2021 TRB ANNUAL MEETING Transportation Research Board
100TH Annual Meeting A Virtual Event January 2021

TRB Session 1435. January 29, 2021

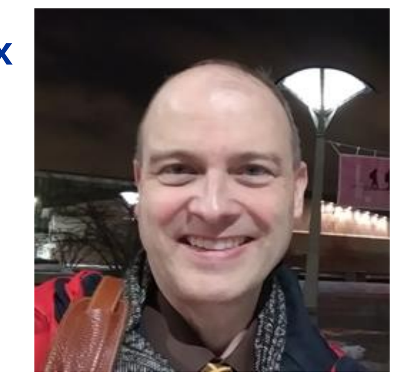
How Autonomous Vehicles May Influence Vertical Curves, At-Grade Railroad Crossings, And Ramp Terminals

HANSON
Engineering | Planning | Allied Services

David R. McDonald, Jr., P.E., Ph.D., PTOE
Chief Roadway Engineer
dmcdonald@hanson-inc.com

Select This Box To Hear from the Author

To hear the audio you may need to modify a setting. In Adobe: *Edit > Preferences > 3D & Multimedia* and then select the **Enable playing 3D content** checkbox.



Abstract

This paper builds on the author's 2017 work on how connected vehicles/autonomous vehicles (CV/AV) may impact the geometric design of roads (1, 2). The previous work explored the potential modifications to stopping sight distance and provided some thoughts on the potential impacts to lane and shoulder widths, roadside modifications, intersections, and parking. How these differences between the human driver and the expected performance of fully automated vehicles may impact the design of roads are further explored in this paper, with attention on vertical curves, at-grade rail crossings, and ramp terminals. Three situations are considered: AV-only roads, AV-separated roads, and mixed-use roads (AV and human-driven vehicles in the same vehicle stream).

Levels of Automation and The Driver

Road owners (public and private) will have to determine when AV vehicles will be the design vehicle and when traditional, human-driven vehicles will be the design vehicle, or if both may be required design vehicles. The design could be different between the two vehicle types. The levels of automation range from 0 (no automation; the driver is in full control) to 5 (full automation; the vehicle can perform all driving functions) (3).

With AVs, the driver will be a computerized system utilizing a variety of sensors. No standardization has been established on the type of sensors AVs will include. OEMs are evaluating the use of different technologies and combinations of technologies.

One of the challenges that will affect future research is the technology is not expected to be uniform in each AV. It is expected the OEMs will continue developing and advancing AV technologies so they meet level 5 automation.

Figure 1 Autonomous Vehicle Source Bigstock.com

Human Driver Design Parameters

HEIGHTS

Passenger Cars per AASHTO "Green Book" (4)
Vehicle Height: 4.3 feet
Driver's eye height: 3.5 feet above the roadway surface.
Object Height:

- **About 2 feet in height (generally representing taillights) or**
- **3.5 feet in height (top of an approaching vehicle)**

Location: Driver is in about the center of the vehicle and the vehicle is centered within the lane.

PERCEPTION AND REACTION TIME (PRT)

This is called "brake reaction time" if the expected outcome is the driver applying the brakes. "Green Book" selected 2.5 seconds to be an adequate brake reaction time for conditions that are more complex than simple conditions, but not for the most complex situations.

When the PRT is needed for a stop, this distance is termed "stopping sight distance" (SSD).

When more reaction time is needed for very complex situations, the "Green Book" applies these various times to a distance called "decision sight distance" (DSD). Depending on the type of maneuver expected and where, the time taken by the driver to execute the maneuver goes from 3.0s to as high as 14.5s for DSD (4).

The basic SSD equation for roadways (generally between -3% and +3% grades) is noted below as Equation 1 and is a common equation found in many roadway design manuals.

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

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

AV Impacts

The impacts CV/AV vehicles may have on SSD were discussed in the prior paper (*1*). Equation 1 and other similar design equations have two key components that can differ between a human and an AV: PRT (in this example, the decision to break) and the rate of execution (in this example, the rate of deceleration).

