Application of Vehicle Impact Simulation for Protective Barrier Design

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1 Abstract

The use of Vehicles As a Weapon (VAW) in targeted terrorist attacks has seen a rapid increase in frequency around the world. In response to such threats, a range of hostile vehicle mitigation (HVM) barriers, typically in the form of metallic bollards, continue to be installed within the urban environment. The validation of such systems has typically relied on full scale physical testing activities to internationally accepted standards (PAS68/IWA14-1). These tests are conducted in idealised environments and in ground conditions which may not represent final installation conditions and do not adequately consider complications of fitment in urban landscapes where existing underground services may provide significant design limitations.

Arup has employed the use of a previously validated N1G vehicle model (developed by the National Crash Analysis Centre and George Washington University) to simulate vehicle impacts on vehicle security barriers. In this study, the vehicle model is also used to assess the performance of two commercial vehicle barrier products seeking certification; an operable bollard system and "wedge" blocker. By conducting analysis in LS-DYNA prior to certification, the opportunity exists to conduct sensitivity studies on ground conditions and fixing methods, informing foundation performance and identifying areas for performance enhancement. Non-standard impact performance tests are also explored using the same simulation models.

This study demonstrates the benefits that can be obtained through the application of advanced simulation techniques to replicate a highly dynamic physical test. The application of these techniques shows the capability to assess further variables such as ground conditions and impacts speeds outside of the scope of the existing testing standards. The ability to review performance in a range of conditions before costly physical testing provides a greater level of confidence of system performance and allows for detailed design optimisation to ensure products deliver the required protection.

2 Introduction

The use of Vehicles As a Weapon (VAW) in targeted terrorist attacks has seen a rapid increase in frequency around the world. Since 2010, 50 vehicle VAW attacks have taken place around the world. 22 of those incidents have occurred in Europe.

In response to such threats, a range of hostile vehicle mitigation (HVM) barriers, typically in the form of metallic bollards, continue to be installed within the urban environment. These barriers are designed to provide protection against both high speed impacts and low speed encroachment whilst remaining permeable for pedestrians.

The validation of such systems has typically relied on full scale physical testing activities to internationally accepted standards (PAS68/IWA14-1) [1-2]. These tests are conducted in idealised environments and in-ground conditions which may not represent final installation conditions and do not adequately consider complications of fitment in urban landscapes where existing underground services may provide significant design limitations. Arup has been applying simulation techniques which are commonplace in the automotive industry to model vehicle impacts on barrier structures. These models are extended to include ground conditions and system foundations more accurately replicating the final installation condition. These models provide an improved understanding of the in-situ condition of the barrier systems and can be used to inform loading on adjacent structures, enabling post impact structural damage assessment and guide the design of appropriate structural reinforcement.

