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Brake Response Times of Advanced Emergency Braking Systems

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Abstract

Advanced Emergency Braking ('AEB') is an Advanced Driver Assistance System ('ADAS') which was first assessed as part of European New Car Assessment Programme ('EuroNCAP') ratings in 2014, but only for car-to-car systems. In 2016, pedestrian AEB system assessments were added to the ratings. Since then, the number and complexity of tests conducted as part of a EuroNCAP assessment has increased rapidly, as has the fitment of AEB systems to new cars. It should however be noted that AEB systems have often been part of an optional 'safety pack' that the original purchaser of the car has to specify, and hence it is essential that a collision investigator checks system fitment before applying this research.

The new Vehicle General Safety Regulation ('GSR2') requires that all cars (and vans) are fitted with an AEB system for frontal vehicles/objects from 2022 for new vehicle models (those homologated after this date), and to all new vehicles from 2024. An AEB system for pedestrians and cyclists is required from 2024 for new vehicle models, and 2026 for all new vehicles. The GSR2 stipulates that all new cars will be fitted with AEB as standard, at the latest from the dates indicated.

This research paper presents the results of tests conducted into the Brake Response Times ('BRT') of AEB systems in cars manufactured between 2019 and 2022. 10 cars were tested, which were selected based on sales figures, propulsion system, and body type. The aim was to represent a realistic spread of cars on public roads in the UK at the time of writing. Each of the cars was subjected to testing at 20 mph (32 km/h) and 30 mph (48 km/h), with scenarios where a pedestrian dummy approached perpendicular to the car's path, from both sides of the car in separate scenarios. Data were analysed to determine the period that elapsed between the pedestrian dummy first becoming visible from behind an obscuring fence and full-rate braking being achieved by the car's AEB system, i.e. the Brake Response Time, and the speed reduction achieved during that period.

Keywords: Advanced Emergency Braking; Autonomous Emergency Braking; AEB; Advanced Driver Assistance Systems; ADAS; EuroNCAP; collision reconstruction; collision investigation

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1. Introduction

There are a wide range of articles published regarding the Perception-Response Time ('PRT') and Brake Response Time ('BRT') of humans over a wide range of scenarios, see for example [1] and [2], which can be applied in the reconstruction of collisions. However, at the time that testing was conducted for this research paper, between October 2022 and March 2023, as far as the author is aware, no research exists regarding the reaction times of Advanced Emergency Braking ('AEB') systems which can be applied by collision investigators during the reconstruction of collisions.

The purpose of this research paper is to define a range of reaction times for AEB systems, such that a collision investigator is able to apply the results of this research alongside that into the reaction times of humans. That will allow the investigator to determine whether it is more likely that the human driver or the AEB system reacted to a hazard and acted to brake the car prior to a potential collision.

Definitions of terms used within this paper can be found within the Glossary at the end.

2. Test Cars

The 10 cars that were tested were as follows. Their propulsion systems, body type, model year, and ADAS sensor type (i.e. camera and/or radar) are presented in brackets after the make and model.

1. BMW iX (electric, SUV, 2022, camera and radar)
2. Ford Focus (petrol combustion engine, estate car, 2019, camera)
3. Hyundai Tucson (petrol combustion engine, SUV, 2021, camera and radar)
4. KIA Niro (electric, hatchback, 2019, camera and radar)
5. Land Rover Discovery Sport (diesel combustion engine, SUV, 2022, camera)
6. Mercedes-Benz A-Class (petrol combustion engine, saloon, 2019, camera and radar)
7. Peugeot 2008 (petrol combustion engine, SUV, 2021, camera and radar)
8. Tesla Model Y (electric, SUV, 2022, camera)
9. Vauxhall Corsa (petrol combustion engine, hatchback, 2020, camera and radar)
10. Volkswagen Golf (petrol combustion engine, hatchback, 2022, camera and radar)

All of the test cars were hired for the duration of their test periods. The cars were all tested in their 'as received' condition; no pre-test calibrations were conducted, in order that the test cars represented the realistic condition of cars found on public roads in the UK.

