1 Introduction

This technical note:

- Briefly reviews issues related to the dark/light and light/dark eye adaptations necessary when a driver passes between lit and unlit road sections
- Looks at minimum unlit distances for road lengths prescribed by some international jurisdictions
- Reports on the results of a crash study of sections of state highway 1 and state highway 2 near Wellington where lit sections are interspersed with unlit sections.
- Makes conclusions and a recommendation regarding the minimum length for unlit sections on New Zealand roads where the unlit sections are abutted at each end by lit sections.

2 Visual adaptation on a road with lit and unlit sections

When vehicles pass from lit to unlit sections of a road and vice-versa there is an adaptation process over time through which the eyes of the driver become accustomed to the new conditions. This process of adaptation includes three sub-processes (Schreuder et al, 1998):

- Changes in pupil diameter
- Sensitivity adaption of the receptors
- Switching on and off of the receptors

The human eye can operate over a very large range of brightness, but at any particular point in time the range is much smaller. The eye must adapt to be able to operate in a different range of brightness. At any particular moment, adapted to a particular lighting level, the eye has a limited range of luminance in which it can operate effectively. This range varies with the level of lighting. In any particular situation, the range is called the “state of adaptation” and the average of that range is called the “adaptive luminance”. This is illustrated in figure 1, taken from Schreuder et al (1998).

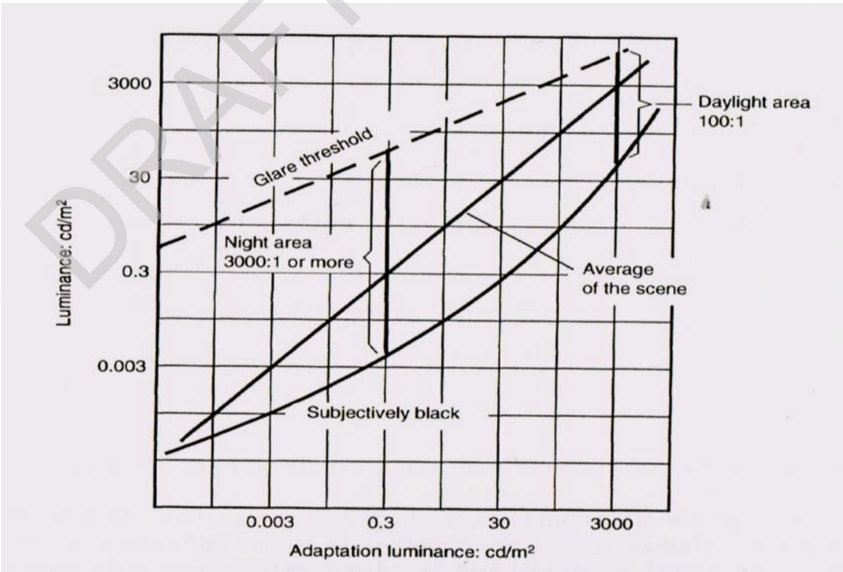

Figure 1: The relation between luminance and adaptation luminance

The pupil diameter can vary between 0 7mm and 2.8 mm between adaption luminances of 0.01 cd/m2 to 1000 cd/m2. This means the surface area of the pupil moves by a factor of 6 over an adaptive luminance change of 100,000 times. This change decreases with age as the elasticity of the pupil decreases. The adaptation of the receptors (rods and cones) is much more important with their switching off and on also important.

The adaptation transition from dark to light is much faster than that from light to dark (Schreuder, 1998). Thus it is prudent to ensure that where unlit road sections between lit sections exist, they should be long enough to allow reasonable light to dark adaptation to take place before the eye is hit by another adaptation from dark to light. Also, the speed of adaptation varies from individual to individual with older individuals taking longer to adapt. This has implications with the driving population tending to get older. The full adaptation from light to dark can take anything up to half an hour depending on the difference in lighting levels. However, when going from lit sections of highway to interspersed unlit sections the transition may be relatively fast. This is because both lighting levels are likely to be above a speed of adaptation related cut-off quoted by Schreuder, et al, 1998 of 0.1 cd/m2. Above this level, speed of adaptation is considered by Schreuder et al to be relatively fast, although no precise figures are given. Lit roads are around 1 cd/m2 and it has been argued that for unlit roads relying on motor vehicle headlamp lighting, the relevant parts of the road surface are usually above 0.1 cd/m2 in luminance (Narisada and Schreuder, 2004). Thus, according to the Schreuder et al, 1998, at levels above the cut off of 0.1cd/m2 the adaptation time should be relatively fast. The actual adaptation luminance level will of course depend on the number of vehicles in the stream with a lone vehicle representing a minimum level.

