Evaluating the relationship between decision sight distance and stopping sight distance: open roads and road tunnels

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Abstract

The paper introduces the implementation of highways' stopping sight distance (SSD) and decision sight distance (DSD) for highways and road tunnels. The paper reviews and documents the developments of the highway design parameters and constructed models of the SSD and DSD in Israel, specifically the parameters of perception reaction time (PRT) and deceleration coefficient required for SSD, and DSD three model elements: pre maneuver distance, braking distance, and distance traveled during maneuver operation. This overview is a perquisite for modeling and calibrating the relationship between DSD and SSD. This direct relationship simplifies the process of evaluating the decision sight distance based on stopping sight distance record without the need of strenuous estimation of the DSD model parameters. The paper focuses first on open roadways and proposes adjusted DSD-SSD models for road tunnels, and an equivalent model as well.

Keywords: stopping, decision, sight, roadway, tunnel.

1. Introduction

The design of interurban highway system is important for the economy and for the fast growth rate of car ownership. A major purpose in highway geometric design is to ensure that the driver is able to see any possible road hazard in sufficient time to take action and avoid an accident. Motor vehicles are operated by drivers that have significant differences in their level of experience and skills. Sight distance is a fundamental issue in highway design policy which directly affects the highway alignment, specifically vertical curves, and horizontal curves, in order to maintain highway safety for the drivers. Highway safety in that matter means safe stopping, safe passing, and safe maneuvering upon an obstruction or any other need of changing the route. Sufficient sight distance must be provided to allow for drivers of all skills and training levels to stop or maneuver around obstacles on the roadway surface and make safe lane changing or turns.

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The first part of this paper overviews the details of two sight distance types which are implemented in the Israeli geometric design policy and controls for rural (interurban) highways (IMOT 2012): stopping sight distance (SSD), and decision sight distance (DSD). This overview covers the parameters of perception reaction time (PRT) and deceleration coefficient required for SSD, and DSD three model elements: pre maneuver distance, braking distance, and distance traveled during maneuver operation. The assessed sight distance design values function as an input for the major purpose of this study which is calibrating a model which directly (empirically) formulates the relationship between DSD and SSD. Such a simplified correlation has not been found in the literature except a rough approximation documented in the British highway design guidelines (DMRB 1993, NRA 2007). The paper ends up with a proposed implementation of SSD and DSD in designing the interurban highway network according to highway classification (Table 8).

2. Stopping sight distance

A major purpose in highway geometric design is to ensure that the driver is able to see any possible road hazardous object in sufficient time to take action and avoid a crash. Stopping sight distance (SSD) is the most important of the sight-distance considerations since sufficient SSD is required at any point along the roadway. SSD is the distance that the driver must be able to see ahead along the roadway while travelling at or near the design speed and to safely stop before reaching an object whether stationary or not. SSD can be limited by both vertical and horizontal curves. The fact that it impacts the design radius of both curves makes SSD so fundamental in the geometric design process (Bassan 2012, 2016).

The stopping sight distance has two components: (1) the distance travelled during the driver's reaction time, usually 2.5 seconds for open roadways; (2) the distance travelled during braking by implementing equivalent deceleration rate (d, meter/sec2).

$$SSD = \frac{t_R}{3.6} \cdot V_d + \frac{V_d^{\,2}}{2 \cdot 3.6^2 \cdot d} \qquad (1)$$

where:

SSD – Minimum stopping sight distance (m)

Vd– Design speed (km/hr). It is approximately the 85th percentile operating speed, and is slightly higher than the posted speed limit.

d– Deceleration of passenger cars (m/s2), equivalent to the longitudinal friction coefficient (f) multiplied by the acceleration of gravity (g=9.81 m/sec2).

t_R– Perception reaction time (s), usually 2.5 seconds

The formula assumes level terrain. Ascending grade decreases the SSD, and descending grade increases the SSD. Trucks, in general, require longer stopping sight distance than passenger cars for a given design speed due to inferior braking characteristics (Bassan 2012, 2015, 2016).

2.1 SSD parameters: literature review

Perception Reaction Time (PRT)

The standard design value that must be used in rural roads is 2.5 seconds (Transit 2003, Austroads 2003, TAC 1999, AASHTO 2004, 2011, Lamm et al. 1999). Table 1 presents a comparison of the PRT parameter in several newer highway geometric design policy guidelines: Australia (Austroads 2009), and PIARC (2003), propose possible lower PRT values than the conventional value of 2.5 seconds in certain circumstances and only UK (NRA 2003) proposes a lower value of 2.0 seconds.

Deceleration and Longitudinal Friction Coefficient

Studies documented by Fambro et al. (1997) have shown that most drivers decelerate at 4.5 m/s^2 (0.459•g) during braking to an unexpected object in the roadway. Experiments showed that 90% of drivers decelerates at rates greater than 3.4 m/s^2, 0.347•g (AASHTO 2004, 2011).

AASHTO (2004, 2011) recommends on 3.4 m/s^2 as a reasonable deceleration rate for obtaining the stopping sight distance and it no longer provides the friction coefficient design values. Most vehicles are able to brake in this rate at least, under wet pavement conditions. The longitudinal friction coefficient in wet pavement surfaces and the modern vehicle braking capabilities enable larger equivalent deceleration rate, than this deceleration rate, e.g. 3.4-4.5 m/sec^2 (AASHTO 2004, 2011, Bassan 2012).

Also, Durth and Bernhard (2000) recommended that the deceleration threshold for calculating the sight distance would be 4.5 m/s^2 after considering the antilock braking systems (ABS) and wet pavement surface. Table 2 presents a comparison of the longitudinal friction coefficient (ft) parameter in several highway geometric design guidelines.

Table 1: Typical comparison of perception-reaction time (sec) parameter in open roadways (partially based on Bassan 2015).

Country	***Open roadways***
Australia (Austroads 2009)	2.5 sec: Absolute minimum for rural highway (high design speed). 2.0 sec: for urban arterial (high design speed) or alerted drivers on rural highways. 1 sec: Constrained condition with maximum vigilance.
Australia (Austroads 2003)	2.5 sec: standard for rural roads. 2.0 sec: minimum reaction time where it may not be practicable to design for a 2.5 second reaction time, such as low-speed alignments in difficult terrain.
UK (NRA 2003)	2 sec
USA (AASHTO 2011)	2.5 sec
PIARC (2003), TAC (1999)	2.5 sec like Canada (9) for 90% of drivers. 0.5-2.0: for alerted and skilled drivers. 3.0-4.5: for non-skilled drivers.

