Use of Level 1 and 2 driving automation on horizontal curves on interstates and freeways

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ABSTRACT

Introduction: Little is known about how the actual use of Level 1 and 2 driving automation systems may be affected by geometric road characteristics in naturalistic driving environments. This study examined the use of these systems on horizontal curves on interstates and freeways.

Methods: We used travel data collected in a field operational test conducted with two 2016 Land Rover Range Rover Evoque vehicles equipped with adaptive cruise control (ACC) and two 2017 Volvo S90 vehicles equipped with ACC and Volvo's Pilot Assist. Logistic regression models estimated changes in the likelihood of ACC use associated with horizontal curvature in the Evoque vehicles, and of Pilot Assist and ACC use in the S90 vehicles, while accounting for traffic conditions.

Results: Drivers were less likely to drive with ACC or Pilot Assist on as horizontal curves became sharper. In the Evoque vehicles, the likelihood of using ACC was 72% lower on the sharpest category of horizontal curves (those with a degree of curvature larger than 2.5 degrees per 100 feet of arc or a radius smaller than 2,292 feet), compared with straight road segments or the flattest horizontal curve category (those with a degree of curvature ≤ 1.5 degrees per 100 feet of arc or a radius no less than 3,820 feet). In the S90 vehicles, the likelihood of using Pilot Assist and ACC declined 75% and 66%, respectively, on the sharpest curves.

Conclusions: Many driving automation systems face challenges on horizontal curves, even within their operational design domain. Future implementations that improve functionality may enhance driver experience and boost drivers' confidence in these systems, which should increase their use and maximize the safety benefits these systems might offer.

Keywords: Driving automation systems; adaptive cruise control; lane centering; horizontal curves; system state; naturalistic driving

INTRODUCTION

Automated vehicles could help to reduce crashes due to driver errors, which lead up to most crashes (Singh, 2015). However, fully automated vehicles will not be widely deployed anytime soon. Currently existing driving automation systems in production vehicles are at SAE International Level 1 or 2 (SAE, 2018). Adaptive cruise control (ACC), which manages speed and distance to the vehicle ahead, is a Level 1 system. Lane centering, which provides steering assistance and keeps a vehicle in the center of the lane, is a Level 1 system on its own. It is frequently combined with ACC as a Level 2 system that in combination provides longitudinal and lateral driving support. The driver is responsible for safe operation of the vehicle with a Level 1 or 2 system.

Level 1 and 2 systems can reduce workload and increase comfort for many drivers (de Winter, Happee, Martens, & Stanton, 2014; Onnasch, Wickens, Li, & Manzey, 2014), but the safety effects of these systems are unclear. A field operational test (FOT) found that ACC was associated with increased headway and less harsh breaking (Kessler et al., 2012). However, there is also evidence showing that when the systems are engaged, drivers pay less attention to driving, and are more likely to take their hands off the wheel and engage in secondary task activities, compared with manual driving (Banks, Eriksson, O'Donoghue, & Stanton, 2018; Endsley, 2017; Kessler et al., 2012; Morando, Gershon, Mehler & Reimer, 2020; Rudin-Brown & Parker, 2004; Victor et al., 2018). These findings suggest that some drivers may place more trust in the automation than is warranted and become complacent and inattentive despite their responsibility to monitor.

Most Level 2 systems in production vehicles are designed for use on limited-access interstates and freeways and in clear weather conditions. Many ACC system capabilities have evolved over a longer period of time and now are designed for a broader set of operating conditions, such as stop-and-go traffic in urban settings. Surveys and a FOT found that ACC and Level 2 systems were more commonly used on high-speed roads than on other road types (Cicchino & McCartt, 2015; Eichelberger & McCartt, 2014, 2016; Reagan et al., 2019; Strand, Karlsson, & Nilsson, 2014). However, even within the intended design domain, these systems have operational limits that may force the driver to assume manual control.

Naturalistic driving data and on-road tests of some Level 2 systems have shown that lane keeping systems may fail when confronted with features that can occur on limited-access roads, such as curves, lane splits, and missing lane markings (American Automobile Association, 2020; Insurance Institute for Highway Safety, 2018; Reagan, Cicchino, & Kidd, 2020).

Self-reported experiences with driving automation technologies have been shown to vary with roadway and traffic conditions. For example, in an on-road study by Reagan et al. (2020), participants reported uncomfortable events associated with using Level 2 automation on limited-access roads. Drivers were more comfortable using these technologies in free-flowing traffic than in heavy stop-and-go traffic (Kessler et al. 2012; Kidd & Reagan, 2018). However, little is known about how the actual use of Level 1 and 2 systems may be affected by road geometry in naturalistic driving environments. This study used data collected in a FOT to examine the frequency of use of Level 1 and 2 driving automation systems in two production vehicles on horizontal curves on interstates and freeways, while accounting for traffic conditions. The findings provide insights into the challenges these systems may face with regard to road geometric characteristics.

