Design and testing of effective Rollover Protective Structures for Light Vehicles
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Abstract - DVExperts International (DVE) has developed requirements for vehicle rollover protection systems for military, mining and civilian use. The world’s major resource companies have identified rollover crashes of light vehicles (Pickups and SUV’s) as a serious problem for both their own and contractor vehicles operated on their sites. The structural rollover protective systems were being developed and manufactured locally for vehicles operating sites to no specific requirement(s) and resulted in a range of outcomes. Following a commercial tender process DVE structural requirements have been adopted for fleets of 4x4 vehicles (Pickups and SUV’s). The rollover structural requirements are based on DVE research into rollover protective systems and define loading, intrusion and robustness criterion. The analysis and testing processes used to develop and validate the rollover protective structural systems. Structural solutions have been manufactured by DUYYS Engineering (South Africa), Largo Tank & Equipment (USA) and Industrias Metalicas Miller (Colombia). The design criteria, analysis and testing processes used to develop and validate the rollover protective structural systems are presented, and provide a basis for roof strength design for all light vehicles, OEM or otherwise.

Keywords: Rollover Protective Structures, ROPS, Occupant Protection, Vehicle Safety

BACKGROUND

This paper originates from a background of professional and forensic engineers, safety researchers, manufacturers and resource industry officials who have had many years experience looking at the catastrophic outcomes of poor design and inadequate design standards in our transport system, as well as designing safer systems [4, 5, 6, 19, 20, 21, 22, 23 & 24]. We have been passionately involved in vehicle safety and rollover research and injury mitigation for over 15 years in Australia, the Americas, South Africa and internationally.

Specifically, the DVE authors have:

- Analysed many rollover crashes in depth, including rollover crashes of passenger cars, Sports Utility Vehicles (SUV’s), military and police vehicles, heavy trucks, buses, All Terrain Vehicles (ATV’s), tractors, forklifts, cranes and trains (refer to Figure 1).
- Carried out in-depth studies of rollover crashes as part of major University research programs, for Government regulatory agencies and major organization such as, the Victoria Police Force and the Australian Defence Forces as well as large international companies looking to improve vehicle design for protection of their vehicle occupants in rollover crashes.
- Lobbied the United States of American agencies such as the National Highway Traffic Safety Administration (NHTSA) [7] and Australian agencies such as the Australian Department of Transport and VicRoads [21] and the Australian New Car Assessment Program (ANCAP) regarding the need for improved transportation safety.

Rollovers are a tremendous problem facing our society worldwide. Although rollovers only account for a small percent (perhaps 2% to 3%) of crashes, they represent nearly one-third of crash-related fatalities and serious injuries. Further, injuries associated with rollover crashes are typically correlated with more societal harm (e.g. more emergency personnel required, higher hospital and long-term care costs, etc., which equates to more tax dollars). Rollovers are the major contributor to serious spinal injuries resulting in paralysis. In an attempt to address the rollover problem, several of the authors began investigating rollover crashes in detail in the early 1990s. Some of this work included a detailed investigation of over 40 injury producing rollover crashes for VicRoads [21], an Australian government body. In addition, extensive real-world field research was completed for the Australian Army to analyze and mitigate rollover injuries occurring in the field [23].

The world’s mining resource companies have identified rollover crashes as a serious safety risk for their workforce. These companies have identified that there is no present sufficient and effective international or national light vehicle design requirements for Rollover Protective Structures (ROPS). There are no acceptable ROPS currently available for vehicles supplied by OEM vehicle manufactures.
such as Toyota, Nissan and Ford. Many of the current ROPS designs in place throughout the world have been determined to be of poor and/or of concerning quality and design. Lack of Consistent ROPS standards is creating confusion within the resource companies, the contract partners and rental companies providing vehicles. Analysis of rolled vehicles revealed that there was roof structural collapse and buckling into the front occupant compartment resulting in glass breakage. Very serious injuries spinal injuries and deaths have occurred in vehicles exhibiting similar roof crush patterns.