Table 2: Typical comparison of deceleration coefficient in open roadways

Country	***Open roadways***
Australia (Austroads 2009)	0.46·g: mean value for braking on a wet sealed road (maximum value when decelerating at an intersection). 0.36·g: 90th percentile value for braking on a wet sealed road. 0.26·g: normal and comfort deceleration on sealed roads. 0.61·g: braking on dry sealed roads (**).
Australia (Austroads 2003)	0.48·g to 0.35·g for Vd= 60km/hr to Vd=120 km/hour respectively.
UK (NRA 2003)	0.25·g, (desirable value): deceleration for maximum driving comfort (wet surface). 0.375·g, (absolute value): one step relaxation (wet surface)
USA (AASHTO 2004, 2011)	d=3.4 m/sec^2 = 0.346·g
Canada. TAC (1999)	0.33·g to 0.28·g for Vd= 60km/hr to Vd=120 km/hour respectively.
Lamm et al. (1999), Germany	0.43·g to 0.32·g for Vd= 60km/hr to Vd=120 km/hour respectively. Values analyzed by braking distance model.

* *g=9.81 m/sec^2*

*** The justification for using the specification for braking on a dry road is based on the difficulty in achieving practical sight distance criteria, specifically when horizontal curves produce excessive lateral offsets to roadside barriers or structures (Austroads 2009) and on typical dry climate or road tunnels.*

2.2 Recommended SSD parameters: Israel perspective

The recommended perception-reaction time (PRT) is a uniform value of 2.5 seconds: 1.5 seconds for perception and 1.0 second for reaction prior to brake application.

The pavement friction coefficient (f) conventional values correspond to various design speeds.

The recommended equivalent deceleration rate (d) is based on: field experiments conducted in Germany by: Lamm et al. (1999), RAA (2008), Bassan (2012). This weighted deceleration rate which is different from other international guidelines such as AASHTO green book (2004, 2011) especially for the lower range of design speeds (50-80 km/hour), takes into account modern braking systems; the quality of tires, which strongly affects the skidding longitudinal friction coefficient between a wet pavement and the tires; and the quality of the pavement (e.g. Stone Mastic Asphalt, SMA).

In spite of the improvement of modern braking systems (generating higher deceleration rates) they still work harder in braking at high speeds due to the aerodynamic resistance force, and essentially result in slightly lower equivalent deceleration rates (Bassan 2012). Therefore, the lower design speeds (30-60 km/hour) were given a considerably higher equivalent deceleration rate (4.3 m/sec^2), whereas the higher design speeds (120-140 km/hour) were given a lower design value of deceleration rate (3.7 m/sec^2).

The equivalent friction coefficient and weighted deceleration are presented in Table 3. These design values assume that the design vehicle is passenger car as opposed to a truck. The stopping sight distance (SSD) values are also presented in Table 3, based on the weighted deceleration recommended values and Equation 1. Also included in Table 3 are SSD design values according to AASHTO (2004, 2011). These design values are based on a fixed deceleration rate of 3.4 m/sec^2: a comfortable deceleration (for 90 percents drivers, AASHTO 2011) which does not depend on design speed)...

Table 3: Equivalent PRT, Deceleration, Friction, and SSD Values Recommended for Design Speed

Design speed (km/hour)	***30***	***40***	***50***	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***
PRT (sec)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
f_{eq}	0.438	0.438	0.438	0.438	0.428	0.418	0.408	0.398	0.387	0.377	0.377	0.377
d (m/s^2)	4.3	4.3	4.3	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.7	3.7
SSD computed (m)	29	43	58	74	94	116	141	169	200	234	267	302
Design SSD (m), rounded for design.	**30**	**45**	**60**	**75**	**95**	**120**	**145**	**170**	**200**	**235**	**270**	**305**
Design SSD (m), USA, AASHTO (2011)	35	50	65	85	105	130	160	185	220	250	285	320

3. Decision sight distance (DSD)

Decision sight distance (DSD) is defined as the distance at which drivers can detect a hazard or signal in a cluttered roadway environment, recognize it (or its threat potential), select the appropriate speed and path, and perform the required action safely and efficiently (Alexander and Lunenfeld 1975).

The decision sight distance (DSD) enables a maneuver which is less risky than the braking maneuver of stopping sight distance until a complete stop. The driver should be able to choose the speed and the suitable path for the specific maneuver required and correct an erroneous maneuver action. This distance is usually suitable when drivers must make complex decisions, when information is difficult to find or is unusual, and when unusual maneuvers are required. Therefore, highway civil engineers should use decision sight distance where information might be perceived incorrectly, making decisions is required, or where control actions are inevitable.

The DSD might be implemented before critical points of the road alignment such as un-signalized intersections, interchanges (merging and diverging ramps), acceleration and deceleration lanes, weaving zones, abrupt changes in the alignment profile, and warning or guidance areas. The Israeli highway design guidelines propose a new DSD model which consists of three driving maneuvers stages:

(1) The pre-maneuver stage.

(2) The braking action from the free flow speed (the design speed for the purpose of highway design) to the maneuver speed.
(3) The maneuver operation.

The representative pre-maneuver time consists of 2 seconds for perception and recognition and 3.5 seconds for deciding the maneuver solution. Therefore, the total pre-maneuver time is 5.5 second and does not depend on the design speed. This pre-maneuver time value is based on the lower bound of McGee's (1979) "hazard avoidance model" (including field work that was performed to operationally validate the DSD model results) which does not include the second phase of the proposed model of this study (braking action).

The maneuver time is the time it takes the driver to fully complete the maneuver (lane change, bypassing or escaping from the hazard, detours or construction areas, exit lane drop, etc.). It involves a change in path and/or speed depending upon the nature of the hazard. Change in path for example signifies that a lane change would be the selected maneuver. A typical maneuvering time range is 3.5-4.5 seconds (based on McGee (1979) and AASHTO (2004, 2011)), even though McGee's range for generating DSD design values is 4-4.5 seconds. The upper limit corresponds to the lowest design speed and the lower limit is appropriate with the highest design speed. The intermediate values of maneuver time (in the current study) were generated by linear interpolation as introduced in Table 4.