METHODS

Data collection from the field operational test

The FOT is part of a larger, ongoing project examining driver use of currently deployed driving automation systems within the Massachusetts Institute of Technology AgeLab's Advanced Vehicle Technology (AVT) consortium. Vehicle travel data were collected using two 2016 Land Rover Range Rover Evoque and two 2017 Volvo S90 vehicles. The Evoque vehicles were equipped with ACC, and the S90 vehicles were equipped with ACC and Volvo's Pilot Assist. Pilot Assist provides steering assistance for lane centering in addition to ACC. These vehicles were instrumented with in-cab and external view video-recording equipment and a sensor suite (Fridman et al., 2017). Drivers aged 18–69 years with a valid driver's license who had driven for at least 3 years, were in self-reported good health, and commuted at least 4–5 days a week on a highway within the greater Boston area were enrolled in the study beginning in the Fall 2016. Each participant received a 1.5-hour training on their assigned vehicle's active vehicle safety technologies and then drove the vehicle for 4 weeks.

Participants

A total of 19 participants driving in the Evoque and 20 in the S90 were included in the analyses. Among those assigned to the Evoque, nine were female and 10 were male. Their ages ranged from 22 to 63 years old with a mean of 42 years old. Nine of the S90 drivers were female and 11 were male. The mean age of the S90 drivers was 47 years old with a range of 24 to 66 years old.

Data

Time-synchronized data were offloaded from the on-board data acquisition systems after the 4 weeks of vehicle use. Data used in these analyses were processed at 1 Hz and included system state information, vehicle speed, and GPS coordinates. ACC and Pilot Assist state information were obtained from computer vision detection of mode icons located in the instrument cluster. ACC in the Evoque was coded as on or off. System states in the S90 were Pilot Assist on, ACC on, or off. When Pilot Assist was engaged, there were two further states, Pilot Assist-on-active and Pilot Assist-on-inactive. Both ACC and steering assistance were engaged when Pilot Assist was on and active. When Pilot Assist was on and inactive, ACC remained engaged, but the steering assistance was temporarily deactivated. Common conditions that lead to the suspension of the lane centering were either driver initiated (e.g., a driver turning on the turn signal or providing steering input), or system initiated (e.g., vehicle speed exceeding 140 km/h, or the system losing track of lane lines due to poor or missing lane markings, sharp curves, etc.). The steering assistance resumed automatically after operating conditions were again met.

We obtained a database of horizontal curves on highways in Massachusetts that included geolocations and radii of curves; horizontal curves were extracted using the method specified in Ai and Tsai (2015). We obtained a second road inventory geodatabase for Massachusetts from the Massachusetts Department of Transportation (MassDOT) data portal (MassDOT, 2018). It contained the Federal Highway Administration's (FHWA's) road functional classification, which categorizes public roads into interstates, other freeways and expressways, other principal arterials, minor arterials, major and minor collectors, and local roads (FHWA, 2013).

Traffic flow classification

Based on recorded speeds, a k-means cluster analysis was used to classify traffic flow into one of two categories: steady or congested. Cluster analysis is an unsupervised learning technique that uses patterns in a set of variables to identify subgroups. A number of variables derived from vehicle speed were used in the cluster analysis, producing a traffic state estimate to match the speed data. These variables included current and recent speed, recent change in speed, speed variability, as well as additional classifiers flagging periods of slow or non-movement. The full list of classifiers along with the specific way they were calculated is provided in Table 1. Steady traffic moved at speeds consistently above the overall average speeds with lower-than-average speed variability. Congested traffic moved at lower-than-average speeds with higher-than-average speed variability.

Table 1. List of classifiers used in the k-means cluster analysis

Variable name	Definition
Speed, current	The current vehicle speed.
Speed, recent	The moving average of vehicle speed over a 10-second window.
Speed, change	The change in current speed relative to the 10-second moving average.
Speed, variability (recent)	The standard deviation of vehicle speed over a 10-second window.
Speed, variability (historical)	The standard deviation of vehicle speed over a 60-second window.
Slow, current	Binary variable: whether or not current vehicle speed exceeds 15 mph.
Stopped, recent	The percent of time during the last 10 seconds the vehicle has spent stopped (i.e., at 0 mph).