Figure 1: Examples of investigation into vehicle rollover – passenger cars, SUVs, military and police vehicles, heavy trucks, buses, ATVs, tractors, forklifts, cranes and trains

It the fundamental opinion of the authors that the only currently mandated roof strength standard, namely the USA Federal Roof Crush Standard FMVSS 216 (also applicable in Canada and Saudi Arabia), is grossly inadequate [4, 5, 10 & 24]. The standard mandates a quasi-static application of force to a vehicle's roof, requiring a minimum strength-to-weight ratio (SWR, equal to roof strength divided by vehicle weight) of 1.5. The currently mandated quasi-static test is merely a roof component test and does not measure the vehicle’s rollover crashworthiness – the ability of the vehicle to manage a rollover crash with minimal bodily injury to its occupants. The vast majority of vehicles meeting the USA quasi-static roof strength standard repeatedly fail catastrophically in foreseeable rollover crashes. The authors have observed significant roof crush in rolled-over vehicles that currently meet the standard, largely due to the fact that the roof structure relies on the vehicle's windshield and other glass to pass the required test.

The continued use of a low-level quasi-static test protocol has resulted, in large part, due to key manufacturers' obfuscation of the need for and ability to develop a dynamic test protocol by reference to repeatability issues and other pseudo-science references. This obfuscation reflects a callous preference for bureaucratic process over function and a patent disregard for the thousands of lives lost annually in rollover crashes [1, 15, 16, 17 & 18].

The authors totally reject the proponents of the so called ‘diving theory’ for serious head and neck injury in rollovers, and attendant theory that roof crush is not a significant contributing factor to risk of
serious injury in rollover. While this theory has been propagated for over 30 years by various vehicle manufacturers and others (e.g. Moffatt 1975 [16]; Orłowski et al 1985 [18]; Bahling et al 1990 [1] and James et al 2007 [15]), it has enabled a sterile debate which has paralysed crashworthiness progress in rollover compared with major gains in frontal and side impact crashworthiness. The lack of a true rollover biofidelic ATD [in place of the Hybrid III] has also allowed continual debate without meaningful progress. The analogy with ‘Nero fiddling while Rome burns’ comes to mind, when considering the rollover toll of approximately 10,000 vehicle occupant fatalities per annum, just in the USA.

Fundamentally what is needed to ensure adequate rollover crashworthiness is a dynamic test protocol which evaluates the performance of the rollover protection system, which is comprised of the restraints, airbags, glazing, and roof strength safety systems and results in effective crashworthiness for multiple rollovers [4, 5, 7, 8, 9, 11, 12, 13, 22 & 23]. Analogously, there have been incontestable safety advances driven by mandated dynamic frontal and side impact test requirements, each which rely on testing the systems approach to crashworthiness. For example, an important highlight with the currently mandated side impact test, which was originally a simple quasi-static side door platen load test, is the fact that real advances in side impact protection did not occur until a dynamic test protocol was implemented.

The authors have observed that major reductions in injury risk can be achieved by the application of well-established fundamental occupant protection design principles that have been known since the early to mid 1900s. The principles of occupant rollover protection are clear – a strong roof structure [3 & 14], good restraint system (including belts and curtain airbags), to prevent intrusion and partial ejection, and appropriate internal padding, effective over multiple rolls. It is entirely feasible to design and manufacture a vehicle that has significant roof strength in both quasi-static and dynamic tests. This is demonstrated in the Volvo XC90 [2], which was required to meet stringent dynamic rollover tests in addition to the minimum mandated quasi-static test and is reported to have roof strength-to-weight ratio (SWR) of over 4.5. When vehicles are built from the ground up, it is very easy to design an optimised and strong vehicle from inception.