3. Method

Tests were conducted using the Dynamics Pad facility at UTAC Millbrook [3]. Prior to testing, the test cars were fitted with an Oxford Technical Solutions Limited [4] RT3003 Inertial Navigational System ('INS'), which was configured based on its position within the car and the car's dimensions. The INS was connected via a radio modem to a base station which provided Real Time Kinematic ('RTK') corrections for a 2 cm positional accuracy. An Anthony Best Dynamics Limited ('AB Dynamics') [5] Soft Pedestrian Target ('SPT') system was used to provide motion to a 4activeSystems GmbH [6] 50th percentile adult male pedestrian dummy with articulating legs. The motion of the pedestrian dummy across the car's path was synchronised to that of the test car by AB Dynamic's 'Synchro' system. All measurement signals, plus two camera views (one facing directly out of the front of the test car, and one facing the car's dashboard) were recorded by a DEWESoft d.o.o. [7] data acquisition system. All of the test equipment is approved for use during testing in accordance with European New Car Assessment Programme ('EuroNCAP') [8] active safety test protocols.

The test scenarios were based on those conducted during EuroNCAP assessments. The pedestrian dummy approached the test car from either the offside (right-hand side) or nearside (left-hand side) at a speed of 5 km/h (about 1.4 m/s); this is a EuroNCAP specified walking speed. The test car approached the dummy, perpendicular to its direction of travel, at test speeds of 20 and 30 mph (about 32 and 48 km/h respectively). The tests were configured such that if the AEB system did not activate and reduce the car's speed prior to the collision, the dummy was positioned in line with the car's longitudinal centreline at the point of collision.

A temporary fencing panel, with an opaque covering, was used to obscure the dummy's acceleration phase from view of the car. The fence was positioned, relative to the longitudinal centreline of the car, based on system performance and test speed; the edge of the fence was located between 1.95 m and 2.5 m from the longitudinal centreline of the test car. In general, the slower a car's BRT, the further away the fence was positioned.

Figure 1 is an edited version of the 'Car-to-Pedestrian Farside Adult' ('CPFA') scenario diagram, taken from the EuroNCAP test protocol 'AEB/LSS VRU systems', version 4.5.1, dated February 2024 (EuroNCAP Figure 7-1), available at https://www.euroncap.com/en/for-engineers/protocols/vulnerable-road-user-vru-protection/.

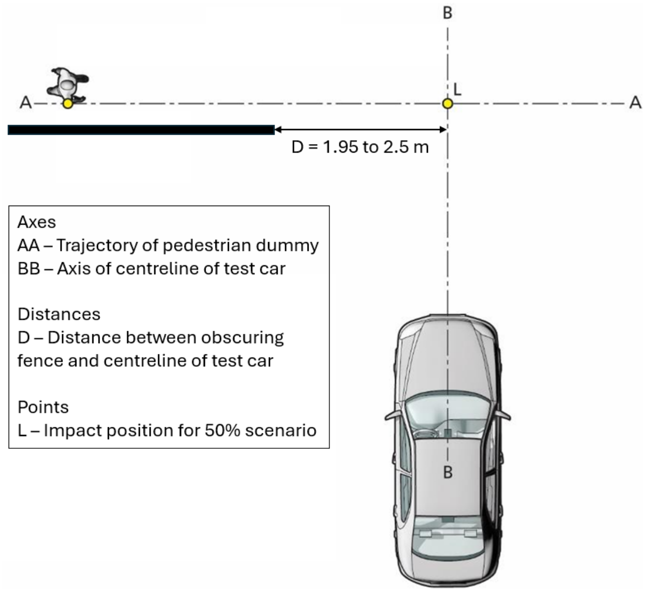

Figure 1 – Test scenario (mirrored for offside approach of dummy)
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Figures 2 and *3* provide an overview of the test setup; Figure 2 shows the view forward from within the Peugeot 2008 and Figure 3 shows an external view facing the approaching Mercedes-Benz A-Class. All tests were conducted in dry conditions during daylight.

Figure 2 – An interior view facing forward out of the Peugeot 2008

Figure 3 – An exterior view facing the approaching Mercedes-Benz A-Class

The test driver accelerated the car to the test speed ±1 mph (1.6 km/h), as indicated by the INS speed display within the data acquisition system, and the cruise control was engaged such that the car approached at approximately constant speed. A faint join in the asphalt test surface was used by the driver to align the car laterally on approach to the test location. The only inputs by the driver, once the speed was stabilised, were minor corrections to the steering to maintain a straight path. The driver did not press the brake pedal and the AEB system was allowed to activate. In some cases, a collision was avoided, however in others the car collided with the pedestrian target.