The maneuver velocities (VM) are lower than the design speed by 10-60 km/hour. As the design speed increases the algebraic difference between Vd and VM increases as well. These velocities are based on empirical evidence gained in Australia (Austroads 2003), where the second and third phase of the proposed DSD model are unified to one phase.

3.1 DSD model equation

The DSD proposed model is introduced in Equation 2:

$$DSD = \frac{5.5}{3.6} \cdot V_D + \frac{{V_D}^2 - {V_M}^2}{2 \cdot 3.6^2 \cdot d} + \frac{T_M}{3.6} \cdot V_M = 1.53 V_D + \frac{{V_D}^2 - {V_M}^2}{25.92 \cdot d} + \frac{T_M}{3.6} \cdot V_M \quad (2)$$

DSD – decision sight distance (m)
Vd - design speed (km/hour)
d – average deceleration rate (m/sec^2), as applied for SSD (design values of Table 3).
T_M – maneuver time (sec)
V_M – average maneuver speed.

3.2 Suitable cases for model implementation

The calculated decision sight distance (DSD) covers the following driving situations:
(1) A non-initiative decision of the driver, while the driver does not expect the hazard. The driver has to consider an escaping maneuver.
(2) An initiative decision of the driver, while the driver expects the hazard e.g. lane change before turning. In such case, the pre-maneuver time is relatively short and the speed reduction is insignificant or even does not exist.
(3) A decision of braking and stopping with utmost comfort, while the pre-maneuver time can be higher than the perception-reaction time that is generally

used for stopping sight distance (SSD) calculation. The total result of DSD computation covers this case even though the DSD components are different.

Table 4 presents the DSD model design parameters and its resulted design values. Also included in Table 4 are DSD values proposed by AASHTO (2004, 2011). These values refer to an avoidance maneuver where the pre maneuver time is larger than the brake reaction time, to provide the driver additional time to detect and recognize the roadway or traffic situation, identify alternative maneuvers, and initiate a response at critical locations. The supplemented design values refer to avoidance maneuver types C or D: speed or path or direction change without a braking component for rural road and suburban road respectively. These maneuver types do not include a braking component but do include an increased fixed value of pre maneuver plus maneuver time. This fixed value (pre maneuver time plus maneuver time) ranges between 10.2 seconds to 11.2 seconds for maneuver type C (rural road) and between 12.1 to 12.9 for maneuver type D (suburban road) ,based on AASHTO (2011). In rural roadways the maneuver process is assumed to be faster than in suburban roads where the driving situation might generate more conflicts to the driver. The DSD proposed values based on Eq. 2 are slightly shorter but similar to maneuver type C, applied for rural roadways in the US (AASHTO 2011).

Another application of DSD is traffic control and Intelligent Transportation Systems. The DSD length could be utilized to examine the necessity of advance warning message sign. The sign might assist the driver to reduce the pre-maneuver time component of the DSD specifically the detection and recognition, and reduce the probability of colliding the hazard. If the sighting distance is too short, then the warning sign could inform the driver which maneuver or maneuver alternatives should be considered in order to escape from the obstruction:

Table 4: Decision sight distance parameters, computed and design values.

Design speed (km/hr)	***30***	***40***	***50***	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***
Maneuver speed (km/hr)	25	30	35	40	50	50	60	60	70	80	80	80
Deceleration (m/sec^2) [1]	4.3	4.3	4.3	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.7	3.7
Maneuver time (sec)	4.5	4.5	4.39	4.28	4.17	4.06	3.94	3.83	3.72	3.61	3.50	3.50
DSD values (m), computed	**80**	**105**	**131**	**158**	**187**	**216**	**247**	**280**	**314**	**347**	**386**	**430**
DSD design values (m), rounded	**80**	**105**	**135**	**160**	**190**	**220**	**250**	**280**	**315**	**350**	**390**	**430**
DSD type C (AASHTO 2011) [2]	85	115	145	170	200	230	270	315	330	360	390	420
DSD type D (AASHTO 2011) [3]	95	125	170	205	235	270	315	355	380	415	450	485

(1) Deceleration rates were adopted from SSD
(2) Maneuver C: speed, path, direction change on rural roadway.
(3) Maneuver D: speed, path, direction change on suburban roadway.

4. DSD-SSD model calibration

Figure 1 presents a scatter plot of the decision sight distance (y axis) and the stopping sight distance (x axis). This scatter plot was constructed by employing data points for design speeds within intervals of 2 km/hour and interpolation of SSD's and DSD's parameters accordingly, based on equations 1, and 2. The scatter plot (Figure 1) therefore presents actual conditions (covering a full range of design speeds: 30-140 km/hour) in order to generate a mathematical relationship between DSD and SSD.

By examining the scatter-plot presented in Figure 1 it appears that a natural logarithmic model would fit the data points practically well. The proposed general form of a model that reflects the relationship between DSD and SSD is therefore as follows:

$$\ln(DSD) = a + b \cdot \ln(SSD) \qquad (3)$$

or:

$$DSD = e^{a+b\cdot\ln(SSD)} \qquad (4)$$

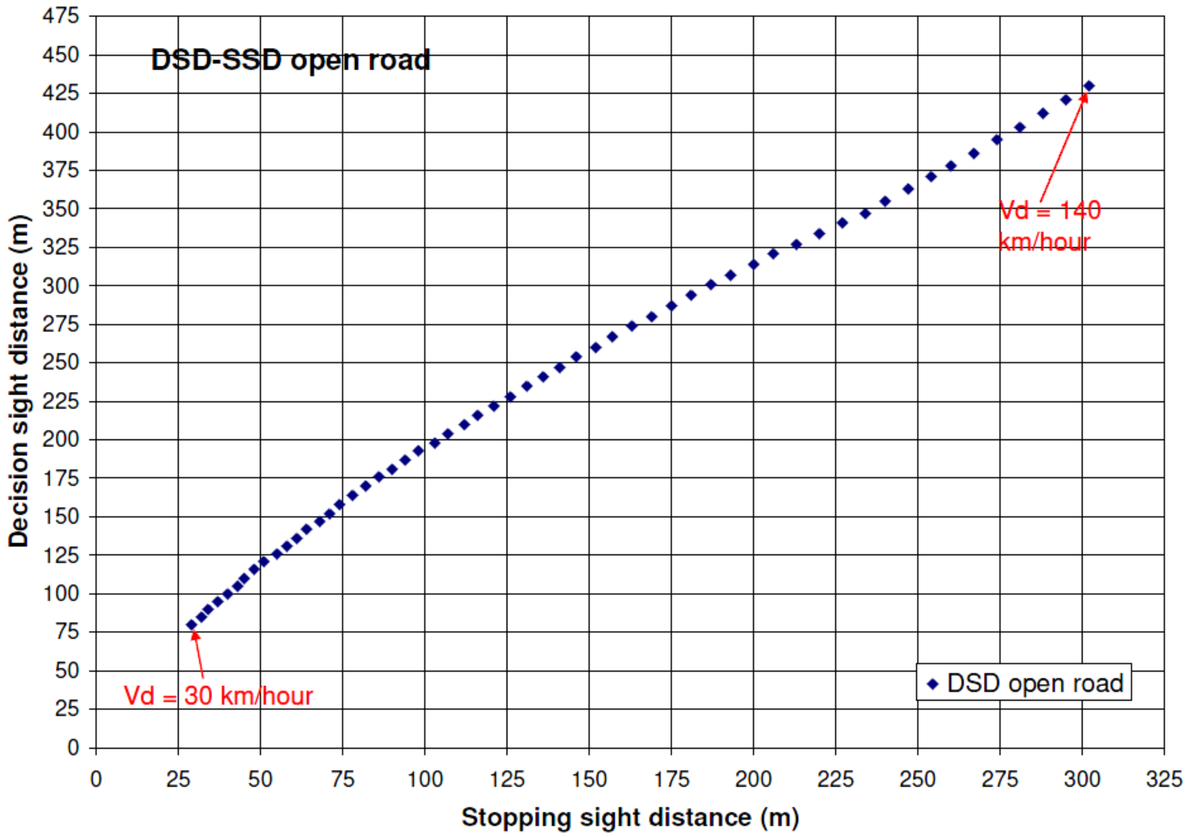

Figure 1: A typical scatter plot of DSD Vs. SSD for open roadways.

A model that reproduces the relationship between DSD and SSD has not been found in the literature except a simplified approximation documented in the British highway design guidelines (DMRB 1993, and NRA 2007). These guidelines propose that the distance required for the driver to reach a decision point is 1.5 multiplied by the "desirable minimum stopping sight distance". This decision point could be located upstream of:

(1) a stop line or yield line along the major road until the intersection with a minor road (intersections).
(2) a stop line or yield line along the major road until a roundabout (roundabouts).
(3) the start of the diverge taper to the back of the diverge nose (diverge ramp terminal).
(4) the back of the merge nose to the end of the merging taper (merge ramp terminal).

The general form of the model presented in Eq. 3 was calibrated by regression analysis according to the data points presented on Figure 1. The resulted exact form of the calibrated model is presented in Eq. 5.

$$DSD = e^{2.0061 + 0.77615 \cdot \ln(SSD)} \quad (5)$$

The resulted coefficient of determination (R2) is 0.99953. This result which is almost equal to 1 means that almost all the variation in the dependent variable (DSD) is explained by the regression line. The reason is that the data points themselves are based on specific modelling of SSD and DSD based on physical and driver behaviour parameters such as: (1) design speed, perception reaction time, and equivalent deceleration rate: for SSD; and (2) design speed, equivalent deceleration rate, pre-maneuver time, maneuver time, average maneuver speed: for DSD. Nonetheless, the exact form of the model presented in Eq. 4 produces a simple form for the relationship between DSD and SSD, which is the major purpose of this study. Other mathematical formulations such as semi natural log variations (e.g. DSD = a + b • ln (SSD)) have resulted in inferior calibration results. Figure 2 presents graphically the resulted relationship between DSD and SSD. It includes also a line that shows the simplified ratio (1.5) between DSD and SSD based on the British road design guidelines (DMRB 1993, and NRA 2007).

5. Implementation of DSD-SSD model for road tunnels

The tunnel alignment should be conventionally designed for stopping sight distance. In general, the tunnel alignment design should avoid dilemma points where the driver is required to make a decision which necessitates a maneuver operation. The reason is the driver difficulty to notice on alignment variations, and therefore taking a decision for maneuver operation. Specifically, the bounded cross section in a road tunnel, exacerbates the driver ability to estimate distances properly while driving along the tunnel lanes and also recognizing of road alignment especially prior to horizontal curves. Also, the bounded cross section functions as a physical obstacle, which has to be considered during the design process, including installations of directional guidance signs, and additional components of complementary systems. Overall the highway engineer might strive to locate the driver dilemma points prior to the tunnel portal before the tunnel entrance or after the tunnel exit. Still, when there are dilemma points along the tunnel alignments (directional guidance signs, diverging ramp terminals, merging ramp terminals, intersections, branch connections, etc.) the design of tunnel alignment may implement decision sight distance.