DECELERATION

The rates of deceleration have been documented in various studies. The "Green Book" notes that most drivers decelerate at 14.8 ft/s^2 or greater to a stop. For SSD, they recommend a deceleration rate of 11.2 ft/s^2 and note that is a comfortable rate for most drivers. The "Green Book" indicates that the 11.2 ft/s^2 takes into account friction available between tires and a wet road surface (4). Other deceleration rates used in design, as noted in the "Green Book," include:

- **Deceleration rate of 11.2 ft/s^2 for roads approaching railroad at-grade crossings (used to establish clear sight lines).**
- **Exit terminal (ramps) deceleration rates range from 2.1 to 6.2 ft/s^2 for vehicles traveling from a higher-speed roadway onto a lower-speed exit ramp. These deceleration rates were determined by assuming a constant deceleration rate in Equation 2 and applying this equation to "Green Book" Table 10-6. A sample of this table, with the calculated deceleration rates, is shown in Table 1.**

$$a = (V_2^2 - V_1^2)/2L \quad \text{(Equation 2)}$$

Where:
a = deceleration rate, ft/s^2
V_1 = initial speed, ft/s
V_2 = final speed, ft/s
L = deceleration length (ft)

Table 1. AASHTO Table 10-6, 2018 Green Book (4)

			Deceleration Length, L (ft) for Design speed of Controlling Feature on Ramp, V' (mph)							
			30		35		40		45	
Highway Design Speed (mph)	Diverge Speed, Va (mph)	Diverge Speed, Va (ft/s)	Average Running Speed at Controlling Feature on Ramp, V'$_a$ (mph)							
			26 mph		30 mph		36 mph		40 mph	
			38.1 ft/s		44.0 ft/s		52.8 ft/s		58.7 ft/s	
			L	a (ft/s^2)	L	a (ft/s^2)	L	a (ft/s^2)	L	a (ft/s^2)
45	40	58.7	250	(4.0)	220	(3.4)	-		-	
50	44	64.5	315	(4.3)	285	(3.9)	225	(3.1)	175	(2.1)
55	48	70.4	380	(4.6)	350	(4.3)	285	(3.8)	235	(3.2)
60	52	76.3	430	(5.1)	405	(4.8)	350	(4.3)	300	(4.0)
65	55	80.7	470	(5.4)	440	(5.2)	390	(4.8)	340	(4.5)

References

1. McDonald, D. How Might Connected Vehicles and Autonomous Vehicles Influence Geometric Design? Presented at fifth Urban Street Symposium, Raleigh, N.C., 2017.
2. McDonald, D. How Might Connected Vehicles and Autonomous Vehicles Influence Geometric Design? Presented at 97th Annual Meeting of the Transportation Research Board, Washington, D.C., 2018.
3. *SAE International Releases Updated Visual Chart for Its "Levels of Driving Automation" Standard for Self-Driving Vehicles.* Society of Automotive Engineers (SAE) International. https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles. Accessed March 3, 2019.
4. AASHTO. *A Policy on Geometric Design of Highways and Streets*, 2018.
5. *Safety Effects of Horizontal Curve and Grade Combinations on Rural Two-Lane Highways*. FHWA. https://www.fhwa.dot.gov/publications/research/safety/13077/002.cfm. Accessed October 2, 2019.
6. *Railroad-Highway Grade Crossing Handbook - 4 Identification of Alternatives*. FHWA. https://safety.fhwa.dot.gov/hsip/xings/com_roaduser/07010/sec04c.cfm. Accessed September 27, 2019.

TRB 2021 ANNUAL MEETING
Transportation Research Board
100th Annual Meeting
A Virtual Event
January 2021

How Autonomous Vehicles May Influence Vertical Curves, At-Grade Railroad Crossings, And Ramp Terminals

HANSON
Engineering | Planning | Allied Services

Potential AV Ramp Terminal Lengths

If the vehicles are 100% AV, 3 adjustments can be made to Eq. 2 to calculate Potential AV ramp terminal deceleration lengths (see Table 2 for a sample of the results):

- **decelerate at 11.2 ft/s^2 ,**
- **maintain vehicle at freeway speed until start of divergence, and**
- **Decelerate to ramp's D.S. instead of avg. running speed.**