Analysis

Vehicle travel data with GPS coordinates were linked to the nearest horizontal curve using ArcMap (Environmental Systems Research Institute, 2018) and to the nearest road segment in the road inventory geodatabase to extract functional class. The analysis was limited to travel on interstates and freeways, where the percentage of miles driven when ACC or Pilot Assist was engaged was much higher than on other road types (Reagan et al., 2019). Forty-seven percent of miles traveled on these roads had horizontal curve information available for analysis, mainly because curve information was extracted for only one direction of travel on the roadway. To avoid the inclusion of data from on and off ramps, travel on curves with radii less than 500 feet was excluded.

Separate logistic regression models were estimated to evaluate changes in the state of ACC recorded at 1 Hz in the Evoque and in the S90 associated with horizontal curve characteristics on interstates and freeways, with a binary ACC state indicator (ACC on versus off) as the dependent variable. For the S90, a similar logistic regression model was estimated to evaluate the use of Pilot Assist at 1 Hz, with a binary state indicator (Pilot Assist on active and inactive combined versus off) as the dependent variable. The independent variables in these models included traffic condition (steady versus congested) and degree of horizontal curvature (straight road or ≤ 1.5 degrees per 100 feet of arc, > 1.5 and ≤ 2.5 degrees per 100 feet of arc, and > 2.5 degrees per 100 feet of arc). These degree of curvature categories corresponded to the following curve radius categories, respectively: ≥ 3,820 feet, ≥ 2,292 and < 3,820 feet, and < 2,292 feet. For example, for a curve with a radius of 4,000 feet, which is the recommended threshold radius of curves in the *Michigan Road Design Manual* (Michigan Department of Transportation, 2017), the degree of curvature is 1.4 degrees per 100 feet of arc.

For observations with system states Pilot Assist-on-active and Pilot Assist-on-inactive at 1 Hz in the S90, a logistic regression was estimated to examine the likelihood of Pilot Assist-on-inactive versus Pilot Assist-on-active associated with horizontal curves. The dependent variable was a binary Pilot Assist state indicator (Pilot Assist-on-inactive versus on-active); the independent variable was the degree of horizontal curvature.

All these models accounted for the correlation potentially present in the data and individual variances. System state data were recorded roughly every second, and it is possible that the neighboring system state data were correlated with each other. Random participant effects as well as random trip effects nested within participants were included in the model estimation.

The estimated parameters for the independent variables were used to calculate changes in the likelihood of ACC or Pilot Assist use associated with these factors (Zhang & Yu, 1998). Variables with p values less than 0.05 were considered statistically significant.

RESULTS

Use of ACC in the Evoque

A total of 4,343 miles of travel on interstates and freeways in the Evoque vehicles were included. About one third of system state observations at 1 Hz had ACC engaged (Table 2). The percentages with ACC on declined as horizontal curves became sharper. The estimated logistic regression modeling results of ACC use in the Evoque are shown in Table 3, as well as the estimated percentage changes in the likelihood of driving with ACC on associated with the independent variables. ACC was more often used under steady traffic conditions. After controlling for traffic conditions, relative to straight road segments or the flattest horizontal curve category (degree of curvature ≤ 1.5 degrees per 100 feet of arc), the likelihood of driving with ACC on was 38% lower on curves with degree of curvatures between 1.5 and 2.5 degrees per 100 feet of arc, and 72% lower on the sharpest category of curves with degree of curvatures larger than 2.5 degrees per 100 feet of arc.

Table 2. Frequency of ACC state observations at 1 Hz in Evoque vehicles by horizontal curve degree of curvature and traffic conditions, on interstates and freeways

	Control state				
	ACC on		Off		Total no. of observations
	No. of observations	%	No. of observations	%	
Degree of curvature in degrees per 100 feet of arc (curve radius in feet)					
≤ 1.5 or straight road (≥ 3,820)	134,918	32.4	281,439	67.6	416,357
> 1.5 and ≤ 2.5 (≥ 2,292 and < 3,820)	9,789	28.6	24,412	71.4	34,201
> 2.5 (< 2,292)	5,339	17.9	24,491	82.1	29,830
Traffic condition					
Steady	126,487	37.7	208,896	62.3	335,383
Congested	23,559	16.2	121,446	83.8	145,005
Total	150,046	31.2	330,342	68.8	480,388

Table 3. Logistic regression modeling results of ACC use at 1 Hz in Evoque on interstates and freeways