Due to the total ineffectiveness of the widely used quasi-static test protocol as a standard for rollover, the authors have developed independent dynamic test protocols to ensure that an effective vehicle structure is designed and implemented. The authors have conducted numerous studies which acknowledge that roofs must be able to sustain SWR values of AT LEAST 4 times (specifically 4 SWR increasing to 6 SWR, recommended to be sustained over 12 inches of deformation) the vehicle weight in order to manage foreseeable rollover forces. In addition, rigorous dynamic rollover tests are required as a safety audit to ensure that the rollover protection is adequate. Invariably in order to achieve this level of protection as an aftermarket fitment, requires the addition of some type of retrofit roll frame, due to the current inadequate roof structural design of the majority of vehicles available on the market. The authors have designed, marketed and implemented optimised rollover protective structures (ROPS) onto a myriad of resource vehicles, including for the mining industry, which have recognized roof crush in rollovers as serious occupational health and safety risk issue.

**DVEXPERTS ROLLOVER PROTECTIVE STRUCTURE (ROPS) CRITERIA**

It is DVE’s philosophical position that engineering design requirement for events which are estimated and/or vary (such as structural rollover protection requirements) should be exceeded rather than being met with a minimal safety factor. The typical engineering design approach is to build in adequate safety factors which protect the system. Exceeding the design requirements by implementing high safety factors allows for errors, omissions, inadequacies, tolerances, material variations and unforeseen circumstances.

It also DVE’s position that the designers have a professional, moral and ethical obligation to satisfy themselves that the requirements that they are designing to are genuine and meaningful. Simply adopting a standard without understanding its basis and effectiveness is, in the authors’ opinion, an abdication of the designers’ moral, ethical and professional responsibility.

DVE has adopted the following criteria in designing and developing ROPS, based on decades of experience, analysis of real-world rollover outcomes, academic and governmental research and
development of functional rollover protective systems [7, 20, 21, 22 & 23]. It should be emphasised that the following criteria would applicable to either a new vehicle development and/or retro-fit solutions.

1. QUASI-STATIC STRENGTH REQUIREMENT: The structure must maintain a minimum of 4 times and desirably increasing progressively up to 6 times the vehicle mass, up to a deformation of 300mm (12 inches) in a quasi-static loading environment, similar to US Standard FMVSS 216. The load should be applied consecutively to both sides of the vehicle at various angles.
   - A loading matrix should be applied, which considers multiple load directions.

2. INVERTED DROP TEST REQUIREMENT: The roof structure and related safety systems must be evaluated dynamically.
   - Digital Inverted Drop Test: A digital simulation of the vehicle and structure being dropped from at least 600mm, on both sides in turn;
   - Physical Inverted Drop Test: The vehicle and structure are dropped twice from at least 600mm, first on the near side at 5° pitch, 25° roll; then on the far side at the same angles.

3. ROLLOVER TEST REQUIREMENT: Ideally, and if economically feasible, a full-scale rollover test should be performed as an audit to validate that the system performs as desired in the real world. Such a dynamic test could be either a dolly-type rollover (e.g. the rollover test described in US standard FMVSS 208) at 50 mph (80km/h) velocity, a dynamic inverted drop test at 50 mph translational velocity, or dynamic tests using the Jordan Rollover System of at least 2 rolls. The author’s recognise the significant potential for using the Jordan Rollovers System (developed by Don Friedman and Acen Jordan of CFIR and XPRTS [5 & 9]) as a reliable, repeatable dynamic rollover test suitable for both vehicle rollover protection design validation and NCAP type star rating for rollover.

4. PERFORMANCE CRITERIA: The performance criteria for the roof and supporting structure for each of the above tests is as follows:
   - No structural failures, including joints, welds and members (thereby maintaining high load capacity and multiple rollover impact protection).
   - No intrusion into the occupant survival space of a 95th percentile male occupant.
   - High buckling load capacity for both longitudinal buckling and local buckling.
   - High structural stiffness.
   - Maintain the structures ductility.
   - No reliance upon the glazing (e.g. windshield) as a structural member.

5. AUDIT and FIELD ANALYSIS: Field analysis of real-world rollover crashes involving the subject vehicle to validate and verify that the structural system performed at a high level as designed and to identify possible areas for improvement of subsequent design iterations.