4. Results

4.1. *Preamble*

The start of the BRT measurement period was defined as the point at which half of the pedestrian dummy became visible past the edge of the obscuring fence panel, for example as shown in *Figure 4*, at a Time to Collision ('TTC') of 1.4 to 1.8 seconds (depending on the position of the fence).

Figure 4 – The start of the BRT measurement period

The end of the BRT period was defined as the point at which peak braking deceleration was achieved, after the brake build-up period had elapsed, determined based on a speed vs. time graph. Video recordings were time aligned with other measurement data, hence the moment shown in Figure 4 could be identified in the data. *Figure 5* provides a graphical illustration of the BRT.

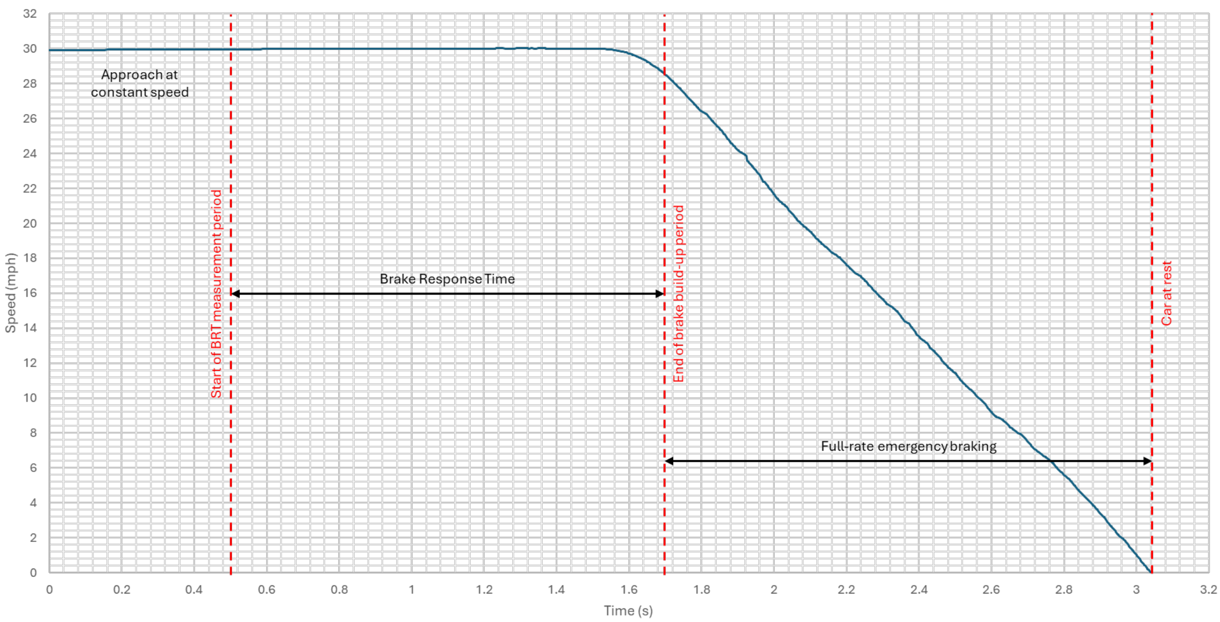

Figure 5 – A graphical illustration of the BRT period

For each car, a minimum of 12 tests were conducted, distributed as evenly as possible between the four scenarios. In total, 195 valid tests were conducted that resulted in AEB system activations. All of those individual test results can be found within Appendix A. For some of the cars, more than 12 tests were conducted in order to ensure a sufficient quantity of valid tests, whereby speed was within ±1 mph (1.6 km/h) of the target test speed and there were no significant steering inputs by the driver on approach to the test area.

4.2. *Brake Response Time*

BRT was selected as the primary test parameter. It allows the collision investigator to apply this research from the point at which an object becomes a hazard, to then account for the elapsed period and the speed loss during the BRT as detailed in this paper, without the need to account for an additional brake build-up period, and thereafter to apply a maximum deceleration to rest in calculations.