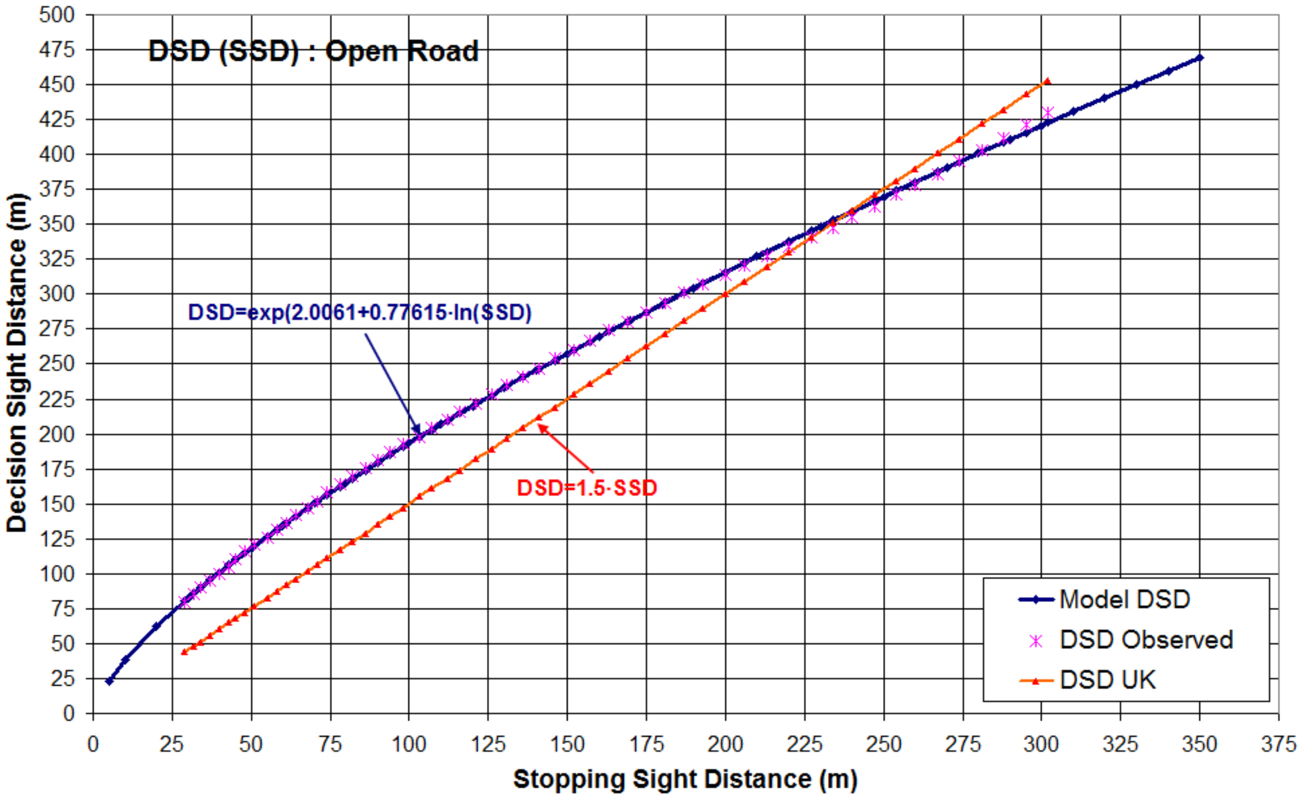

Figure 2: Graphical presentation of the relationship between DSD and SSD for open roadways (proposed model and British guidelines).

The stopping sight distance parameters for road tunnels are extensively documented in Bassan (2015). The road tunnel alignment was categorized in this study into three groups:

- End of Tunnel (EOT) zone which is assumed to be sited along 150 meters from the tunnel entrance or exit (tunnel portal).
- Dry tunnel on which the tunnel walls are watertight or usually there is no rain where the tunnel is designed.
- Moist tunnel which is an intermediary situation between wet and dry road surface. Such tunnel is not fully watertight.

Table 5 summarizes the SSD and DSD parameters which are different than the typical parameters introduced for open roadways in Table 3 and Table 4. These parameters were developed to compute adjusted SSD and DSD values for the design of road tunnel alignment (Table 6) in order to generate modified tunnel models that reproduce the relationship between SSD and DSD.

Table 5: Typical SSD and DSD parameters for road tunnels (partially based on Bassan (2015).

SSD		***50***	***60***	***70***	***80***	***90***	***100***	***110***	***120***
Tunnels	PRT (sec)	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
Dry tunnel	f_{eq}	0.7	0.7	0.675	0.650	0.625	0.600	0.575	0.55
	d	6.867	6.867	6.622	6.377	6.131	5.886	5.641	5.396
Moist tunnel	f_{eq}	0.569	0.569	0.552	0.534	0.516	0.499	0.481	0.464
	d	5.584	5.584	5.411	5.238	5.066	4.893	4.720	4.548
End of tunnel (wet)	f_{eq}	0.438	0.438	0.428	0.418	0.408	0.398	0.387	0.377
	d	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.7
DSD									
Tunnels: Pre maneuver time	PMT (sec)	5.0	5.0	5.0	5.0	5.5	5.5	5.5	5.5

Clarifications for Table 5:

f_{eq}- longitudinal friction coefficient; d- equivalent deceleration.

Parameters for a design speed of 30, 40 km/hour are identical to the parameters for a design speed of 50 km/hour.

Parameters for a design speed of 130, 140 km/hour are identical to the parameters for a design speed of 120 km/hour.

Table 6: Stopping sight distance and decision sight distance: computed values for road tunnels.

Design speed (km/hr)	***30***	***40***	***50***	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***
Dry tunnel:												
SSD (m)	18	26	35	46	58	73	101	122	144	170	194	218
DSD (m)	75	97	120	143	170	192	232	259	290	321	352	387
Moist tunnel:												
SSD (m)	19	28	39	50	65	81	112	135	161	189	216	245
DSD (m)	75	98	121	145	173	197	238	268	300	332	366	404
EOT												
SSD (m)	21	32	44	58	75	94	129	155	184	217	249	283
DSD (m)	76	100	124	149	178	205	247	280	314	347	386	430

Table 7 summarizes the parameters of the calibrated models for the three tunnel situations (moist, dry, and EOT). The table also includes the parameters of the open road model presented the previous section. The general form of the DSD-SSD model is introduced in Equations 3 and 4. A graphical presentation of these road tunnel models that produce the relationship between SSD and DSD for road tunnels is shown in Figures 3-5 respectively. Figure 3 depicts moist tunnel, Figure 4 depicts dry tunnel, and

Figure 5 depicts EOT. Figures 3-5 consist of data points of actual conditions and the simplified DSD-SSD approximation line of the British highway design guidelines (DMRB 1993, and NRA 2007). The model parameters and graphical presentation show slight differences between the line patterns. The line which represents the simplified ratio (1.5) between DSD and SSD based on the British road design guidelines, is closest to the open road calibrated model (Figure 2), and gets distant from the road tunnel models' lines.