DVE SOLUTION DEVELOPMENT

The Duckling ROPS

In early 2003 DVE were engaged by SafeDrive International to examine and analyse ROPS for Schlumberger. DVE fundamentally identified that the internal ROPS systems that were being used in most remote locations were typically poorly designed, compromised the internal occupant space and were structurally inadequate. Therefore, DVE developed a structural ROPS solution, named the “Duckling ROPS” in which the rollover crash protection is provided by the combination of the base vehicle’s OEM restraints and the creation of the survival space around the vehicle occupant cabin. Specifically, the survival space is maintained via a cantilevering, laterally and longitudinally diagonally braced structure, which is secured to the tub of the pickup. Figure 2 illustrates the...
Duckling ROPS on a range of Pickups and shows how the survival space is maintained by a line drawn from the top of the ROPS cantilever to the bonnet of the vehicle. DVE’s Duckling ROPS solution was simple to manufacture requiring only 45° and 90° cuts to structural steel tubes, sheet metal cutting and simple bending and welding.

Figure 2: The Duckling ROPS on a range of Pickups with a line drawn to demonstrate maintenance of occupant survival space

**Real World Crashes of the Duckling ROPS**

There have been multiple real-world field rollover crashes of pickups fitted with the Duckling ROPS structure around the world. Figure 3 illustrates two different rolled vehicles equipped with Duckling ROPS. The key points to note are in relation to these rollover crashes are that the roof structural integrity and related occupant survival space were maintained and the glazing was retained (e.g. elimination of ejection portals), which prevented serious injuries from occurring in each case.

Figure 3: Rolled Vehicles Equipped with Duckling ROPS

**Development of the Swan ROPS**

The world’s leading resource companies have a global health and safety requirement to provide light vehicle ROPS protection for the fleet of vehicles that operate on their sites worldwide. DVE was awarded a competitive tender contract to provide ROPS designs to one of the world’s leading resource companies. In response, DVE developed an iterative ROPS system concept, named the ‘Swan ROPS’,
which was based on the principles previously used in the Duckling ROPS but was more aesthetically pleasing while maintaining functionality (refer to Figure 4 left). Further development and pre-production of the Swan ROPS concept was initiated, DUYS (located in New Germany, South Africa) were appointed to manufacture the Swan ROPS (refer to Figure 4 right).

Figure 4: Swan ROPS Design Concept Drawing (left) and Resulting Pre-Production Swan ROPS developed

Non-Linear Finite Element Modelling (FEA) of the Swan ROPS

DVE further developed and evaluated the Swan ROPS upper structure using digital non-linear FEA modelling techniques. Digitally, loads of between four to six times the vehicle mass were applied to the ROPS upper structure model in nine different orientations and at three varying roll angles (20°, 30° and 40°) and three varying pitch angles (5°, 10° and 15°). Figure 5 illustrates an image-capture of the FEA modelling output, showing the multiple structural finite elements and associated strength output. The non-linear modelling illustrated that there was yielding and plastic deformation of the structure, however the structure did not catastrophically fail and/or deform such that there would be significant intrusion into the vehicle occupant cabin.

Figure 5: Image-Capture of the non-linear FEA modelling of the Swan ROPS upper structure

Dynamic Modelling of the Swan ROPS

Subsequent to the FEA digital modelling, DVE developed a series of dynamic crash test models to further evaluate the Swan ROPS, using the computer program LS-Dyna. A C2500 pickup vehicle model was obtained from the US National Highway Traffic Safety Administration (NHTSA) database was utilized and the Swan ROPS design was digitally adapted to the vehicle shape. Several types of dynamic crash test modelling were performed, including inverted drop testing and rollover testing.
**Dynamic Inverted Drop Test Modelling**

Three models of dynamic inverted drop testing were performed at various heights and configurations in order to evaluate structural integrity of the Swan ROPS. In each drop test model, the inverted vehicles were released in free-fall at release angles of 25° in roll and 5° in pitch, which are commonly used angles for this type of testing. The vehicle system was modelled both with and without the ROPS structure at varying drop heights, resulting in increasing input energy as the height was increased. The inverted drop test modelling matrix was as follows:

**Drop Test 1:** The OEM C2500 pickup vehicle (without ROPS) was dropped from a height equivalent to 600 mm (refer to Figure 6).