The results provide the percentiles for BRT (seconds) detailed in Table 1. The total range stretched from 0.76 to 1.97 seconds.

Analysed data were compared between the different types of propulsion systems, however no trend was identifiable. For example, the three electric cars tested ranked first (BMW iX), third (Tesla Model Y), and ninth (KIA Niro) when the 50th percentile BRTs from individual cars were compared.

Data were also compared between offside (right) and nearside (left) approaches of the pedestrian dummy, and it was found that there was a negligible difference between results achieved between the two dummy approach directions (average 1.20 s BRT for nearside approach, average 1.22 s BRT for offside approach).

The test cars were fitted with a combination of solely camera based systems, and systems which combined the use of camera and radar. No trends were identified between the different types of system.

Table 1 – Brake Response Time results

	Percentile		
	10%	50%	90%
BRT (s)	0.88	1.17	1.50

4.3. *Speed Reduction during BRT*

Of the 195 total valid tests completed, 99 were at a test speed of 20 mph (32 km/h) and 96 were at a test speed of 30 mph (48 km/h). The percentiles for the speed reductions achieved during the BRT period are detailed in Table 2. The 50th percentile speed reduction across all tests was 1.8 mph (2.9 km/h). The total range stretched from 0.6 to 4.1 mph (or 1.0 to 6.6 km/h) for tests conducted at 20 mph (32 km/h), and 0.4 to 4.1 mph (or 0.6 to 6.6 km/h) for tests conducted at 30 mph (48 km/h).

Analysed data were again compared between the different types of propulsions systems and system configurations, and again it was found that there was a negligible difference.

Table 2 – Speed reduction results

	Percentile		
	10%	50%	90%
Speed reduction from 20 mph	1.0 mph (1.6 km/h)	1.7 mph (2.7 km/h)	2.7 mph (4.3 km/h)
Speed reduction from 30 mph	1.1 mph (1.8 km/h)	2.0 mph (3.2 km/h)	3.5 mph (5.6 km/h)

4.4. *Consistency of Performance*

In total, 207 valid tests were conducted with the test cars approaching the pedestrian dummy. Of those 207 tests, 12 resulted in no AEB system activation, and hence no speed reduction prior to collision. That results in an overall system activation rate of 94.2%.

However, it should be noted that those non-activations were all by the Land Rover Discovery Sport and the Volkswagen Golf, which had activation rates of 78.9% and 52.9% respectively. The systems in the other cars all activated consistently and every time. That is not to say that all systems on Land Rover and Volkswagen cars are inconsistent with their AEB performance, since only one car from their respective ranges was tested. It is also possible that the specific Land Rover and Volkswagen cars tested might have been affected by an uncontrolled factor, for example a poor calibration following a windscreen replacement.

5. Discussion

Further research and testing would need to be conducted before it would be possible to determine whether the results of this study apply to other scenarios, for example those involving other vehicles. However, the author sees no reason why this research could not be applied to other scenarios, provided the moment at which an object becomes a hazard can be quantified, and that the hazard requires a rapid response and full-rate braking, for example when the hazard develops at a TTC of about 1.4 to 1.8 seconds (as in the testing in this paper). The collision investigator would need to be careful in applying this research to other scenarios, for example where the AEB system might delay its response until full-rate emergency braking is required to avoid a collision, before which the driver might have the opportunity to brake at a lower rate and avoid the collision.

All tests were conducted in dry conditions and with good levels of ambient lighting. AEB system performance is likely to be worse in adverse weather conditions, although further research and testing would need to be conducted to quantify the reduction in performance. Ambient lighting might also affect system performance, particularly those which rely solely on a camera; systems which include a radar are likely to perform better in darkness than those without.

6. Conclusions

For the scenarios tested, whereby a pedestrian dummy entered the path of the test cars from behind an obscuring fence, it was found that Advanced Emergency Braking systems acted with a 50th percentile Brake Response Time of 1.17 seconds, and that during that period, the 50th percentile speed reduction achieved was about 1.8 mph (2.9 km/h). Those figures do not include instances where the system did not react to the presence of the pedestrian.