Table 2 Potential AV Design Values – Ramp Decel. Length

Highway Design Speed V (mph)	Diverge Speed, Va (mph)	Diverge Speed, Va (ft/s)	Average Running Speed at Controlling Feature on Ramp, V'$_a$ (mph): 30 mph, 44.0 ft/s, L	a (ft/s^2)	35 mph, 51.3 ft/s, L	a (ft/s^2)	40 mph, 58.7 ft/s, L	a (ft/s^2)	45 mph, 66.0 ft/s, L	a (ft/s^2)
45	45	66.0	108	(11.2)	77	(11.2)	-		-	
50	50	73.3	154	(11.2)	122	(11.2)	86	(11.2)	46	(11.2)
55	55	80.7	204	(11.2)	173	(11.2)	137	(11.2)	96	(11.2)
60	60	88.0	259	(11.2)	228	(11.2)	192	(11.2)	151	(11.2)
65	65	95.3	319	(11.2)	288	(11.2)	252	(11.2)	211	(11.2)

Similarly, for on-ramps, the impacts of 100% AVs can be explored. See the paper for developed tables.

- **Increase the vehicle acceleration to just under the lowest manufactured vehicle's acceleration rate, 7.0 ft/s^2**
- **Start accelerating exactly and the controlling point**
- **Traffic stream has created a gap for the vehicle.**
- **The ramp vehicle will merge at mainline traffic speed.**

Crest Curves

Equations 3, 4, 5, and 6 are used by many design guidelines to calculate the minimum lengths of crest curves. Examples are these curves are shown in Figure 2.

$$L = 2S - \frac{200(\sqrt{h_1}+\sqrt{h_2})^2}{A} \quad (3)$$

When S is greater than L

$$L = \frac{AS^2}{200(\sqrt{h_1}+\sqrt{h_2})^2} \quad (4)$$

When S is less than L

$$K = L/A \quad (5)$$

$$K = \frac{S^2}{200(\sqrt{h_1}+\sqrt{h_2})^2} \quad (6)$$

Where:

L = length of vertical curve, ft
A = algebraic difference in grades, percent
S = sight distance, ft
h_1 = height of eye above roadway surface, ft
h_2 = height of object above roadway surface, ft
K = horizontal dist. needed to produce a 1% change in gradient

