How Might Connected Vehicles and Autonomous Vehicles Influence Geometric Design?

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Abstract: With the continued research on connected and autonomous vehicles showing promise for implementation, how may this influence the future of geometric design of our roads and highways? This paper examines various horizontal, vertical, and cross sectional elements used in design today and how they may be influenced by these new technologically advanced vehicles.

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INTRODUCTION

With connected vehicle (CV) and automated vehicle (AV) technologies continuing to advance and more locations permitting vehicles using such technologies on their roads, we should expect to see a vehicle fleet that contains many of these vehicles in the future. These vehicles will depend less and less on human input to maneuver. A fully-autonomous vehicle will be capable of navigating a roadway without human input. This vehicle senses everything around it and adapts to its environment (Figure 1).

There is much debate on the laws that are needed regarding these vehicles, how they may interact with traditional vehicles, and when this transition to a predominant composition in the fleet may occur. Much of the current research is focused on advancing the technology and infrastructure to make these vehicles a reality. This paper does not focus on those issues, instead it looks at how these vehicles, especially a full fleet of these vehicles, could impact roadway geometrics.

Figure 1 Autonomous Vehicle Source Bigstock.com

There are three components to our roadway system: the road environment, the vehicle, and the road users. The road component includes physical features such as the pavement and roadway geometry; the environment such as weather and lighting; and the operational features such as speed and traffic control. The vehicle includes the vehicle's physical features such as weight, geometrical dimensions, and mechanical performance. The road users include drivers, occupants, and other users of our roadway system such as pedestrians and bicyclists. The road users have different characteristics or human factors. These include the users' knowledge or familiarity of the roadway system, their physiological characteristics such as seeing and hearing, and their skills and behavior such as the ability to act to a situation. All of these components impact the engineers' design of a road.

There are many types of drivers on the road today. There are those that could be considered poor drivers or even impaired drivers (see Figure 2). There are also exceptionally skilled drivers (see Figure 3).

Figure 2 An Impaired Driver Source: Bigstock.com

Figure 3 Highly Skilled Driver Source: Bigstock.com

Then there are all the drivers in between these two extremes. Much of our design criteria has been set to accommodate most vehicles and drivers that we expect to be using our road. Unfortunately, the drivers on each end of the driving age spectrum often have either undeveloped or diminished capabilities that could cause them to fall outside of the engineers' design parameters. Younger drivers have less experience, misjudge risks, and may be pressured by peers (Figure 4). Aging drivers may have decreased vision, physical abilities, and diminishing cognitive abilities (Figure 5). With the baby boomers aging, the older population is one of the fastest growing populations by percentage in the United States.

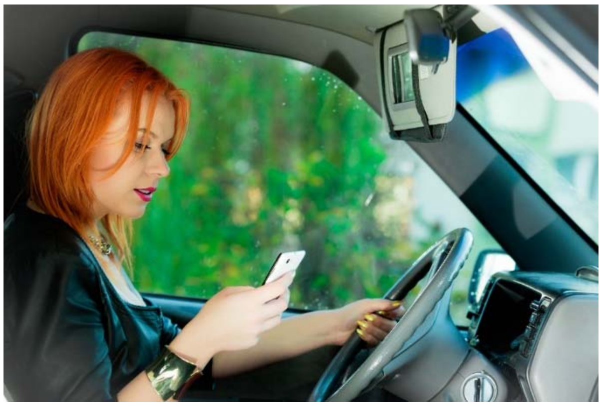

Figure 4 Younger Distracted Driver Source: Bigstock.com

Figure 5 Elderly Driver Source: FHWA

There is also a wide range of vehicles on our roads today that are in various states of condition and many have quite differing physical features. This is a variety of drivers and vehicles to accommodate and if one were to look closely at the design criteria, one would find it varies a bit by criteria, but in general, roadway engineers are designing for a below average driver and a lower performing vehicle. Even with such design guidance to the engineer, there are still many crashes and fatalities. For example, according to the Bureau of Transportation Statistics, there were 35,092 fatalities in 2015 due to crashes in the United States (BTS, 2016). Many of these crashes and fatalities are due to human error (or poor decisions). The vision is that CV and AV vehicles will significantly reduce the number of crashes and fatalities by eliminating the human factors and closely monitoring the vehicle's overall condition. Autonomous vehicles utilize numerous sensors and are driven by a computer with sophisticated software.

There are many types of roads. In general we have a few types that are quite different. There are higher speed roads (see Figure 6) that may have fewer access control points and there are somewhat lower speed urban roads that may have many access points (especially intersections and driveways) (see Figure 7). Let's examine some of the design criteria that could be influenced by this technology and how this may impact our road design. For this paper, only a few geometric design criteria will be examined.