The considerations above mean that the length of unlit sections between lit sections needs control so that it does not become too short. World-wide, some jurisdictions have minimum length rules for such sections. There is almost no information available as to the derivation of such rules. They may or may not have a genesis based on driver adaptation times.

3 Guidance from jurisdictions on the minimum unlit length between lit sections of road

A number of jurisdictions offer guidance on the minimum unlit length between lit sections of road. This guidance is often couched as a warrant for continuous lighting rather than minimum distances. Table 1 contains the guidance for a number of jurisdictions. There are jurisdictions e.g. Missouri where continuous lighting is only considered if the length is greater than a minimum rather than setting a minimum unlit gap in a lighting installation. However, this may relate to a minimum feasible length for putting an isolated lighting installation in place rather than any safety consideration related to light adaptation.

Table 1: Guidance from some jurisdictions about minimum unlit distances between lit road sections

Jurisdiction	Guidance
Texas	**Warrant Condition for Continuous lighting** Sections where three or more successive interchanges are located with an average spacing of 1.5 miles or less and adjacent areas outside the right of way are substantially urban in character.[1] **Warrant condition for intersection Safety Lighting** Existing substantial commercial or industrial development that is lighted during hours of darkness, is located in the immediate vicinity of intersection, or where the crossroad approach legs are lighted for 0.5 miles or more on each side of the inter-section[2] (Based on AAASHTO Guidance)
Minnesota	Continuous freeway lighting is considered to be warranted on those sections where three or more successive interchanges are located with an average spacing of 1.5 miles (2.4km) or less, and adjacent areas (Based on AAASHTO Guidance) outside the right of way are substantially urban in character[3].
Missouri	Continuous lighting shall be provided when the proposal includes the lighting of two or more intersections less than 500 feet (150m) apart, typically in urban or suburban areas. Where an intersection is not involved, continuous lighting can be considered if the length of roadway to be lighted is at least 500 feet[4].
New York State[5]	Continuous lighting is considered warranted on those sections of a controlled-access highway where two or more successive lighted interchanges or ramps are located with an average spacing of 1/2 mile (0.8 km) or less.
Norway	Short distances (< 500 m) between lighted areas to obtain continuity. CEDR. (2009)
Estonia	In rural areas, sections between grade separated interchanges if the distance between interchanges is less than 2000 m CEDR. (2009)
Finland	On motorways between lit interchanges, carriageway shall be lit if distance between "noses" is <1500 m. CEDR. (2009)

[1] http://onlinemanuals.txdot.gov/txdotmanuals/hwi/continuous_lighting1.htm Viewed 18/5/2015

[2] http://onlinemanuals.txdot.gov/txdotmanuals/hwi/safety_lighting1.htm Viewed 18/5/2015

[3] http://www.dot.state.mn.us/trafficeng/lighting/2010_Roadway%20Lighting_Design_Manual2.pdf Viewed 18/5/2015

[4] http://morail.org/business/manuals/Lighting_Manual/Chapter%20I.pdf Viewed 18/5/2015

[5] https://www.dot.ny.gov/divisions/operating/oom/transportation-systems/repository/policylight.pdf Viewed 18/5/2015

Canada:	Light if < 1.5 km between interchanges CEDR. (2009)
Australia	Light if < 2 km between interchanges CEDR. (2009)
Victoria	It is undesirable to leave short unlit sections between lit areas as this causes significant fluctuations in lighting levels which may be particularly hard on the eyes of persons with visual difficulties. Where a lighting installation at any of the above locations results in an unlit road section less than 300m in length between lights (excluding flag lights), lighting should be provided to fill the resultant gap. (VicRoads, 2014)
United Kingdom	There should not be an unlit gap of less than four times the stopping sight distance (around 700metres) between lit sections. (Highways Agency, 2007)[6].

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4 Crash investigation-Short unlit sections SH1 and SH2, Wellington

Given the variation in the distances quoted in Table 1 by various jurisdictions it was considered worthwhile to carry out a local crash study related to some short unlit sections of state highways 1 and 2 in the Wellington. This is described in the following subsections.