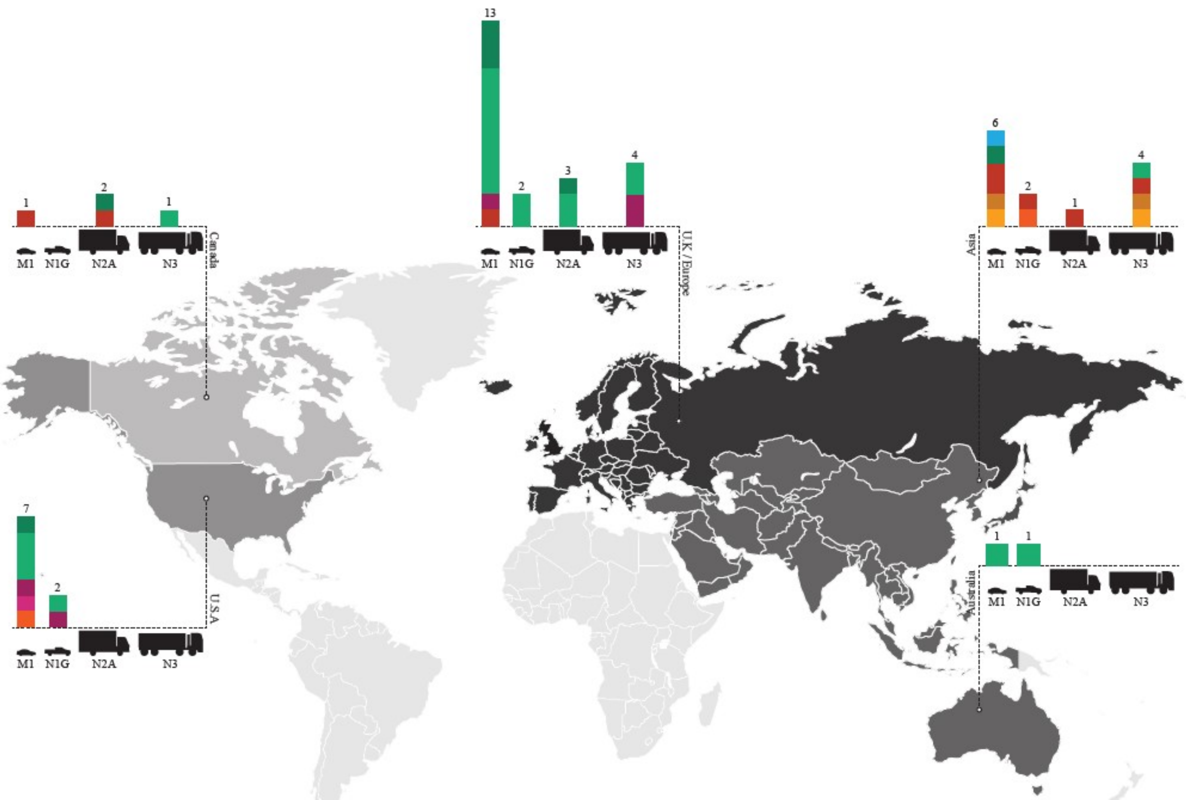


Fig.1: Global VAW incidents since 2010 (information gathered from various news agencies)

Arup has employed the use of a previously validated Silverado model, developed by the National Crash Analysis Centre and the George Washington University in 2009, and further validated in 2015 which is used to simulate NCAP Frontal Full Wall [3]. This vehicle meets dimensional requirements for the 2500 kg N1G vehicle as outlined in IWA14-1:2013. Through the use of LS-DYNA, this detailed vehicle model has then been compared against a rigid bollard impact test completed by UKs Centre for Protection of National Infrastructure (CPNI) [4-5]. This rigid bollard test was specifically designed to replicate the setup of the PAS68:2013 barrier crash test requirements. This provides a single validation point for a localised central frontal impact against a (near) rigid impactor, resulting in maximum load transfer to the vehicle structure; a test setup not typically included as a regulatory crash test in vehicle performance certification.

In this study, the vehicle model is also used to assess the performance of two commercial vehicle barrier products seeking PAS68:2013/IWA14-1 certification; an operable bollard system and “wedge” blocker. By conducting analysis in LS-DYNA prior to certification, the opportunity exists to conduct sensitivity studies on ground conditions and fixing methods, informing foundation performance and identifying areas for performance enhancement. Non-standard impact performance tests are also explored using the same simulation models.

This study demonstrates the benefits that can be obtained through the application of advanced simulation techniques to replicate a highly dynamic physical test. The application of these techniques shows the capability to assess further variables such as ground conditions and impacts speeds outside of the scope of the existing testing standards.

Impact tested, or “rated” security barriers, are largely developed for the protection of high security assets from targeted ramming events. Used extensively to protect the boundaries of financial institutes, foreign embassies and international airports etc., these barriers are designed to resist high energy vehicle impacts and create a stand-off distance against vehicle borne improved explosive devices (VBIED). They were conceived to mitigate these threats, but now adopted for VaW too. Due to recent events in a number of countries around the world, these bollard systems are being applied extensively around city streetscapes to protect highly populated pedestrian areas. Whilst these products may have some applicability, urban environment design involves the complex interaction of a range of competing design constraints. Subsequently, selection and placement of bollard systems should consider some of the following issues:

- Road user safety – Bollards are often placed in close proximity to roads and are not designed with road user safety as a primary consideration;
- Pedestrian movement – Bollards take up valuable pavement width impacting on the movement of pedestrians;
- Restricted mobility users – Bollard spacing can significantly affect accessibility for people with restricted mobility (e.g. wheel chair users);
- Cyclists – Bollard systems can be a significant obstacle for cyclists in cities promoting environmentally friendly travel methods;
- Aesthetics – Bollard systems are limited in aesthetic design appeal;
- Existing underground services – Bollard products require significant foundations / footings. This can be problematic in the urban environment where underground services can be extensive;
- Structural limitations – Suspended slab structures with limited thickness are not uncommon in urban construction. These can pose significant limitations on product fitment; and,
- Emergency Services Access – The placement of barriers which restrict vehicle access needs careful consideration for how emergency services can continue to access areas.