Figure 6 Higher Speed Roadways Source: Bigstock.com

Figure 7 Urban, Lower Speed Roadways Source: USDOT

SIGHT DISTANCE

An important element of design is sight distance. This is the distance required for a driver to perceive an object. Sight Distance impacts the following:

- Offset of objects along the road to provide Horizontal Sight Offset distance (HSO) (See Figure 8 for an example of HSO). This includes such items as:
    - Bridge abutments,
    - Median barriers,
    - Crash walls, and
    - Parapets;

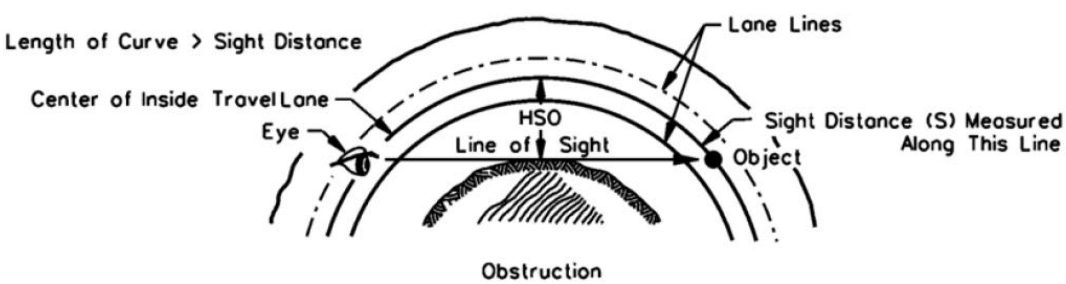

Figure 8 Example Sight Line for HSO Offset, Source: IDOT BDE 2016

- The road itself:
    - Crest curves and
    - Sag curves in conjunction with overhead structures;
- Distance or headway between vehicles which could influence:
    - Capacity of a lane,
    - Intersection storage, and
    - Turn bay lengths; and
- Intersection sight distance (ISD).

One of the most important types of sight distance is stopping sight distance (SSD). SSD is the distance required to perceive an object in a roadway and bring the vehicle to a stop. Per the AASHTO Green Book, "…the sight distance at every point along a roadway should be at least that needed for a below-average driver or vehicle to stop." SSD is used by the engineer to impact numerous components along the road. Equation 1 is the traditional formula for Stopping Sight Distance (SSD) for level roads.

$$SSD = 1.47\ Vt + 1.075\frac{V^2}{a}$$ (Equation 1)

Where:
SSD = stopping sight distance, ft
V = design speed, mph
t = brake reaction time, 2.5s
a = deceleration rate, ft/s^2

In equation 1, the brake reaction time is set as 2.5 seconds. This amount of time exceeds the 90th percentile of reaction time for all drivers per the Green Book. Unfortunately, brake reaction time increases with age, when a driver is tired or fatigued, has a complex task to maneuver, is physically impaired, or is under the influence of alcohol or other drugs. Engineers can account for the more complex situations that may require more than 2.5 seconds of reaction time. Those situations are often designed to provide Decision Sight Distance (DSD) which is a greater distance than SSD. Depending on the AV technology, the processing of data will be quite fast. At the ITE Midwest District Conference in 2016, AV technology was noted to be communicating with its environment 10 times per second under test conditions. Even faster communications would not be surprising to the author. If we remove the human driver from the SSD equation and replace that driver with the AV technology, the brake reaction time could significantly decrease. Let's take a look at reducing the brake reaction time to 1 second and to 0.3 second. Utilizing the formula in Equation 1, we can compare the stopping sight distance for some sample design speeds for several break reaction times of the current 2.5s, 1s and 0.3 s (See Table 1). The sensors are not only fast in processing the data, they are also quite sophisticated such that they are starting to allow recognition of objects that may be behind something else (such as beyond another car or over a hill).

Table 1 Comparison of SSD and Brake Reaction Times of 2.5s, 1s and 0.3s

Design Speed	**t**	**SSD Calculated**	**T**	**SSD Calculated**	**t**	**SSD Calculated**
MPH	Seconds	Feet	Seconds	Feet	Seconds	Feet
40	2.5	300.6	1	212.4	0.3	171.2
50	2.5	423.7	1	313.5	0.3	262.0
60	2.5	566.0	1	433.7	0.3	372.0
70	2.5	727.6	1	573.2	0.3	501.2

Additional research will be needed to establish design guidelines for how SSD could be modified for use in design, but let's take a look at what could happen. For Horizontal Sight Distance, we use an eye height of 3.5 feet and an object height of 2 feet and the driver's eyes see in a straight line. This requires objects to be placed beyond or under the HSO sight line. Objects within this sight line would compromise the driver's ability to stop in time. With this technology, the AV vehicle is not constrained to these dimensions and there will be an opportunity to reduce the offset distances used in design. This would allow objects to move closer to a lane. This would also allow for some sharper horizontal curves to be considered and used.