4.1 Background:

Driver's eyes take time to adapt to changes in light level, particularly the transition from light to dark. The lighting on SH1 and SH2 near Wellington is continuous only on the most highly trafficked sections. Further from the central areas intersections and approaches are lit but sections between intersections remain unlit. According to lighting adaptation theory drivers will have reduced vision when transitioning from a lit to an unlit area and this effect may be identifiable in CAS crash data.

4.2 Method:

This study looked at 27 sections of lit and unlit road. The lit sections varied from 0.4 km to 3.2 km in length and the unlit sections from 0.7 km to 5.3 km in length. (See Figures 2 and 3). The sections were matched against CAS crash data for the period 2010 – 2014.
The CAS route positions were used to locate crashes and the CAS movement codes were used to identify the direction of travel of the key vehicle. This information allowed the location of the crashes to be expressed in terms of the distance driven since the last transition from a lit area into an unlit area and vice versa.
Night time safety performance was assessed using two measures;

- The night to day crash ratio. The lower the night to day crash ratio the better the night time crash performance.

[6] http://www.standardsforhighways.co.uk/ha/standards/DMRB/vol8/section3/td3407.pdf

- The night time crash rate (crashes per hundred million vehicle kilometres). A lower crash rate is indicative of greater night time safety.

The crash sample size for the study is unfortunately small (868 crashes, 283 at night and 585 during the day, including reported non-injury crashes). The critical crashes that occur near the interface of changes in lighting are very much smaller in number again. The twin evaluation measures help to provide a broader picture of the crash experience.

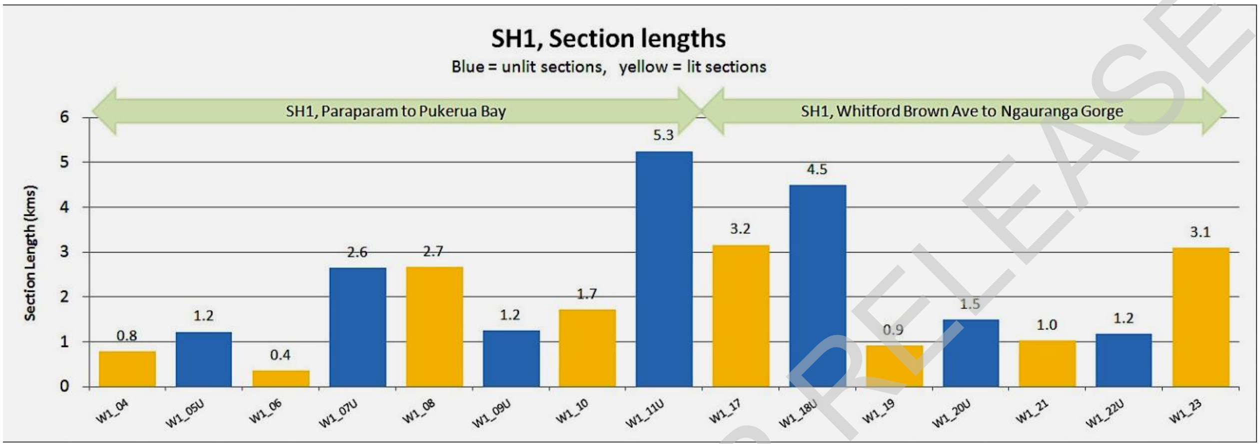

Figure 2: The lit (orange) and unlit (blue) sections in the study from state highway 1 between Paraparaumu and Ngauranga gorge with section length in kms