Parameter		Estimate	Standard error	*p* value	Estimated change in likelihood (%)
Intercept		−4.6771	0.7344	<.0001	
Traffic condition	Steady versus congested	2.4461	0.0202	<.0001	326.3
Degree of curvature (degrees per 100 feet of arc) categories (baseline: degree of curvature ≤ 1.5 or straight road, or curve radius ≥ 3,820 feet)	> 1.5 and ≤ 2.5 (radius: ≥ 2,292 and < 3,820 feet)	−0.6524	0.0203	<.0001	−38.3
	> 2.5 (radius < 2,292 feet)	−1.5537	0.0229	<.0001	−71.6

Use of Pilot Assist and ACC in the S90

A total of 3,414 miles traveled on interstates and freeways in the Volvo S90 were analyzed. Pilot Assist was on (active or inactive) in 14% of system state observations and ACC was on in 7% (Table 4). The percentages with Pilot Assist on or ACC on decreased as horizontal curvature increased. Among travel observations with Pilot Assist engaged, Pilot Assist was active in 96% and inactive in 4% (Table 5). It was also more often inactive as curves became sharper.

Table 4. Frequency of ACC and Pilot Assist state at 1 Hz in Volvo S90 by horizontal curve degree of curvature and traffic conditions, on interstates and freeways

	Control state						
	Pilot Assist on		ACC on		Off		
	No. of observations	%	No. of observations	%	No. of observations	%	Total no. of observations
Degree of curvature in degrees per 100 feet of arc (curve radius in feet)							
≤1.5 or straight road (≥ 3,820)	51,188	15.2	23,946	7.1	262,088	77.7	337,222
> 1.5 and ≤ 2.5 (≥ 2,292 and < 3,820)	2,545	8.4	1,808	6.0	25,883	85.6	30,236
> 2.5 (< 2,292)	1,111	4.7	767	3.3	21,552	92.0	23,430
Traffic condition							
Steady	47,354	18.2	23,002	8.9	189,299	72.9	259,655
Congested	7,490	5.7	3,519	2.7	120,224	91.6	131,233
Total	54,844	14.0	26,521	6.8	309,523	79.2	390,888

Table 5. Frequency of Pilot Assist state at 1 Hz by horizontal curve degree of curvature on interstates and freeways

	Pilot Assist state				
	Pilot Assist on and active		Pilot Assist on and inactive		
Degree of curvature in degrees per 100 feet of arc (curve radius in feet)	No. of observations	%	No. of observations	%	Total no. of observations
≤ 1.5 or straight road (≥ 3820)	49,607	96.9	1,581	3.1	51,188
> 1.5 and ≤ 2.5 (≥ 2,292 and < 3,820)	2,386	93.8	159	6.2	2,545
>2.5 (< 2,292)	900	81.0	211	19.0	1111
Total	52,893	96.4	1,951	3.6	54,844

Table 6 shows the logistic regression results of the use of ACC and Pilot Assist recorded at 1 Hz in the Volvo S90 on interstates and freeways, as well as the estimated percentage changes in the likelihoods of driving with Pilot Assist on or ACC on associated with the independent variables. Both Pilot Assist and ACC were more likely to be used in steady traffic. Compared with straight roads or the flattest curves (degree of curvature ≤ 1.5 degrees per 100 feet of arc), the likelihood of driving with Pilot Assist and ACC on declined 43% and 27%, respectively, on horizontal curves with degrees of curvature between 1.5 and 2.5, and declined further (75% and 66%, respectively) on curves with degrees of curvature larger than 2.5.

When Pilot Assist was engaged, the likelihood of lane centering being inactive decreased 11% on horizontal curves with degrees of curvature between 1.5 and 2.5, and increased 141% on curves with degrees of curvature larger than 2.5, compared with straight roads or the flattest curves (Table 7). Only the increase was statistically significant.

Table 6. Logistic regression modeling results of ACC and Pilot Assist use in Volvo S90 on interstates and freeways

Parameter		Pilot Assist on versus off: Estimate	Pilot Assist on versus off: Standard error	Pilot Assist on versus off: *p* value	Pilot Assist on versus off: Estimated change in likelihood (%)	ACC on versus off: Estimate	ACC on versus off: Standard error	ACC on versus off: *p* value	ACC on versus off: Estimated change in likelihood (%)
Intercept		−6.0193	0.814	<.0001		−7.5307	0.7329	<.0001	
Traffic condition	Steady versus congested	1.6001	0.0224	<.0001	302.1	1.6882	0.0314	<.0001	380.7
Degree of curvature (degrees per 100 feet of centerline) categories (baseline: degree of curvature ≤ 1.5 or straight road, or curve radius ≥ 3,820 feet)	> 1.5 and ≤ 2.5 (radius: ≥ 2,292 and < 3,820 feet)	−0.6461	0.0352	<.0001	−43.2	−0.3358	0.0382	<.0001	−26.8
	>2.5 (radius <2,292 feet)	−1.5084	0.0472	<.0001	−74.6	−1.1473	0.0505	<.0001	−66.3