The range of considerations outlined above indicate the challenge in selection and installation of vehicle barriers in the configuration in which they were tested.

3 Vehicle Security Barrier Certification

There are two standards which can be used to certify the performance of Vehicle Security Barriers (VSBs) within the UK and Europe; PAS68:2013 and IWA 14-1:2013. Both standards require full scale physical testing by an authorized testing body. In both testing standards, the barrier is deemed to pass if one (or more) of the following objectives is achieved:

1. Brings the test vehicle to a rest
2. Resist/restrain/deflect the test vehicle from advancing beyond the VSB

An overview of the salient points from the two standards are outlined below:

PAS 68:2013 is the UK developed barrier testing standard. As one of the first standards developed for certification of vehicle barriers, many barriers available on the market are tested according to PAS 68 (2013 and previous versions). PAS 68:2013 assesses the performance of VSBs against vehicle categories which cover the typical range of vehicles available within the European market. Key vehicle dimensions are defined for the impacting vehicle and performance is based on a pass/fail when impacted at set speeds and angles. The distance the vehicle datum (typically bulkhead) penetrates past the barrier line is recorded along with the dispersion of debris weighing greater than 25kg.

IWA 14-1:2013 is an international testing standard used to determine the performance of vehicle barriers. Developed by an ISO Workshop Agreement, the IWA 14-1:2013 follows a similar structure to PAS 68:2013, however, it has three minor differences; major debris dispersion is not measured, vehicle penetration is measured from the front face of the VSB as opposed to the back and finally, other vehicle ranges are considered.

IWA 14-1:2013 is becoming the internationally applied vehicle barrier testing standard. However, like PAS68:2013 it was developed with the protection of critical infrastructure in mind. This can generate conflicts when applied to the challenging constraints of urban streetscape design. Barrier performance is only provided for specific vehicle types and set impact speeds which may not represent the changing conditions of a city. Limited guidance is provided on the testing conditions, such as ground conditions, terrain features and environmental effects which raises concerns of applicability in-situ. Furthermore, both test standards require full load application to one barrier giving no indication of performance in more complex impact conditions (e.g. multiple impacts, oblique angles).

3.1 Impact Testing Vehicle Types

PAS68:2013 details vehicle types that are typically of those seen on UK roads, whereas IWA 14-1:2013 is aimed at an international audience. As such, IWA 14-1:2013 details a number of additional vehicle categories on top of the PAS68:2013 outlining the full range of UNECE international vehicles. This provides a wide range of potential test vehicles. Test vehicles are subdivided into six categories ranging from typical B/C class car up to a commercial 30t truck. The standard defines upper and lower bounds for key dimensions which must be adhered to for each vehicle category when used to rate a products via physical impact testing. Whilst the testing standards do not specifically outline the test vehicle make and model, these critical dimensions aim to provide some bounding geometric limits on test vehicles so as to ensure some level of consistency when conducting the testing. Table 1 gives an overview of the test vehicle categories presented in IWA 14-1:2013.

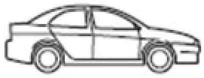
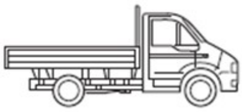
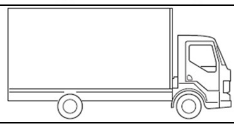
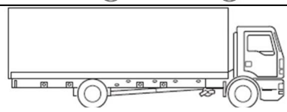
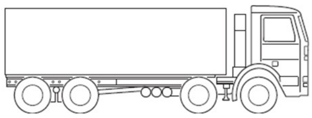
Type of Vehicle	**UNECE International Class**	**Illustration**	**Limit Gross Vehicle Mass (kg)**	**Max Vehicle length (mm)**	**Max Vehicle Width (mm)**	**Nominal Wheelbase (mm)**
Car	M1		1500	4860	1910	2700
4x4 (day cab)	N1G		2500	5800	2050	3200
Day cab vehicles	N1		3500	6580	2275	3805
	N2(A&B)		7200	10010	2600	5275
	N3(C-F)	 	30000	11470	2725	6800

Table 1: IWA 14-1:2013 test vehicle categories

3.2 The N1G Vehicle

For the purposes of this study, Arup has chosen to adopt the N1G vehicle type; specifically, the Chevrolet Silverado. A higher gross vehicle mass can result in significantly higher impact energies on vehicle barriers making the N1G a more onerous test condition. The N1G is a highly accessible vehicle type which has no additional driving license requirements over and above that of a M1 vehicle type.