Looking further at Equation 1, there could be more opportunity for AV to decrease SSD. The second part of the equation 1.075 (V^2/a) is the distance the vehicle travels while the brakes are applied. The deceleration rate in this equation is based on 11.2 ft/s^2 which is the comfortable deceleration rate for approximately 90% of the drivers (Green Book). When there is an urgent need to stop, drivers may decelerate at a rate greater than 14.8 ft/s^2. The AV vehicles could be programmed to provide a greater deceleration rate. Pavement and weather conditions would need to be considered, but if the deceleration rate was increased from 11.2 ft/s^2 to 12.5 ft/s^2, as an example, SSD would further decrease. Table 2 shows an example of how the SSD could be impacted.

Table 2 Comparison of SSD and Brake Reaction Times of 2.5s and 0.3s; Deceleration Adjusted on Level Roadway

Design Speed	**t**	**SSD Calculated (a=11.2 ft/s^2)**	**t**	**SSD Calculated (a=11.2 ft/s^2)**	**SSD Calculated (a=12.5 ft/s^2)**	**SSD Calculated (a=14.8 ft/s^2)**
MPH	Seconds	Feet	Seconds	Feet	Feet	Feet
40	2.5	300.6	0.3	171.2	155.2	133.9
50	2.5	423.7	0.3	262.0	237.1	203.6
60	2.5	566.0	0.3	372.0	336.1	287.9
70	2.5	727.6	0.3	501.2	452.3	386.8

LANES

If the vehicle is fully automated, would vehicle dimensions change? Would mirrors still be needed? If the vehicles are sensing lane lines and other objects (adjacent vehicles and barriers), do we need as much space in a lane or between vehicles? How close could vehicles get to one another side by side? Could the offset between two side by side vehicles drop to one-foot or less? Most lanes are between nine and twelve feet in width. According to the AASHTO "Green Book", the design vehicle dimension for passenger cars is 7.0 feet and most buses and trucks are on the order of 8 to 8½ feet wide. If the vehicles remain the same width, mirrors are no longer needed, and the buffer between vehicles can drop significantly, then we may be looking at narrower lanes for the same amount of vehicles due to this technology (see Figure 9 for a narrow flex lane). That could impact reduce what engineers use for our standard lane widths. That could save on pavement. We may be able to fit more lanes in the same amount of space we designed for traditional vehicles. This savings would occur in horizontal tangent sections. As the horizontal alignment were to increase in curvature, off tracking of vehicles would need to be evaluated and it is expected that lane widths would need to increase to accommodate such off tracking.

Figure 9. Narrow Flex Lane. Source: FHWA, http://www.ops.fhwa.dot.gov/publications/fhwahop10023/chap2.htm

SHOULDERS

Would shoulders still be needed? Perhaps the controlling factor for a shoulder would be to accommodate drainage spreads or to accommodate an AV that is predicting a breakdown. The shoulder would no longer needed to provide site distance. However, could the vehicles be so sophisticated that they "know" not to drive on pavement by sensing a drainage spread and just avoid the inside or outside lane during rain events? Or could the vehicles identify a need for maintenance before it happens and avoid nearly all breakdowns on the road?

ROADSIDE

Most designers utilize a design publication dedicated to roadside safety, *Roadside Design Guide* by AASHTO. Additional guidelines have been published to describe how to test roadside safety devices (MASH). If the AV technology can sense the edges of roads, objects, other vehicles, and the weather, do we still need safety devices or shoulders? We currently protect vehicles from roadside objects and other vehicles. We design the roadside to be traversable and with a clear zone whenever possible to accommodate errant vehicles and provide them a chance for recovery. With the assumption that AV can stay in their lane, couldn't we eliminate most, perhaps all, of these safety features? No more guardrail, no more attenuators, no more cable median barrier, no more concrete median barrier and crash walls. We would be able to build steeper slopes without clear zones or barrier (see Figure 10). This would be a tremendous cost savings on earthwork and roadside safety features.

Figure 10. Example of a Steeper Grade That May No Longer Warrant Barrier Protection
Source: FHWA http://www.fhwa.dot.gov/engineering/geotech/pubs/nhi10024/nhi10024.pdf

URBAN ENVIRONMENT

The urban environment was briefly touched on earlier. Autonomous vehicles could significantly impact the paved footprint. One location where significant changes could occur is at intersections.