**Drop Test 2:** The OEM C2500 pickup vehicle equipped with a Swan ROPS was dropped from a height equivalent to 600mm (refer to Figure 7).

**Drop Test 3:** The OEM C2500 pickup vehicle equipped with a Swan ROPS was dropped from a height equivalent to 900mm, (refer to Figure 8).

The LS-Dyna inverted drop test modelling illustrated that there was significant roof structural intrusion for the OEM production vehicle not equipped with a ROPS system when dropped from a height of 600 mm. Specifically, the OEM roof structure intruded nearly to the dash level, severely compromising occupant survival space. Alternately, the drop test modelling of the ROPS-equipped vehicle from an equivalent height of 600 mm resulted in minimal intrusion and preservation of occupant survival space. Further testing of the ROPS-equipped vehicle from a 50% higher height of 900 mm (50% more input energy) demonstrated that the structure was capable of withstanding a very high loading environment with minimal roof intrusion. Although there was some yielding and plastic deformation of the Swan ROPS structure itself as well as to the vehicle chassis, the structure did not catastrophically fail or deform such that the occupant compartment intrusion was minimal.

![Figure 6: LS-Dyna inverted drop test modelling of OEM production vehicle (without ROPS) dropped from height equivalent to 600 mm resulting in significant roof intrusion](image-url)
A model of a rollover crash test was performed to further evaluate the structural performance of the vehicle equipped with the Swan ROPS system. The simulated rollover test was comprised of several input parameters including an initial drop height of 600mm, a lateral projection (e.g. lateral translational speed) of 30km/h, a forward projection (e.g. forward translational speed) of 30km/h and an input roll rate of 180°/s. This rollover test simulation demonstrated that the ROPS-equipped vehicle experienced minimal roof intrusion resulting in the preservation of occupant survival space even in a very demanding crash environment. As in the simulated inverted drop tests, although there was some yielding and plastic deformation of the Swan ROPS structure itself as well as to the vehicle chassis, the structure did not catastrophically fail or deform such that the occupant compartment intrusion was minimal.
Physical Inverted Drop Testing of the Swan ROPS

In order to further evaluate the rollover crashworthiness of the Swan ROPS system, DVE and DUYS Component Manufacturing worked in coordination in order to fund and perform physical inverted drop testing of an OEM production Toyota Hilux pickup vehicle (2002), both with and without ROPS. The testing was intended to confirm the digital test results of the three previously performed inverted drop test simulations. The physical inverted drop test was conducted by releasing the inverted vehicles in free-fall onto rigid 20mm steel plating which covered a 100mm thick concrete floor. Three sequential tests were conducted using the same vehicle:

Drop Test 1: The OEM Toyota pickup vehicle equipped with a Swan ROPS was dropped from a height equivalent to 600mm (refer to Figure 10).

Drop Test 2: The same OEM Toyota pickup vehicle equipped with a Swan ROPS that was dropped from a height of 600mm was consecutively dropped a second time from a height of 900mm (refer to Figure 11).

Drop Test 3: The OEM Toyota pickup vehicle without ROPS was dropped from a height equivalent to 600mm (refer to Figure 12).

The physical inverted drop testing confirmed the results of the computer simulations. The drop testing of the vehicle equipped with the Swan ROPS illustrated that there was yielding and plastic deformation of the structure, however the structure did not catastrophically fail or deform resulting in minimal intrusion into the vehicle occupant cabin. Alternately, the drop testing of the OEM vehicle without ROPS resulted in structural failure of the roof structure and resulting intrusion into occupant survival space.
Figure 10: Test 1 drop of Toyota pickup equipped with Swan ROPS dropped from height equivalent to 600mm resulting in maintenance of occupant survival space

Figure 11: Test 2 drop of same Toyota pickup equipped with Swan ROPS dropped from height equivalent to 900mm resulting in maintenance of occupant survival space
Figure 12: Test 3, Toyota pickup without ROPS dropped from equivalent to 600mm resulted in roof structural collapse and compromise of occupant survival space.