Fig.2: Popular 4x4 Vehicles: a) Toyota Hilux, b) Ford Ranger, c) Chevrolet Silverado

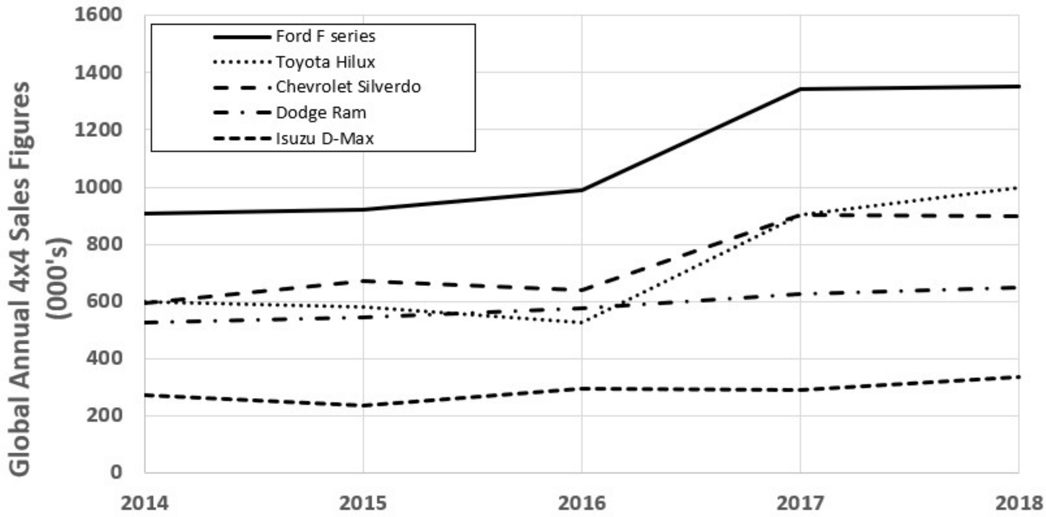


Fig.3: Global N1G sales figures for last 5 years [5]

Figure 2 presents some typical N1G style vehicle types popular in the US, Europe and Australia. Global annual sales figures for sports utility vehicles indicate three models continue to dominate; Ford F-series, Toyota Hilux, Chevrolet Silverado, see Figure 3.

Table 2 identifies the key vehicle characteristics (and tolerance) for the N1G vehicle category as defined in IWA-14-1. Table 2 also compares the dimensions for the Toyota Hilux (2007 MY), Silverado (2007 MY) and Ford F-series (2010 MY). All three vehicle types meet the critical dimensional requirements defined in the IWA14-1 testing.

Specifications	**IWA-14 N1G**	**Toyota Hilux**	**Chevrolet Silverado**	**Ford F-series**
Kerb Weight (kg)	Unspecified	1635	2130	1845
Max Payload (kg)	Unspecified	1095	898	1225
Test Vehicle Mass (kg)	2500 +/- 75	-	-	-
Wheelbase (mm)	3200 +/- 500	3085	3650	3225
Vehicle Length (mm)	5200 +/- 600	5260	5740	5359
Vehicle Width (mm)	1850 +/- 200	1835	2030	1849
Height from ground to lowest edge of the chassis rail at the front (mm)	435 +/- 75	-	435	500

Table 2: IWA 14-1:2013 vehicle characteristics comparison

4 N1G (Silverado) Validation

In this investigation, Arup has utilised a developed Chevrolet Silverado 2007 MY vehicle. A high fidelity, validated vehicle model has been made available by the NCAC [7]. The model was developed to investigate potential material mass reduction and used as a baseline vehicle to estimate crash performance. This work was completed by George Mason University. The Silverado has been validated for the NCAP full frontal test when travelling at a velocity of 56 km/h and has shown good correlation in a frontal collision impact. In order to bring the Silverado model from 2622 kg down to the mass category of the N1G, non-structural ancillary masses (e.g. spare wheel) have been removed, otherwise the model has remained unchanged.

The validation of vehicle impact against a rigid wall provides an appropriate read-across when simulating barriers that present a large flat frontal area, such as blockers or high walls when one or both of the chassis rails are engaged. However, this validation is unlikely to offer correlation when investigating the highly concentrated front impact of a bollard. In the event of a bollard impact, there is potential for neither of the chassis rails to be engaged and instead a significant proportion of the impact load is transferred through the subframe, engine and surrounding ancillaries. Physical testing of this type of impact is scarce. Subsequently, the CPNI and MIRA have completed both a rigid wall test and a rigid post impact test at a velocity of 48km/h. In both cases a Toyota Hilux is used. These two test arrangement have been replicated in this study using the aforementioned Silverado model. It should be noted due to security restrictions, typically CPNI post test data are very limited. Often only accelerometer data of the vehicle and engine block is available.