Table 7: Parameters' summary of the calibrated models, SSD vs. DSD, for road tunnels and open roadway.

Parameter	***a***	***b***	***R-Squared***
Dry tunnel	2.50119	0.6393	0.999061
Moist tunnel	2.4516	0.6418	0.99929
EOT	2.3521	0.65264	0.999175
Open roadway	2.0061	0.7076	0.99953
Equivalent model	2.4251	0.6398	0.9805

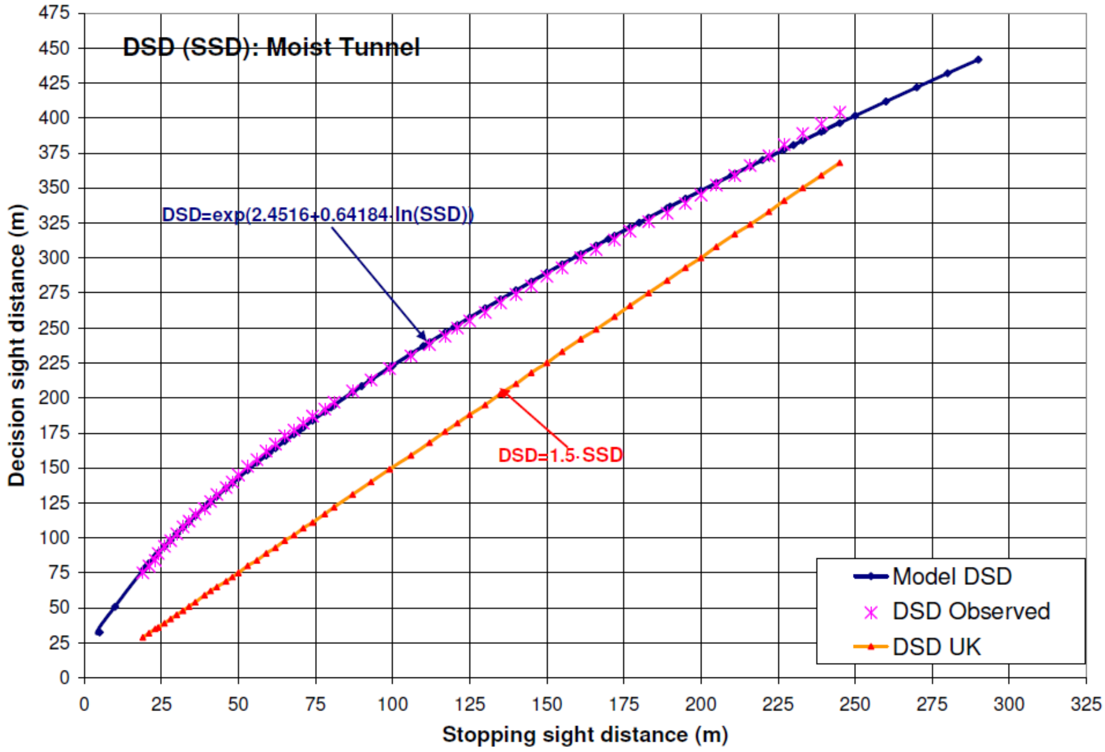

Figure 3: Graphical presentation of the relationship between DSD and SSD for moist tunnel (proposed model and British guidelines).

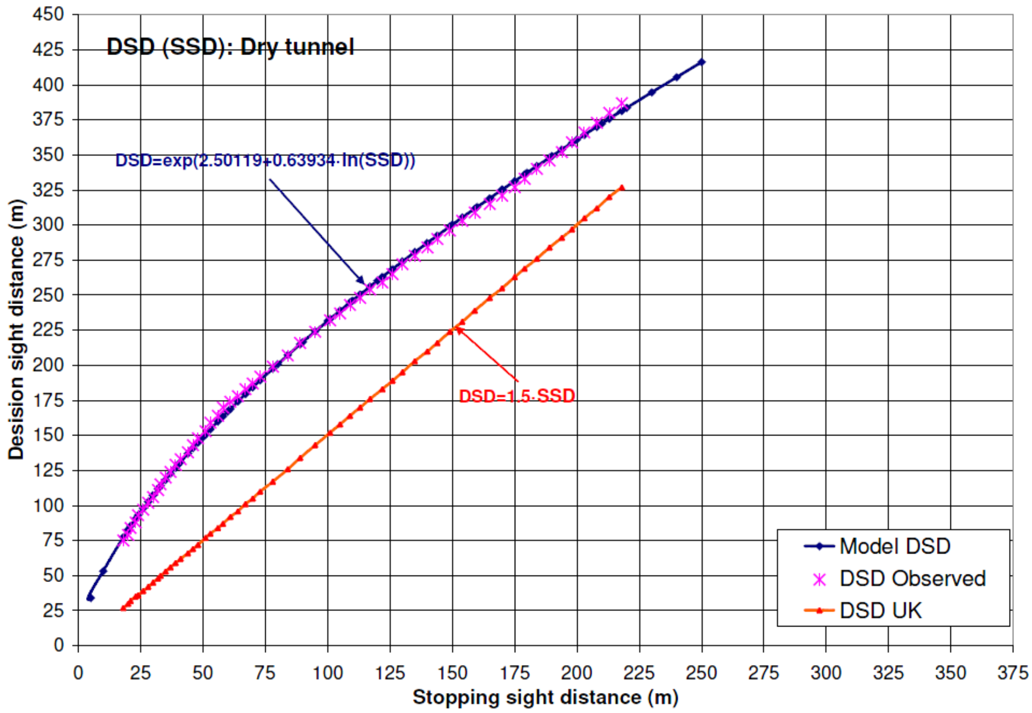

Figure 4: Graphical presentation of the relationship between DSD and SSD for dry tunnel (proposed model and British guidelines).