Over all tests conducted, there was a 94.2% AEB system activation rate. The non-activations were all from the Land Rover Discovery Sport and the Volkswagen Golf; during those tests, the AEB system did not activate and there was no speed reduction prior to the collision.

Glossary

Advanced Driver Assistance System ('ADAS') – automotive systems which are designed to enhance the safety of the driver and other road users, and to assist the driver in their normal driving tasks.

Advanced Emergency Braking ('AEB') – a system which can automatically detect a potential collision and activate the vehicle's braking system to decelerate the vehicle, with the purpose of avoiding or mitigating a collision.

Brake Build-Up Time – the period during which the rate of deceleration builds during braking, as the brake pads/shoes come into firm contact with the brake discs/drums.

Brake Response Time ('BRT') – the period elapsed between an object becoming identifiable as a hazard which requires an emergency response, to the point at which full-rate emergency braking is achieved.

Inertial Navigational System ('INS') – a device which utilises sensors, such as gyroscopes and accelerometers, and combines their measurement signals with positional data from a Global Navigational Satellite System ('GNSS')

Global Navigational Satellite System ('GNSS') – a general term describing any satellite constellation that provides positioning, navigation, and timing data

Perception-Response Time ('PRT') – defined in the textbook "*Forensic Aspects of Driver Perception and Response*" edited by Dr David Krauss, 4th Edition, Lawyers and Judges Publishing Co. Inc. Tucson Az. 2015, as "*the interval between the appearance of some object or condition in the driver's field of view and the initiation of a response. Between those two points the driver must become aware of the potential hazard (detection), reach some conclusion regarding what it is and what it is doing or likely to do in the near future (identification), decide what action, if any, is appropriate (decision), and put that action into effect (response).*"

Real Time Kinematic ('RTK') – uses base station infrastructure to resolve an area's GNSS positioning errors.

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Data Availability Statement

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

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Appendix A – Valid test results

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
BMW iX	20	Offside	0.87	0.88	1.11	1.34
			0.88		1.10	
			1.00		1.93	
			0.91		1.27	
			0.80		1.26	
			0.84		1.35	
		Nearside	0.81	0.86	1.20	1.47
			0.85		1.33	
			0.88		2.06	
			0.83		1.13	
			0.91		1.84	
			0.88		1.25	
	30	Offside	0.77	0.86	1.30	1.88
			0.96		2.17	
			0.88		2.03	
			0.76		1.75	
			0.83		1.16	
			0.97		2.17	
			0.90		2.19	
			0.83		2.26	
		Nearside	0.93	0.86	1.24	1.57
			0.77		1.42	
			0.89		1.88	
			0.84		1.20	
			0.80		2.10	
			0.91		1.55	
Ford Focus	20	Offside	0.91	1.00	1.37	1.31
			1.14		1.85	
			0.83		0.81	
			1.13		1.21	
		Nearside	1.12	1.07	1.70	1.30
			1.26		0.94	
			1.17		1.53	
			0.91		1.45	
			0.90		0.90	

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
Ford Focus	30	Offside	1.22	1.18	1.49	2.04
			1.05		2.09	
			1.06		1.63	
			1.29		2.45	
			1.26		2.53	
		Nearside	1.10	1.14	2.02	2.05
			1.18		1.67	
			0.94		2.46	
			1.14		2.31	
			1.22		1.53	
			1.27		2.31	
Tesla Model Y	20	Offside	0.76	0.88	1.16	1.45
			1.04		2.02	
			0.90		1.87	
			0.79		0.83	
			0.92		1.36	
		Nearside	0.91	1.16	1.04	1.89
			1.32		4.03	
			0.97		1.77	
			1.12		0.70	
			1.16		2.94	
			1.43		2.14	
			1.23		0.58	
	30	Offside	1.43	1.12	2.12	2.12
			0.95		1.42	
			1.27		3.28	
			1.01		2.31	
			0.94		1.46	
		Nearside	1.32	1.31	2.59	1.91
			1.23		1.36	
			1.39		2.46	
			1.30		1.23	
Hyundai Tucson	20	Offside	1.08	1.07	2.31	2.12
			1.06		3.30	
			0.98		1.83	
			1.18		0.84	
			1.26		2.15	
			0.87		2.29	