Figure 13 shows the Toyota pickup with ROPS dropped from equivalent to 600mm and then from 900mm resulted in maintenance of occupant survival space, whereas Figure 14 shows the Toyota pickup without ROPS dropped from equivalent to 600mm resulted in roof structural collapse and compromise of occupant survival space.

Figure 13: Post Test 1 and 2, the Toyota pickup with ROPS dropped from equivalent to 600mm (Test 1) and then from 900mm (Test 2) resulted in maintenance of occupant survival space.

Figure 14: Post Test 3, the Toyota pickup without ROPS dropped from equivalent to 600mm resulted in roof structural collapse and compromise of occupant survival space.

**Production Manufacture of the Swan ROPS**

As a result of all of the development work, including simulated and physical dynamic testing, two fundamental types of Swan ROPS were designed by DVE and manufactured by DUYS in order to meet the varying needs of a workforce. The two solutions included: 1) a Swan ROPS which fitted into a standard OEM pickup truck bed and 2) a Swan ROPS fitted into an aftermarket drop down rear tray manufactured by DUYS (refer to Figure 15). The Swan ROPS has been designed to mount and function safely when fitted to single, king (extended) and dual (crew) cab pickup vehicles.
Real World Crashes of the Swan

At the time of submission, there have been a total of four real-world field rollover crashes of vehicles equipped with the Swan ROPS:

Rollover 1: The first rollover occurred at an estimated speed of 60km/h. The vehicle involved rolled over one quarter turn onto its side. There was minimal intrusion into the occupant survival space and there were no reported serious injuries.

Rollover 2: The second rollover crash occurred on a public road at an estimated speed of 113km/h, when the vehicle rolled over and then slid while inverted with the bonnet and ROPS in contact with the ground/roadway before coming to a halt. The design of the Swan ROPS protected the vehicle cabin by preserving the occupant survival space (refer to Figure 16). The driver sustained only minor cuts in what could have otherwise been a dangerous outcome.

Rollover 3: The third rollover occurred in a mine site, when the driver reportedly took avoidance action and rolled the vehicle at approximately 60km/h. The design of the Swan ROPS protected the vehicle cabin. The driver broke the driver’s side window in-order to exit the vehicle. Refer to Figure 17.

Rollover 4: The fourth rollover occurred on a public road at an estimated speed of +100km/h, in wet conditions the driver lost control the vehicle rolled over and then slid while inverted with the bonnet and ROPS in contact with the ground/roadway before coming to a halt. The design of the Swan ROPS protected the vehicle cabin by preserving the occupant survival space (refer to Figure 18). The driver sustained only minor cuts in what could have otherwise been a dangerous outcome.
Dynamic Drop Testing of the Swan

Subsequent to the four rollovers that occurred involving vehicles equipped with the Swan ROPS, it was desired by the authors to conduct additional and more stringent dynamic rollover testing as a supplementary safety audit. In order to further evaluate the rollover crashworthiness of the Swan ROPS system, DVE and DUYS worked in coordination in order to perform physical rollover testing of a series of OEM pickup vehicles both with and without ROPS. The testing involved suspending an inverted vehicle supported by a rigid cantilever structure mounted to the rear of an 8-ton truck (Figure 19). When the 8-ton truck reached a specified forward translational speed, ranging from 40 to 80 km/h, the vehicles were dropped onto the roadway and allowed to rollover. All vehicles were dropped onto their right driver side and allowed to roll left side leading (clockwise). This testing environment represents one that would be more demanding than an actual rollover due to the fact that the vehicle had no rotational velocity at the point where the roof or ROPS structure first contacted the ground. Due to the fact that in a typically pre-rollover loss of control phase typically involves some combination of braking, swerving and yawing, it is likely that the speed at the initial point of loss of control would be on the order of +20km/h greater than the evaluated translational test speeds.
A total of seven vehicles, both with and without ROPS were tested in a rollover test environment. The first test was conducted on an available dual (crew) cab pickup was intended to evaluate the test protocol to ensure that the procedure was valid. The remaining six tests were conducted on single cab pickups in order to compare structural performance of vehicles without ROPS to vehicles with ROPS. All tests were conducted at drop heights of less than 400mm and the vehicles were released with a forward-leading yaw orientation. Figure 20 and Figure 21 and are examples of the testing outcomes for a vehicle with and without ROPS, in this case at a translational speed of 60km/h (likely equivalent to an effective loss of control speed of 80km/h or higher).