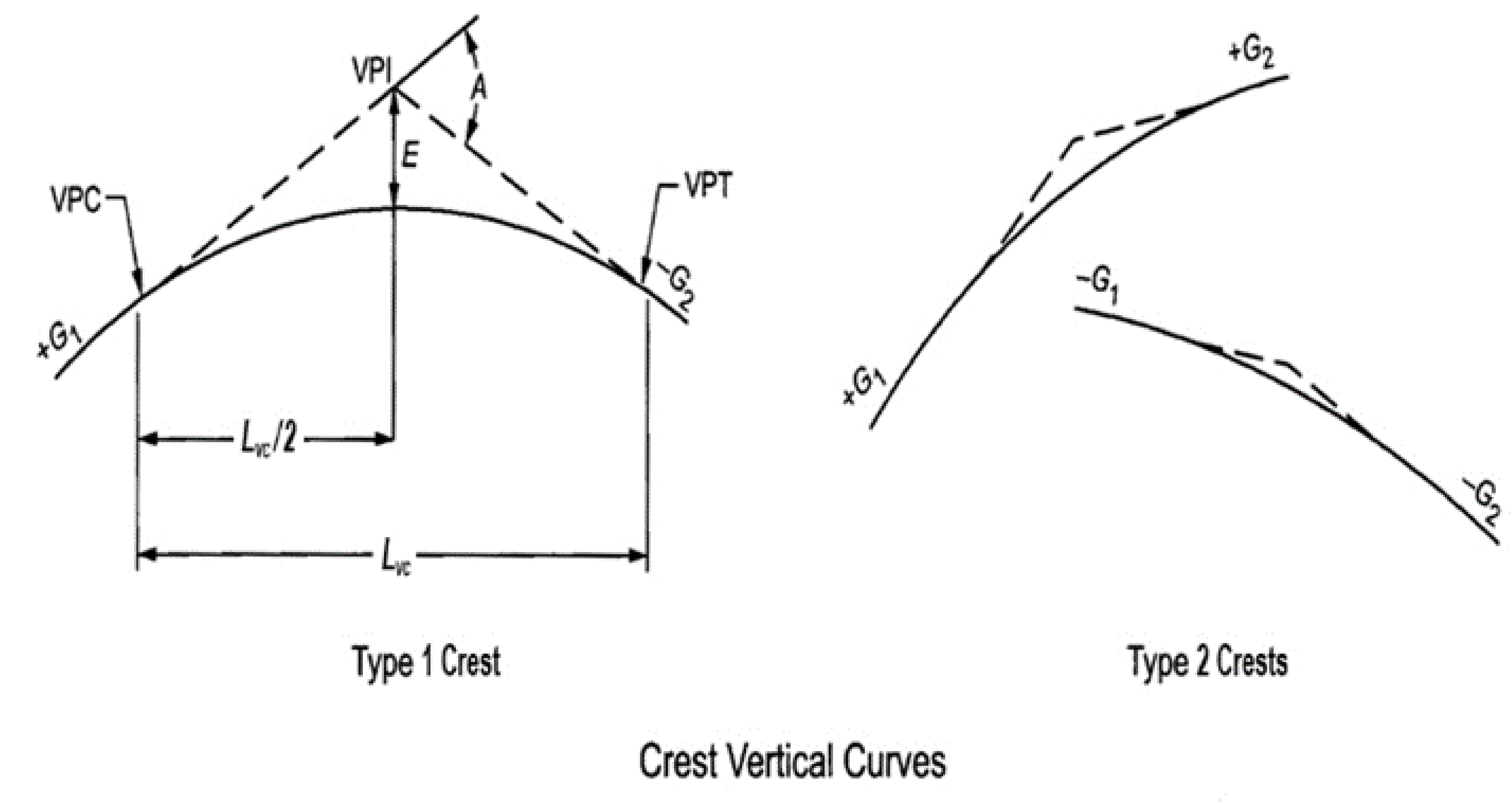


Figure 2 Example Crest Curves Source FHWA (5)

With Crest Curves, 4 components in the equations can be impacted by a fleet of all AVs:

- **PRT could decrease from 2.5s to 0.1s**
- **Deceleration Rate from 11.2 ft/s^2 to 14.8 ft/s^2**
- **Driver Eye Height (from 3.5 ft to top of vehicle ~ 4.3 ft)**
- **Object Height (from 2.5 ft to 0 ft –if AV reads markings)**

See Table 3 for an example of how Crest Curve Design Values could change for a fleet of AVs (this assumes line of sight is still important for AVs).

Table 3. Crest Curves: Green Book vs Potential AV Values

	h_1 (ft)= 3.5; h_2 (ft)= 2.0; a = 11.2 ft/s^2					h_1 (ft)= 4.3; h_2 (ft)= 0.0; a = 14.8 ft/s^2				
Design Speed	t	SSD Calc.	SSD Rounded for Design	Rate of Vertical Curvature, K		t	SSD Calc.	SSD Rounded for Design	Rate of Vertical Curvature, K	
mph	s	ft	ft	Calculated	Design	s	ft	ft	Calculated	Design
30	2.5	196.6	200	18.5	19	0.1	69.8	70	5.7	6
35	2.5	246.2	250	29.0	29	0.1	94.1	95	10.5	11
40	2.5	300.6	305	43.1	44	0.1	122.1	125	18.2	19
45	2.5	359.7	360	60.0	61	0.1	153.7	155	27.9	28

At-Grade RR Crossings

Two sight lines and related sight distances are important for this design situation. 1. Corner sight distances on the approach are analyzed such that clear areas are provided to vehicles approaching the railroad tracks 2. clearing distance requirement: a clear distance parallel to the track that is void of vegetation and obstacles. This distance is needed for stopped vehicles to determine when an adequate clear gap from a soon-to-be crossing train exists so the vehicles may safely proceed. This is also shown in Figure 3 and in this example is termed "track sight distance" by this agency. If technology allows, AVs may be able to sense approaching trains without the needing a line of sight. This would eliminate or significantly reduce the size of clear area needed near at-grade rail crossings.

Angled crossings may be acceptable. A curved road or curved rail alignment could become acceptable at a crossing. Similar adjustments to intersection design could also apply, because the approach corner sight distance is very similar to the intersection sight distance prescribed at intersections. This sight distance should be studied further as another design element and the associated criteria that could be impacted by AVs.