4.1 Rigid Wall

The rigid wall test completed at MIRA, by CPNI, was completed using a Toyota Hilux travelling at a velocity of 48 km/hr. Due to the lack of information publicly available, the only comparison that can be made is in regards to the force-time history of the instrumental wall. The force time history graph is displayed in Figure 4. Whilst the vehicle types are similar, there remain some fundamental differences between the Hilux and Silverado. The drivetrain for the Hilux is a 3.0L V4 manual whereas the Silverado is modelled with a 4.8L V8 automatic. Due to the increased mass and size of the larger engine and gearbox, it is expected that the Silverado model would generate a higher peak loading. A direct comparison of the peak force delivered between the two vehicle types illustrates this.

When comparing the mass of the two vehicle types, the Hilux required approximately 800kg of ballast to bring the kerb weight up to the required N1G testing mass requirement, whereas the Silverado model achieved the testing mass without the addition of any ballast. Consequently, the greater kerb mass (and payload capacity) of the Silverado variant is expected to be supported by a stiffer and stronger chassis. This may also account for the higher peak forces in the Silverado model and the longer positive phase duration observed for the Toyota Hilux (due to the greater addition of ballast) when comparing the force-time histories. Overall, the force-time profile illustrates that the Silverado delivers a similar loading curve to the Toyota Hilux, with similar trends and total impulse recorded during the physical testing.

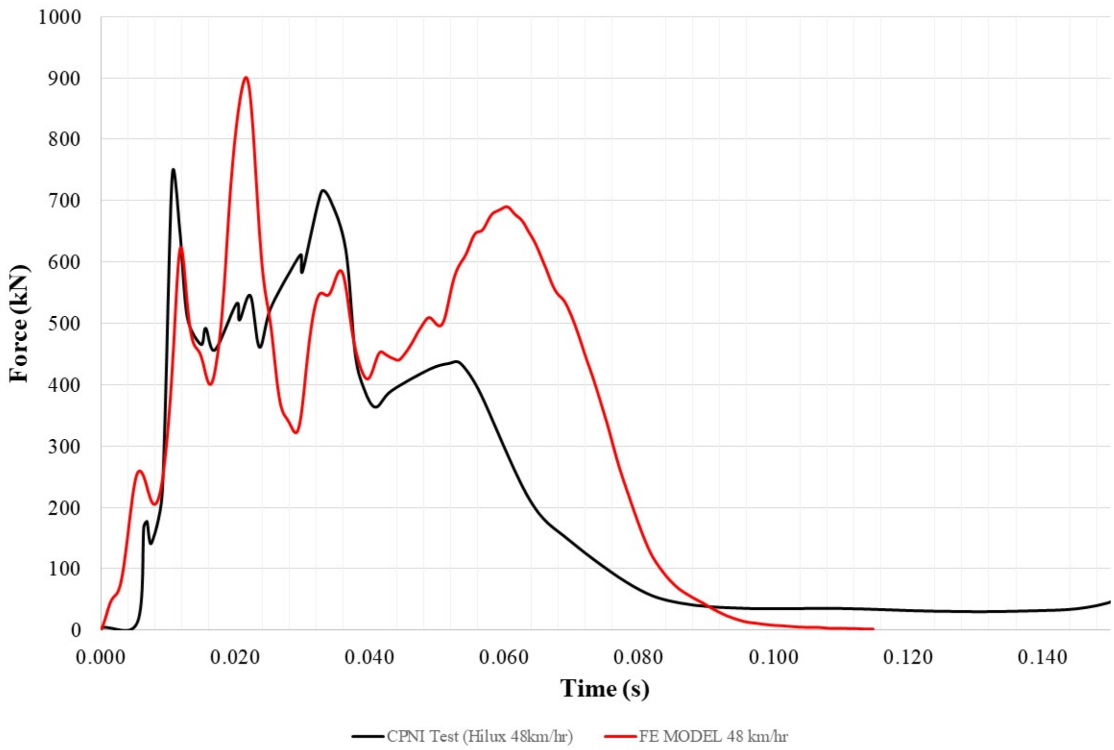


Fig.4: Comparison of Force-Time history for the CPNI Test (Hilux) vs Silverado model for rigid wall at 48 km/hr

4.2 Rigid Bollard Test

The CPNI tested a 2500kg N1G (Toyota Hilux) travelling at a velocity of 48 km/hr at MIRA using a near “rigid bollard”. A comparison of this test and the Silverado model is highlighted in Table 4. The bollard has been modelled with 25.4 mm wall thickness, with a near rigid material stiffness parameters. It is fixed at the ground plane.