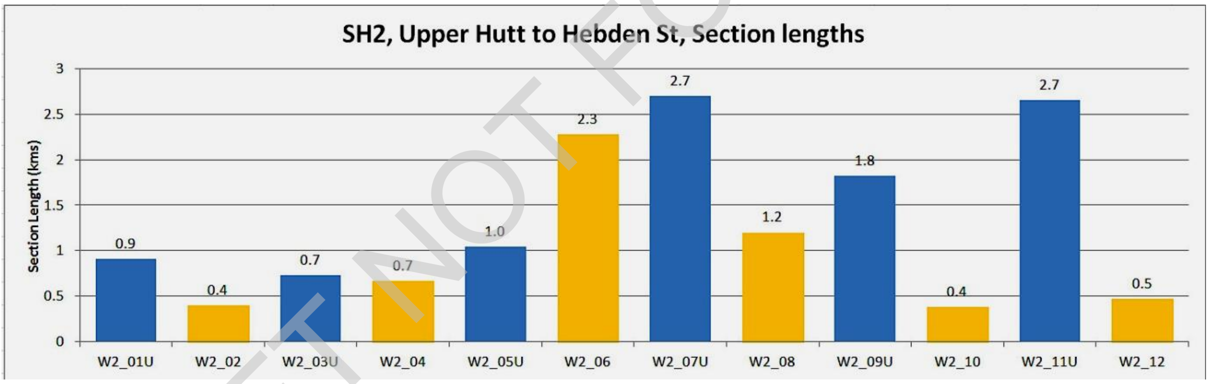

Figure 3: The lit (orange) and unlit (blue) sections in the study from state highway 2 between Upper Hutt (Maori Bank) and Hebden St. With section length in kms shown

4.3 Results:

4.3.1 Section Length

Plots were made of section length against the night time crash rate (crashes/HMVKms[7]) for both the lit and unlit sections. As the lit sections contain all the intersection crashes, intersection crashes were eliminated from the analysis to help compatibility between datasets and avoid the need for complex modelling of crash rates at intersections.

For both lit sections (Figure 4) and unlit sections (Figure 5) there is a suggestion in the data that night crash rates tend to be higher when the length of section is short (i.e. 1 km or less). The trend

[7] HMVkms means hundred million vehicle kilometres

is not strong but is consistent with the knowledge that short sections of lighting (or of no lighting) are more demanding on a drivers' eye adaptation than longer sections.

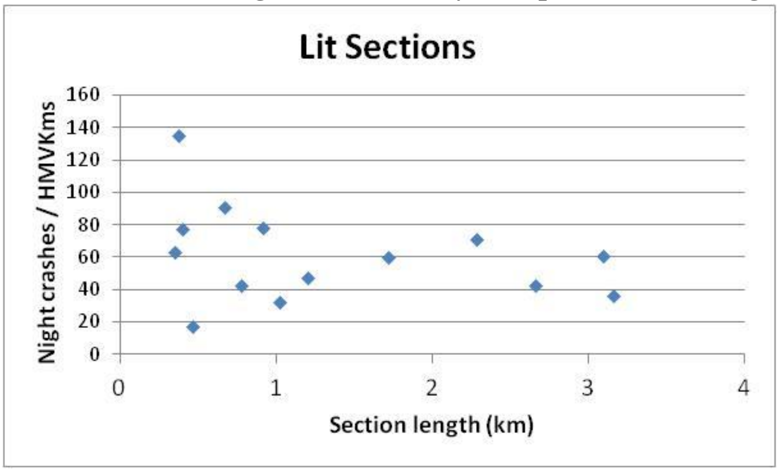

Figure 4: Crash rate per HMVKms for all crashes on lit sections by section length.

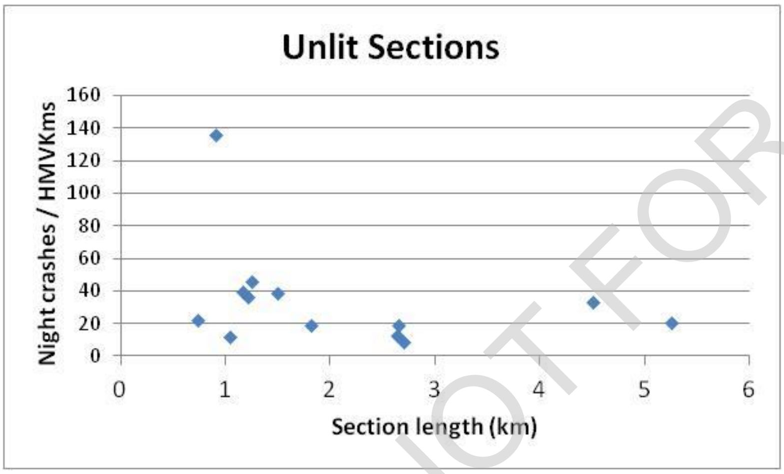

Figure 5: Crash rate per HMVKms for all crashes on unlit sections by section length.

4.3.2 Transition Zone

By examining crash location and direction of travel it is possible to identify those crashes that are in a transition zone between lit and unlit sections. The UK highways agency design manual (see Table 1) requires isolated unlit sections less than 4 times the stopping sight distance (typically 600 -900 metres) to be considered for continuous lighting. A value of 700 metres was chosen as the transition zone length for this study. Such lengths correspond to a travel time of around 30 seconds. Two groups of crashes were established designated below as G1 and G2.