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
Hyundai Tucson	20	Nearside	1.42	1.15	2.82	2.58
			1.19		2.19	
			0.99		2.36	
			1.19		2.99	
			1.03		2.77	
			1.06		2.37	
	30	Offside	1.03	1.10	3.40	3.37
			0.99		2.99	
			1.04		3.38	
			1.10		3.41	
			1.00		3.10	
			1.11		3.72	
			1.42		3.61	
		Nearside	1.27	1.21	3.95	3.42
			1.21		2.87	
			1.29		3.85	
			1.14		3.56	
			1.16		2.87	
Mercedes-Benz A-Class	20	Offside	1.54	1.22	1.71	1.68
			1.13		1.74	
			1.23		1.94	
			1.13		1.35	
			1.08		1.65	
		Nearside	0.84	0.99	1.34	1.39
			0.98		1.26	
			1.08		1.64	
			0.94		1.12	
			1.09		1.58	
	30	Offside	1.07	1.24	2.15	1.65
			1.00		1.65	
			1.55		1.58	
			1.52		1.82	
			1.14		1.58	
			1.19		1.13	

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
Mercedes-Benz A-Class	30	Nearside	1.26	1.17	1.47	1.65
			1.09		1.53	
			1.23		1.96	
			1.21		1.55	
			1.27		2.01	
			1.12		1.49	
			1.01		1.52	
Land Rover Discovery Sport	20	Offside	1.33	1.18	1.10	1.44
			1.22		1.70	
			1.09		1.68	
			1.04		1.41	
			1.24		1.28	
		Nearside	1.09	1.16	1.25	1.40
			1.17		1.34	
			1.36		1.60	
			1.00		1.39	
	30	Offside	1.30	1.26	1.07	1.31
			1.67		1.44	
			1.18		1.40	
			1.12		1.22	
			1.14		1.82	
			1.13		0.92	
Peugeot 2008	20	Offside	1.16	1.19	1.84	2.65
			1.34		3.91	
			1.08		2.21	
		Nearside	1.18	1.17	2.76	2.85
			1.12		2.03	
			1.10		2.55	
			1.26		4.06	
	30	Offside	1.30	1.19	2.90	2.61
			1.19		1.73	
			1.18		3.10	
			1.10		2.69	
		Nearside	1.37	1.33	2.96	3.05
			1.29		3.41	
			1.32		2.55	
			1.33		3.34	
			1.34		2.98	

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
Vauxhall Corsa	20	Offside	1.39	1.26	2.64	2.36
			1.31		2.87	
			1.19		2.53	
			1.14		1.75	
			1.26		2.01	
		Nearside	1.07	1.08	1.48	2.08
			1.07		2.43	
			1.08		1.77	
			1.10		2.64	
	30	Nearside	1.37	1.47	1.77	1.81
			1.46		1.60	
			1.28		1.97	
			1.64		1.63	
			1.59		2.07	
KIA eNiro	20	Offside	1.14	1.30	2.20	2.32
			1.30		2.36	
			1.47		2.04	
			1.28		2.32	
			1.29		2.70	
		Nearside	1.22	1.24	2.40	2.03
			1.22		1.90	
			1.34		1.92	
			1.19		1.56	
			1.25		2.35	
	30	Offside	1.53	1.47	2.58	3.12
			1.36		3.47	
			1.34		3.78	
			1.56		2.75	
			1.54		3.02	
		Nearside	1.61	1.45	3.70	3.76
			1.43		3.52	
			1.40		4.13	
			1.35		3.68	
Volkswagen Golf	20	Offside	1.85	1.63	0.63	0.94
			1.75		1.05	
			1.30		1.14	

Car	Test Speed (mph)	Scenario	BRT (s)		Speed reduction (mph)	
			Test	Average	Test	Average
Volkswagen Golf	20	Nearside	1.33	1.45	1.04	0.97
			1.33		0.97	
			1.47		0.88	
			1.56		1.06	
			1.65		0.81	
			1.38		1.07	
	30	Offside	1.86	1.90	0.91	0.81
			1.89		0.86	
			1.90		0.74	
			1.90		0.54	
			1.97		0.98	
		Nearside	1.46	1.52	1.06	0.73
			1.41		0.74	
			1.69		0.39	