Fig.5: Silverado model setup of the rigid post impact, replicating IWA14-1 test setup

As previously discussed, due to security restrictions the CPNI provides only a limited amount of information in relation to the testing. In this case, no force-time histories are available and only peak accelerations and forces outlined. Table 3 provides a comparison of the peak accelerations and forces between the physical test and the simulation. In both cases, the peak force is derived from the coupled engine/gearbox mass multiplied by the peak recorded accelerations. As is illustrated in Table 3, the major differences are the peak engine acceleration magnitude and the time at which it occurs.

Test Analysis (Single Bollard)	**CPNI Instrumented Test**	**Silverado Model**	**Delta**	
			Acceleration	**Time**
Peak Vehicle Acceleration (g)	43g @ 55ms	41.3g @ 67ms	1.7g	12ms
Peak Engine Acceleration (g)	136g @ 27ms	153g @ 54ms	17g	27ms
Average Vehicle Acceleration (g)	13g	9.96g	3g	
Max Vehicle Displacement (m)	0.71m	1.13m	0.42m	
Peak Force (kN)	504 kN	624 kN	120 kN	

Table 3: Comparison of the CPNI Instrumented Bollard Research Test and the Silverado Model.

Figure 6 demonstrates that at a time of 27 ms (time of peak engine force recorded for the Hilux test), the major impact on the bollard for the Silverado is the radiator and cooling pack. Inspection of the Toyota Hilux shows that the engine block sits closer in behind the cooling pack, whereas the engine block in the Silverado is set approximately 200 mm behind the cooling pack. This offset leads to the peak force in the Silverado model occurring later at 54 ms.

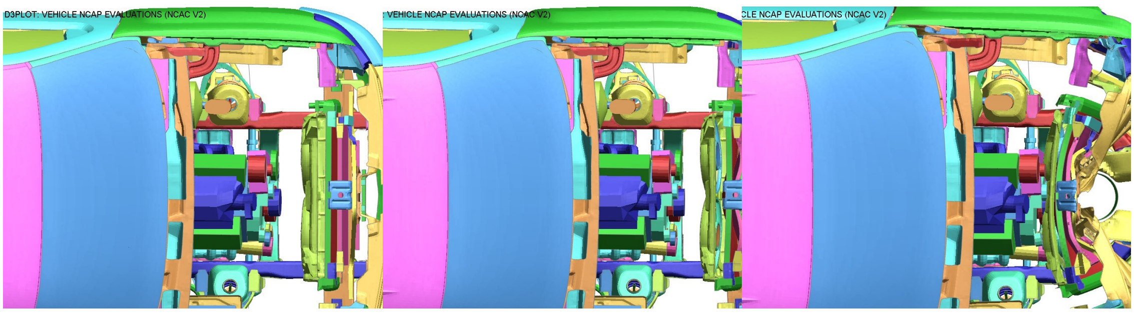


Fig.6: (a) Time at 0 ms, (b) Time at 27 ms (Hilux Peak Acceleration) (c) Time at 54 ms (Silverado Peak Acceleration)

Figure 7 presents the post impact deformed shape of the physical test and simulations. This indicates a similarity between the two vehicle types' post impact damage.

Fig.7: Comparison of damage between the Test at Mira and the CPNI Test [6].

5 Barrier Simulation

The comparison activities demonstrate that the Silverado vehicle model meets the IWA14-1:2013 dimensional requirements and comparison to the CPNI physical testing yields good agreement of global response characteristics. The Silverado has been tested to investigate the response of a Wedge Blocker and a Surface Mounted Operable Bollard System which are currently unrated against impact from this vehicle classification.

5.1 Wedge Blocker

The wedge blocker simulated here is a surface mounted retractable blocker developed by AVS-Elli. The blocker is connected to a slab using anchor bolts and has been simulated using *MAT_PLASTIC_KINEMATIC [8] 450 MPa steel elastic-plastic material properties. It is designed to sit 110 mm off the finished surface and opens and closes using a pneumatic system. The wedge blocker has a footprint of approximately 3400 mm x 1400 mm and achieves a barrier height of approximately 800 mm when fully deployed.

