist	Speeds ≤ 37 mph	Urban
	Automated Roadwork Assistance	Low Speeds	Work Zone
	Automated Parking	Low Speeds	Urban
L3	Automated Highway Driving	High Speeds	Highway
	Coordinated Convoy	Speeds ≤ 56 mph	Highway
	Emergency Stopping Assistance	Incapacitated Driver	Highway
	Automated Parking	Low Speeds	Urban
L4	Automated Urban Shuttle	Low Speeds	Urban
	Automated Universal Shuttle	All Speeds	All Roads
	Emergency Stopping Assistance	Incapacitated Driver	All Roads
	Automated Parking	Low Speeds	Urban

Table 5.
Key Variables for Crash Layers

Location	Crash Type	Driving Conditions	Travel Speed	Driver Conditions
Highway	Animal	Daylight	No Speed Limit	Recognition Error
Intersection Related	Backing	Non-Daylight	Low Speed	Decision Error
Non-Highway	Control Loss	Adverse Weather	High Speed	Erratic Action
Ramp Related	Crossing Paths	Clear Weather		Under the Influence
Work Zone	Cyclist	Dry Surface		Drowsy
	Lane Change	Slippery Surface		Physical Impairment
	Left-Turn Across Path/ Opposite Direction			Not Cited
	No Driver			
	Non-Collision			
	Object			
	Opposite Direction			
	Other			
	Parking			
	Pedestrian			
	Rear-End			
	Road Departure			
	Vehicle Failure			