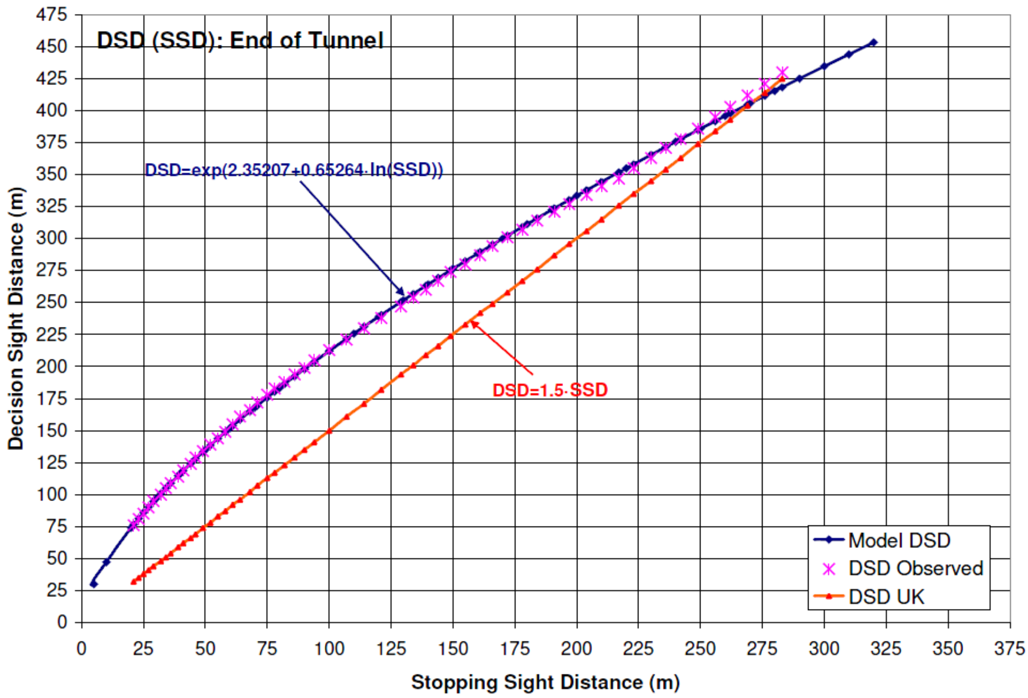

Figure 5: Graphical presentation of the relationship between DSD and SSD for End of Tunnel (EOT) zone (proposed model and British guidelines).

6. Equivalent DSD-SSD model

A calibration of equivalent DSD-SSD model for open roads and road tunnels can be performed by utilizing data points of actual conditions for all four road and tunnel conditions covered in this study. The calibration results of the equivalent model are included in Table 7. Figure 6 illustrates a graphical presentation of DSD-SSD equivalent model based on the DSD-SSD data sets of open roadways, moist tunnel, dry tunnel, and EOT zone. The line pattern of the equivalent model presented is similar to the EOT calibrated model. Such equivalent model can be used for practical purposes, as a simplified conversion from SSD to DSD, without the necessity of assuming physical and driver behavior parameters, or assuming the design speed, and without the need of making an assumption of the road condition.

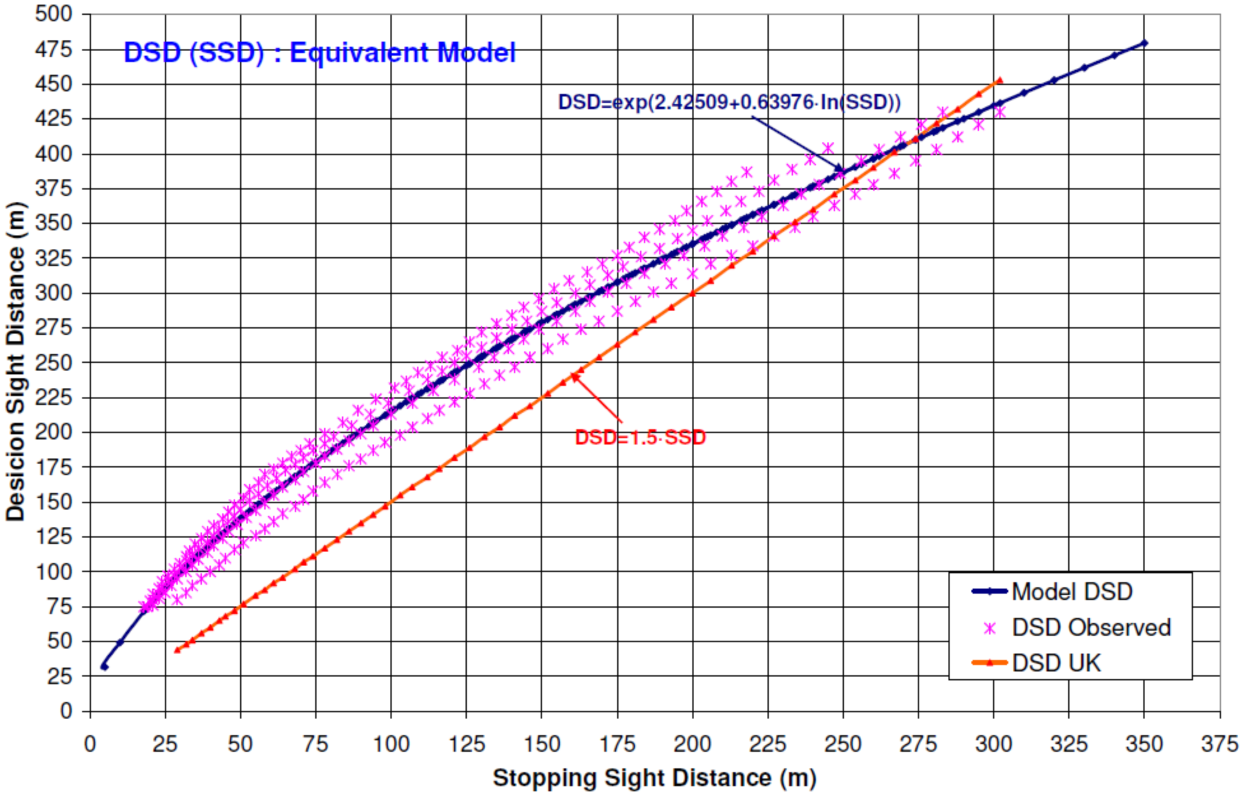

Figure 6: Graphical presentation of equivalent model demonstrating the relationship between DSD and SSD for open roads and road tunnels (proposed model and British guidelines).