1. G1: Transition crashes where the key vehicle had travelled less than 700 metres since a changeover point from lit to unlit or equally from unlit to lit.
2. G2: Crashes where the key vehicle had travelled more than 700 from a changeover point (to a maximum of 4kms).

Within each crash group crashes were identified as either being in an unlit or a lit section. Two measures of performance were used; Night to day crash ratio and night crashes per HMVKms.

The safety impact of these transitions is illustrated in Tables 1 to 9. The tables view the 700m to 4.7 km section (G2) as the baseline condition. This means that a positive percentage change G2 to G1 indicates the first 700m section may be less safe than the 700m to 4.7 km section. Conversely, a negative percentage change G2 to G1 indicates the first 700m section may be safer than the 700m to 4.7 km section. Crash movement codes used are from the Transport Agency's Crash Analysis System (CAS),

4.3.3 Transition from Lit to Unlit:

This is the transition of most concern because drivers require some time to become adapted to a lowered level of lighting. Tables 2 to 5 indicate that within the first 700m of a lit to unlit transition night time crash risk is generally higher than in equivalent sections 700m to 4.7 km from the transition point. This result applies whether the night to day crash ratio method or the night crashes / HMVKms crash rate method is used.

Table 2: All crash movements, unlit sections

Transitioning to Unlit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	71	114	
Night Crashes	36	48	
Total crashes	107	162	
N/D crash ratio	0.51	0.42	20%
Night Crashes/HMVKms	35.8	23.6	52%

Table 3: All crash movements, injury only, unlit sections

Transitioning to Unlit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	14	29	
Night Crashes	11	14	
Total crashes	25	43	
N/D crash ratio	0.79	0.48	63%
Night Crashes/HMVKms	10.9	6.9	59%

Table 4: Single vehicle loss control crashes (C&D Types), unlit sections

Transitioning to Unlit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	35	49	
Night Crashes	9	19	
Total crashes	44	68	
N/D crash ratio	0.26	0.39	-34%
Night Crashes/HMVKms	8.9	9.3	-4%

Table 5: Rear end crashes (F Type), unlit sections

Transitioning to Unlit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	19	35	
Night Crashes	19	14	
Total crashes	38	49	
N/D crash ratio	1.00	0.40	150%
Night Crashes/HMVKms	18.9	6.9	175%

4.3.4 Transition from Unlit to Lit:

The transition from unlit to lit conditions is of a lesser concern because the adaptation of the eye is relatively rapid in taking on increased light conditions. Tables 6 to 9 show that the transitions from unlit to lit sections show a less pronounced change in crash risk compared to lit to unlit transitions with increases indicated for injury crashes.

Table 6: All crash movements, Lit sections

Transitioning to Lit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	112	150	
Night Crashes	57	70	
Total crashes	169	220	
N/D crash ratio	0.51	0.47	9%
Night Crashes/HMVKms	57.5	51.7	11%

Table 7: All crash movements, injury only, lit sections

Transitioning to Lit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	29	34	
Night Crashes	10	18	
Total crashes	39	52	
N/D crash ratio	0.34	0.53	-35%
Night Crashes/HMVKms	10.1	13.3	-24%

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Table 8: Single vehicle loss control crashes (C&D Types), lit sections

Transitioning to Lit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	31	37	
Night Crashes	18	31	
Total crashes	49	68	
N/D crash ratio	0.58	0.84	-31%
Night Crashes/HMVKms	18.1	22.9	-21%

Table 9: Rear end crashes (F Type), lit sections

Transitioning to Lit	G1	G2	% change
Distance from start	0 - 700m	700-4700m	G2 to G1
Day crashes	48	64	
Night Crashes	18	24	
Total crashes	66	88	
N/D crash ratio	0.38	0.38	0%
Night Crashes/HMVKms	18.1	17.7	2%

4.4 Summary

There was some evidence that short sections (around 1km in length) tended to have a higher night crash rate than longer sections. However the number of short unlit sections was too limited for convincing results.

By identifying direction of travel of crash vehicles it was possible to identify crash risks for vehicles within the transition zone (the first 700m of each section) and compare this with risks for greater distances.