Intersections

With the AV sensing other vehicles and communicating with other vehicles, there is the potential to eliminate stop signs and traffic signals. The vehicles could be programmed and managed for each to take the most efficient timing when passing through an intersection. As vehicles pass through an intersection, conflicting vehicles would either wait or the traffic streams could be adjusted by changing the approach speeds of vehicles to form gaps for conflicting vehicles to pass through. Intersection delay should decrease and capacity of each lane should increase. Turn bays could shorten in length or even be eliminated. Many medians used to serve as a buffer between traffic or to control turning movements, could be eliminated. Intersection sight distance would become irrelevant. The vehicles appear to be heading towards sensors that could “see” around objects in corner sight lines at intersections. Gaps would be established by the sophisticated programming and adjusting of vehicles. As with higher speed roads, urban streets could narrow, but additional space would need to be provided at locations of turns to accommodate vehicle wheel path offsets and overhangs. Traffic control costs could be significantly reduced by eliminating traffic signals and potentially signs.

Parking

Both the urban and suburban setting would be impacted by these vehicles. There are a few models being watched and evaluated regarding ownership of these vehicles. One possibility would be that a person owns their own personal AV. Another possibility would be shared car type AVs. If the shared vehicle model plays out, there may be a few large storage locations that are fleets of AV vehicles waiting to be summoned? Would AV vehicles park at stores and other locations, or would they just drop off the occupants go to a nearby parking area and then come back and get the passengers or be rerouted to pick up others? Could this reduce the amount of on-street parking (See Figure 11)? Eliminating on-street parking could further narrow our paved foot print. If the public no longer owns personal vehicles, would driveways be needed at homes? Could many driveways be eliminated? This could really impact the guidelines used for designing access management.

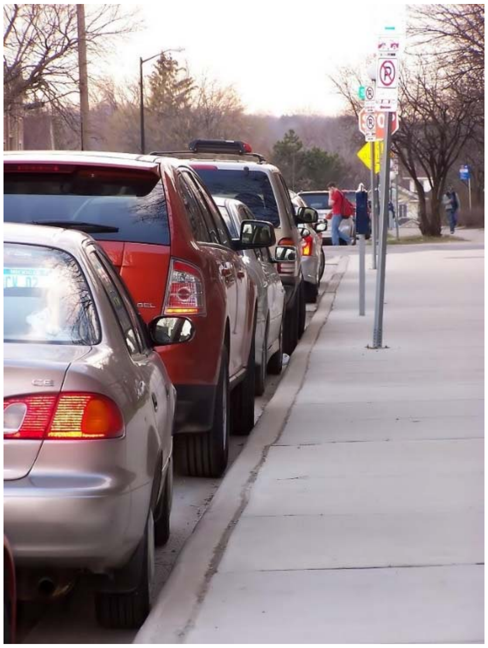

Figure 11 Would On-Street Parking Be Needed? Source: Bigstock.com

Figure 12 Are Driveways Needed for Vehicles? Source: Bigstock.com

OTHER CONSIDERATIONS

The design discussed so far has all been for permanent roads. Other impacts could be needed for temporary conditions such as work zones. There could be geometric impacts, but there may be more of a need to add things to the work zones that assist the AV (Figure 13). This will be a very important future needed area of study. We may also learn that the technology needs something more than what we design now for our roads. We may learn that pavement striping must meet very specific requirements or that signs need to have higher standards of quality or sensors may need to be placed in certain locations along or in the roads. We may learn that standards of snow removal may be required to limit the timing of snow and ice on roads or we may learn there could be requirements on how the snow and ice is removed.

Figure 13 Work Zones Source Bigstock.com

CONCLUSION

This discussion has examined potential geometric design impacts once we have a full fleet of autonomous vehicles. We may not reach that point as there could be vehicles that either transition much later into CV/AV technology or never do. Possible candidates are maintenance vehicles, construction equipment, police cars, garbage trucks, and likely others (Figure 14).

Figure 14 Maintenance Vehicles Source: Bigstock.com

In the author's opinion, significant design criteria changes will not occur until the traditional vehicles with drivers are separated (or even removed completely) from the CV/AV vehicles. Once we start to have dedicated CV/AV lanes, we should expect to see changes to our geometric design guidelines. NCHRP has commenced researching this transition to dedicated lanes under NCHRP 20-102(08) "Dedicating Lanes for Priority or Exclusive Use by CVs and AVs". Even under the separated conditions of CV/AV dedicated lanes, the CV/AV vehicles will still need to account for traditional vehicles being in their traffic stream from time to time such as for emergency vehicles, maintenance vehicles, and when traditional drivers simply choose to ignore the requirement that those lanes are for the exclusive use of CV/AV vehicles. More collaboration is needed between vehicle design engineers and roadway design engineers to maintain current geometric design guidelines so that our future highways and streets will accommodate the needs of our roadway users and our vehicles.

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