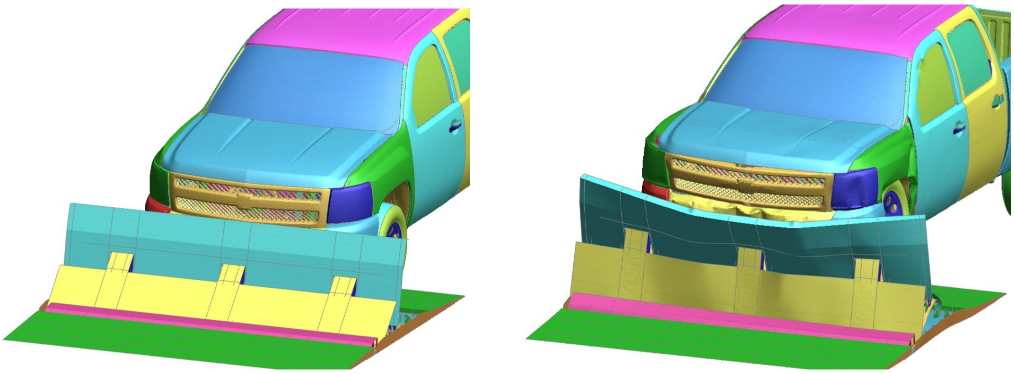


Fig.8: (a) N1G Silverado and wedge blocker at 0 ms (b) N1G Silverado and wedge blocker at 135 ms, when the vehicle achieves 0 m/s forward velocity.

The wedge blocker in this scenario (48 km/hr impact speed) sufficiently stops the vehicle from penetrating past the barrier, whilst damaging the vehicle to render it undriveable. Consequently, the wedge blocker would meet the requirements set out by IWA 14-1:2013 for this vehicle type and impact speed and immobilizes the vehicle by trapping it. Figure 8 illustrates the penetration distance for the wedge blocker is 0 m.

The wedge blockerdamages the vehicle, as it causes the vehicle to ride up whilst simultaneously reducing its velocity . The damage to the vehicle is similar to the rigid bollard test for the bumper but less severe which is demonstrated in Figure 9.

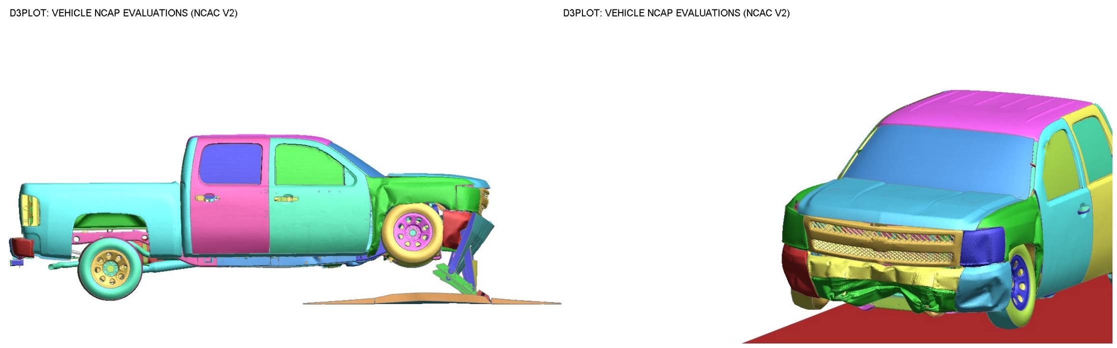


Fig.9: (a) N1G Silverado riding upthe wedge blocker(b) N1G Silverado at 135 ms, showing the damage to the front of the Vehicle.

The wedge blocker takes 135 ms to slow the vehicle to a resting velocity. The peak engine is 30 g and occurs at 48 ms. This is due to the wedge blocker plate crumpling. The benefits of using such a system, is that it can be installed on thin suspended slabs, where foundation depth is limited.

5.2 Operable Bollard

Operable bollard systems are used where vehicle access may be required. This product, marketed as 'Matador' and manufactured by Heald, is designed to allow a bollard to slide laterally in a track generating an increased open gap wide enough for vehicle movements. It is also designed to be surface mounted, requiring no excavation during fitment.

The system pictured below is made up of a 25.4 mm base plate and a 25.4 mm top plate with 25.4mm stiffeners joining the two plates together. It has a total foot print of 2340 mm x 4600 mm and a total mass of 8200 kg, therefore providing a substantial resistance to the vehicle impact. The bollard has been modelled with a wall thickness of 19mm and a height of 1200 mm off the finished floor line. The bollard is assumed to be manufactured from S355 seamless steel tube, a common material for metallic bollard systems. The bollard has a shroud that extends 150 mm up the base connection, to provide extra support. In the model, this is represented by a constrained nodal rigid body connection.