Using the night crash rate index (Crashes / HMVKms) the following changes in risk in the transition zone between lit and unlit sections were found:

- All crashes were 52% higher
- Injury crashes were 59% higher
- Single vehicle were crashes 4% lower
- Rear end crashes were 175% higher

The changes when transitioning from unlit to lit were smaller with the following results:

- All crashes were 11% higher
- Injury crashes were 24 % lower
- Single vehicle crashes were 21% lower
- Rear end crashes were 2% higher

The results tend to support with crash experience the evidence from adaptation science. There is evidence here that the transition zones between lit and unlit do tend to have higher crash rates than unlit sections further removed from the transition zone.

The data available is too course to make reliable predictions on the number of crashes that could be saved, by avoiding short unlit lengths within a lit section but doing so should have a tangible benefit on night time safety performance.

4.5 Cautionary statements

1. The sample size is relatively small. The large percentage changes identified in the tables may be an artefact of that small sample.
2. The small sample also means that no crash changes were statistically significant. However the results tend to support other areas of knowledge.

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5 Conclusions

The literature indicates that there are concerns related to adaptation where short lengths of unlit roads are interspersed with lit sections of road. The literature indicates that adaptation entering a dark area from a lit area should be more severe than that entering a lit area from an unlit area.

In terms of crashes the small sample crash study undertaken on lit and unlit sections of SH1 and SH2 near Wellington suggested that there may be safety problems associated with transitions between interspersed lit and unlit sections, more so than similar transitions between unlit and lit sections. This effect particularly applies where unlit sections are relatively short in terms of distance or travel time, with indicative travel times being around 30 seconds. .

6 Recommendation

That lighting designs involving short sections of unlit road between lit sections should be discouraged. The lengths in question correspond to travel times of around 30 seconds.

Reference

CEDR. (2009). *Road Lighting and Safety, Conference of European Directors of Roads*. Report CEDR Paris.

Narisada, Kohei and Schreuder, Duco (2004) Light Pollution Handbook, Springer

Schreuder, D A (1998) Road Lighting for Safety, Thomas Telford

VicRoads (2014) Traffic Engineering Manual Volume 1, Chapter 6 – Edition 5

Highways Agency (2007) TD 34/07 "Design of road lighting for the strategic motorway and all purpose trunk road network"

Appendix 1: Tables of stopping distance and travel distance by speed

Table A1

AUSTROADS STOPPING SIGHT DISTANCE (Arndt, ARRB, 2010)

Design Speed (km/h)	Absolute Minimum Values			Desirable for Urban/Rural			Desirable Major Highways / Motorways	
	R_T = 1.5s	R_T = 2.0s	R_T = 2.5s	R_T = 1.5s	R_T = 2.0s	R_T = 2.5s	R_T = 2.0s	R_T = 2.5s
40	30	36		34	40	45		
50	42	49		48	55	62		
60	56	64		64	73	81		
70	71	81		83	92	102	113	123
80	88	99		103	114	126	141	152
90	107	119	132	126	139	151	173	185
100		141	155		165	179	207	221
110		165	180		193	209	244	260
120		190	207		224	241	285	301
130		217	235		257	275	328	346

Table A2

UK HIGHWAYS AUTHORITY "4 TIMES SSD" RULE APPLIED TO AUSTROADS (2010) STOPPING SIGHT DISTANCE

Design Speed (km/h)	Absolute Minimum Values			Desirable for Urban/Rural			Desirable Major Highways / Motorways	
	R_T = 1.5s	R_T = 2.0s	R_T = 2.5s	R_T = 1.5s	R_T = 2.0s	R_T = 2.5s	R_T = 2.0s	R_T = 2.5s
40	120	144		136	160	180		
50	168	196		192	220	248		
60	224	256		256	292	324		
70	284	324		332	368	408	452	492
80	352	396		412	456	504	564	608
90	428	476	528	504	556	604	692	740
100		564	620		660	716	828	884
110		660	720		772	836	976	1040
120		760	828		896	964	1140	1204
130		868	940		1028	1100	1312	1384

Table A3

DISTANCE TRAVELLED (in metres)

Travel Speed (km/h	Time in seconds				
	10	**20**	**30**	**40**	**50**
40	110	220	**330**	440	560
50	140	280	**420**	560	690
60	170	330	**500**	670	830
70	190	390	**580**	780	970
80	220	440	**670**	890	1110
90	250	500	**750**	1000	1250
100	280	560	**830**	1110	1390
110	310	610	**920**	1220	1530
120	330	670	**1000**	1330	1670
130	360	720	**1080**	1440	1810