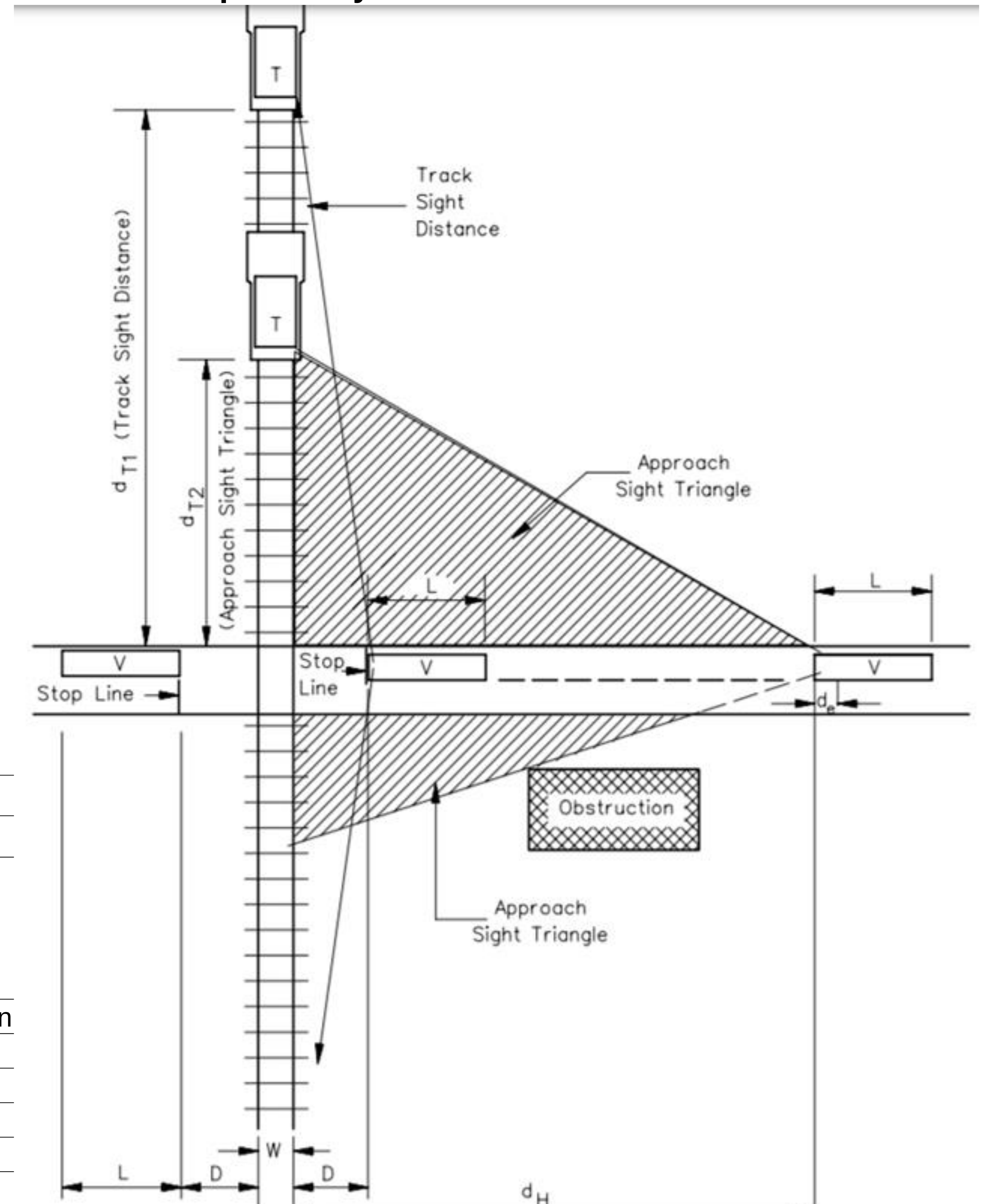


Figure 3 Example of Approach Sight Triangles for Vehicles, At-Grade RR Crossing Source FHWA (6)

Author Thoughts

1. **As long as human driven vehicles are part of the traffic stream, road design should continue to follow our traditional design guidelines (such as AASHTO Green Book).**
2. **If the vehicle fleet for a road is fully AV, this paper presents opportunities to change design criteria related to sight distances, acceleration, and deceleration**
3. **Interim condition, mixed human and AV: AV should be able to adapt to the currently designed roads. A way to take advantage of AV technology would be to provide AV only lanes.**