The simulation shows the system sufficiently stops the vehicle from penetrating past the vehicle security barrier, whilst severely damaging the vehicle to render it undriveable. Consequently, the bollard would meet the requirements set out by IWA14-1:2013. Figure 10 illustrates the penetration distance for the bollard is 0 m when the vehicle is brought to rest.

The simulation shows that the peak force of 472 kN occurs at 53 ms after initial impact, this coincides with the time the engine contacts the bollard. This is in agreement with CPNI physical testing (outlined above), where the peak force occurs due to the engine and transmission contacting the bollard. The major difference between the almost rigid bollard and the surface mounted bollard is the movement systems allows more flex of the bollard, reducing the peak loading, however, the bollard systems can be seen to stop the vehicle penetration.

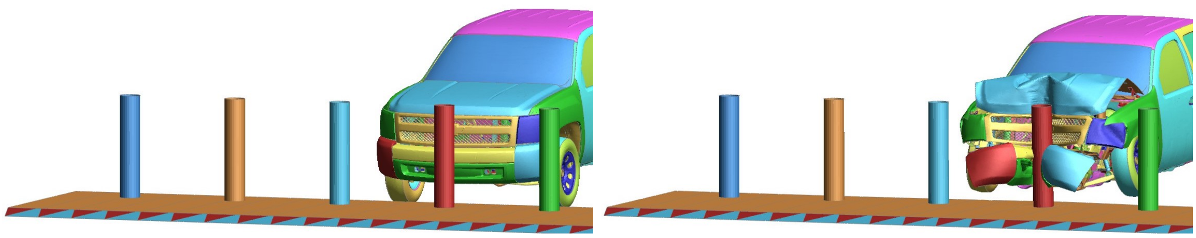


Fig.10: (a) N1G Silverado at 0 ms (b) Time of Peak Engine Acceleration.

6 Summary

Existing methods to determine the performance of vehicle security barriers involve expensive vehicle testing activities. Whilst these provide a useful pass/fail of performance for a given system against a given test arrangement, little additional information is provided which can be used to indicate performance when conditions outside those explicitly tested could occur. As such, the physical testing is limited in its applicability to non-standardized environments.

In this study an existing validated vehicle model has been adapted and applied to modelling high speed impacts on vehicle security barriers. The Silverado vehicle model, an N1G vehicle classification, has been compared against available test data provided by the CPNI with agreement of peak forces and accelerations. This validated model has then been applied to investigate the performance of two different vehicle security barriers.

This study has shown that validated models are able to provide adequate indications of performance of bollard systems and provide the additional significant benefit of providing an indication of barrier response to overmatch conditions; where impact speeds or positions may be outside the set testing bands in the existing standards, ultimately providing a better understanding of the barriers performance under a much broader range of scenarios.

Furthermore, this study shows the potential to use simulation to predict the performance of a range of existing obstacles and street furniture which is not readily physically tested to the existing physical test standards. This provides significant potential to offer estimations of performance on existing items and assist in developing integrated hostile vehicle schemes which utilise the existing landscape to provide proportionate and appropriate protection for crowded places.

7 Literature

[1] PAS68:2013, Impact test specifications for vehicle security barrier systems, August 2013
[2] IWA14-1:2013, Vehicle security barriers — Part 1: Performance requirement, vehicle impact test method and performance rating, November 2013
[3] Marzougui, D, Samaha, R, Cui, C & Kan, C, "*Extended Validation of the Finite Element Model for the 2007 Chevrolet Silverado Pick-Up Truck*", NCAC 2012-W-003, 2012, 1-14
[4] Centre for the Protection of National Infrastructure, "*Hostile Vehicle Mitigation Guide",* UK Edition 2010
[5] Centre for the Protection of National Infrastructure, "*Toyota Hilux – SUV – Single Instrumented Bollard – 48 km/h",* K0024 Technical Summary Report
[6] Global Automotive Database (www.autobei.com)
[7] Mohan, P, Ritter, M, Marzougui, D, Brown, D & Kan, C, " Modelling, Testing and Validation of the 2007 Chevy Silverado Finite Element Model", NCAC 2009-W-005
[8] LSTC, LS-DYNA *Keyword User's Manual Volume 1, Livemore Software Technology Corporation*