Table 7. Logistic regression modeling results of the system state Pilot Assist-on-inactive versus Pilot Assist-on-active in Volvo S90 on interstates and freeways

Parameter		Estimate	Standard error	*p* value	Estimated change in likelihood (%)
Intercept		−4.2684	0.5048	<.0001	
Degree of curvature (degrees per 100 feet of centerline) categories (baseline: degree of curvature ≤ 1.5 or straight road, or curve radius ≥ 3,820 feet)	> 1.5 and ≤ 2.5 (radius: ≥ 2,292 and <3,820 feet)	−0.1248	0.0992	0.2083	−11.4
	> 2.5 (radius < 2,292 feet)	0.9242	0.1013	<.0001	140.6

DISCUSSION

To the best of our knowledge, this is the first publicly available study based on FOT data that examined the use of Level 1 and 2 driving automation systems by road geometric characteristics on interstates and freeways. Drivers were less likely to drive with ACC or Pilot Assist as horizontal curves became sharper. The reductions in the likelihood of using Pilot Assist were larger than ACC in Volvo S90 vehicles, and lane centering of Pilot Assist was more likely to be on standby on the sharpest curves. These findings demonstrate that even within the broad design domain, there are roadway features such as curves where drivers are less comfortable using the technology or that conditions may have been such that the systems disengaged.

Previous research found significant reductions in rear-end crash rates associated with front crash prevention and in head-on, sideswipe, and single vehicle crash rates associated with lane departure warning (Cicchino, 2017, 2018). Rear-end crashes may potentially be further reduced by ACC due to on average greater following distances that could prevent crash imminent situations from developing (Kessler et al. 2012). Because they provide steering assistance instead of only a warning, lane centering systems may further reduce lane-drift or lane-departure related crashes. However, underuse would limit their potential safety benefits (Reagan et al., 2019). The crash reduction benefits from lane centering may also be limited by its reduced use on horizontal curves, since roadway departure crashes are more likely to occur on horizontal curves than on straight segments (Glennon, Newman, & Leisch, 1985; Lord, Brewer, Fitzpatrick, Geedipally, & Peng, 2011; McGee 2018).

Although there are not as many sharp curves on interstates and freeways as on other road types, driving automation systems that have limited operational ability on curves may discourage drivers from using them due to a lack of confidence. Lane line tracking for lane centering becomes more difficult as curves become sharper. Similarly, on sharp curves, ACC may fail to detect a vehicle in front in the same travel lane or mistakenly detect a vehicle in an adjacent travel lane. Enhancements in capabilities in dealing with higher curvature conditions will likely increase driver confidence and functional safety benefits. Some owner manuals recommend not using systems in congestion, while some encourage the use of ACC in congested traffic. The core feature of ACC is that it adjusts vehicle speed to maintain a preset headway to the vehicle ahead and, thus, would be especially beneficial in congested traffic. If the system works well, it could reduce the opportunity for conflicts and provide safety and operational benefits in non-free-flowing traffic.

As is the case in most naturalistic research, this study has several limitations. The driving automation systems evaluated were limited to those implemented in two vehicle models, and it is unknown if the findings would apply to other systems. Participants did not own the vehicles, and they drove them for only one month. Drivers with more experience with the automation systems may use these systems differently. It was unknown if the on-to-off transitions were initiated by systems or drivers, and if drivers turned ACC or Pilot Assist off in response to the systems not operating appropriately, or did so proactively before entering a curve. The analysis did not examine transitions among system states with regard to transitions between straight segments and curves. Drivers might not change the system state immediately when they entered or exited a curve. If there was a lag between the time the driver encountered the curve and the time the system was switched on or off, that might have led to an underestimation of the effects of horizontal curves on use of the driving automation systems.

Driving automation systems face challenges on horizontal curves, even within their intended design domain. Given what is known about the limitations of current implementations of Level 1 and 2 automation on horizontal curves, the decreased likelihood of system use on curves may indicate prudent monitoring of the systems and driving environment by drivers. As noted previously, future implementations that improve functionality may enhance the driver experience and boost drivers' confidence in these systems, which should increase their use. Improved system performance in challenging roadway and traffic environments would maximize any safety benefits.

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