7. Summary and practical issues

The paper revisits several developments related to stopping sight distance (SSD) and decision sight distance (DSD), partially based on Israeli geometric design policy and controls for rural (interurban) highways' and urban freeways' (1) system. These developments include: physical and operational parameter improvements of the stopping sight distance and a new model development of decision sight distance (DSD).

This proposed model which has the elements of pre-maneuver times, partial braking component, and maneuver component, could be comparable to the avoidance maneuver types C (rural roadway) and D (suburban roadway) of AASHTO (2011). However, its components do not cover avoidance types A, B of AASHTO (rural road and urban road respectively), which have a full braking component. A DSD with full braking could include a pre-maneuver time which is not larger than the brake reaction time of SSD but a braking component with a lower equivalent deceleration rate which characterizes a more comfort braking compared to SSD.

The SSD and DSD computed values function as an input for the major purpose of this study which is calibrating a model which directly formulates the relationship between DSD and SSD. Such a simplified correlation has not been found in the literature except a rough approximation documented in the British highway design guidelines. The resulted models enable a reliable estimation of the decision sight distance based on the stopping sight distance, without considering the design speed element. The proposed "general form" model is a typical natural logarithmic model. The model was calibrated by regression analysis and showed an excellent fit to the SSD and DSD inputs which signify a better representation of the SSD – DSD relationship compared to the simplified ratio proposed by the British road design guidelines (DMRB 1993, and NRA 2007). One model was calibrated for open roadways; three other calibrated models were adjusted for road tunnel: dry pavement surface, moist pavement surface, and End of Tunnel (EOT) zone; and a final equivalent model was calibrated according to all data sets of open roadways and road tunnels. A graphical summary of all calibrated models producing the relationship between SSD and DSD is presented in Figure 7. The model parameters and graphical presentation show slight differences between the line patterns.

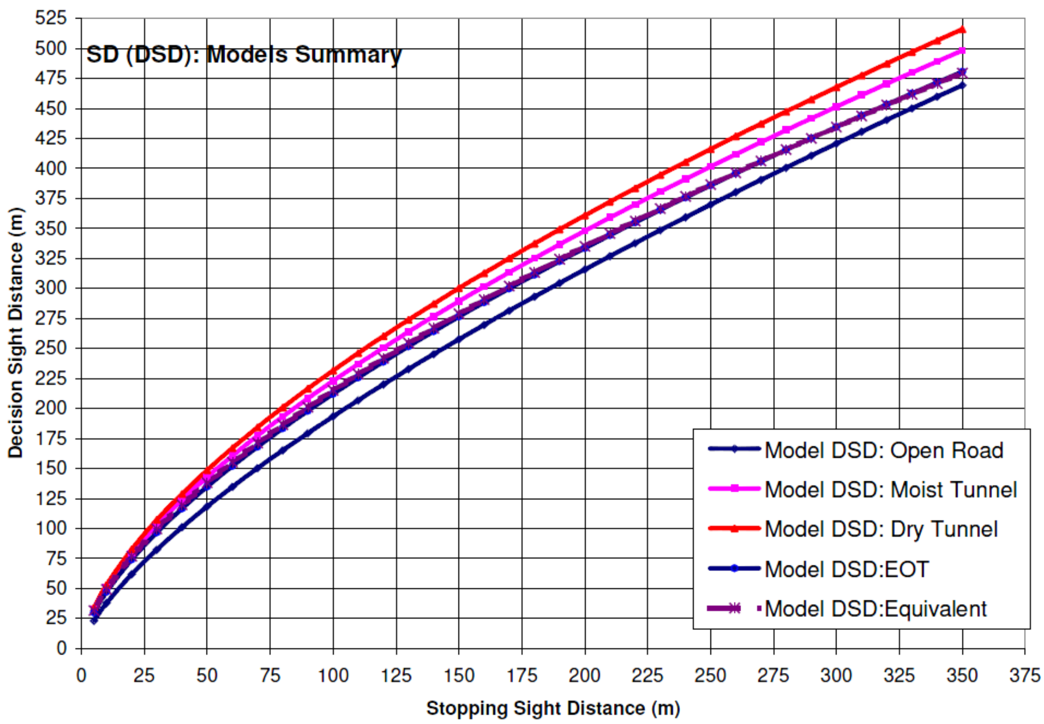

Figure 7: Graphical presentation summary of the relationship between DSD and SSD for: open roadways, road tunnels, and equivalent model.

Generating SSD-DSD relationship for additional DSD avoidance maneuver types such as stopping in rural roads (e.g. type A in AASHTO (2011)), might be considered for further research.

The highway engineer might strive to locate the driver dilemma points prior to the tunnel portal before the tunnel entrance or after the tunnel exit and therefore apply the SSD in the tunnel alignment design. Nonetheless, when there are dilemma points along the tunnel alignments the design of tunnel alignment may implement DSD.

The integration of the two sight distance types (SSD and DSD) in designing the interurban highway network is finally determined as a design policy by implementing them according to highway classification. On freeways and long trips on highly trafficked highways with considerably high operating speeds, without traffic flow interference (such as intersections and access to proximate land uses), the Israeli highway design policy recommends employing decision sight distance in the design of highway alignment, in order to make the driving calm and comfortable. Employing decision sight distance instead of stopping sight distance would result in larger vertical radii and more restricted horizontal sightline offset. Such outcome can directly increase the construction cost and environmental landscape disruptions in order to maintain driving safety. On other roadway categories, the stopping sight distance would be preferable for the design of highway alignment. Table 8 presents SSD and DSD design policy criteria recommendations.

Table 8: Parameters' summary of the calibrated models, SSD vs. DSD, for road tunnels and open roadway.

Sight Distance (SD)Type	***Highway Category***				
	Freeway / Urban freeway	***2-Way Divided: Major highway / Minor highway***	***2-Lane Undivided: Major highway***	***2-Lane Undivided Minor (regional) highway***	***Local (access) road***
Stopping SD	–	Always	Always	Always	Always
Decision SD *	Basic for design	Prior to interchange or intersection (lane reduction or increase)	Prior to interchange or intersection (lane reduction or increase)	lane reduction or increase	–

** To be implemented for road tunnels prior to dilemma points along the tunnel alignment (section 5).*

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