An anomaly occurred during Test #1 (vehicle with a ROPS) the inverted vehicle was accidentally released while the 8-ton tow vehicle was stationary. There was no apparent damage to the ROPS or vehicle roof structure resulting from the accidental release. Subsequently, when this first ROPS-equipped vehicle was tested in the dynamic rollover environment, the frame assembly failed at the ROPS attachment points resulting in detachment of the ROPS after the first ground contact.

The results of all the testing are provided in Table 1.

It should be noted that a new Nissan (2007) vehicle was used for Test #2, whereas older Toyota Hilux’s (2000) were used for the other tests.

In general, the OEM vehicles not equipped with ROPS experienced extremely severe intrusion into the occupant compartment (refer to Figure 22, Figure 24 and Figure 25). All three of the single cab vehicles tested without ROPS experienced intrusion of 480mm to 530mm (16.5 inches to 20.8 inches). Intrusion resulted from severe structural failures including the collapse of joints and buckling of critical roof members. This severe and catastrophic deformation resulted in fracture and loss of all key glazing, introducing large potential ejection portals. Further, the corresponding inward buckling of the B-pillar resulted in the introduction of seatbelt slack, greatly limiting the effectiveness of the designed restraint system.

In contrast, the vehicles equipped with the Swan ROPS experienced virtually no roof intrusion (refer to Figure 23, Figure 24 and Figure 25). The ROPS structure protected the vehicle cab and occupant survival space extremely well, with no resulting structural failures. Even in the vehicle where the ROPS structure detached due to failure of the vehicle frame at the point of attachment, the majority of the rollover energy was absorbed by the ROPS in the initial ground contact resulting in preservation of the occupant survival space. This demonstrates the satisfactory performance of the DVE criteria, the ROPS structure, in both design and manufacture.
Figure 20: Still images taken from video footage of dynamic rollover test at 60km/h translational speed - vehicle equipped with ROPS system resulting in maintenance of occupant survival space
Figure 21: Still images taken from video footage of dynamic rollover test at 60km/h translational speed – OEM vehicle without ROPS system resulting in significant intrusion and buckling into occupant compartment
<table>
<thead>
<tr>
<th>Test #</th>
<th>Vehicle Description</th>
<th>ROPS</th>
<th>Release Speed (km/h)</th>
<th>Drop Height (mm)</th>
<th>Roll / Pitch Angle</th>
<th>Event Description &amp; Outcome</th>
<th>Glass Fracture</th>
<th>Max Crush (mm)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>2000 Toyota Hilux Crew Cab (#147)</td>
<td>No</td>
<td>60</td>
<td>350 to A-pillar</td>
<td>25° / 5°</td>
<td>Vehicle rolled ¾ revolutions &amp; yawed ~180° coming to rest on right passenger side facing direction of travel</td>
<td>All moveable glass, w/shield and rear glass</td>
<td>190</td>
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<tr>
<td>1</td>
<td>2000 Toyota Hilux Single Cab (#151)</td>
<td>Yes</td>
<td>60</td>
<td>230 to ROPS, 560 to A-pillar</td>
<td>25° / 5°</td>
<td>Vehicle rolled laterally 2 ½ revolutions &amp; came to rest on its wheels—failure of the frame resulted in detachment of the ROPS after the initial ground contact</td>
<td>All moveable glass, w/shield and rear glass</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>2000 Toyota Hilux Single Cab (#171)</td>
<td>Yes</td>
<td>60</td>
<td>200 to ROPS, 610 to A-pillar</td>
<td>10° / 5°</td>
<td>Vehicle rolled laterally 2 ¾ revolutions and came to rest on its left side</td>
<td>None</td>
<td>~0¹</td>
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<tr>
<td>3</td>
<td>2007 Nissan Hardbody Single Cab² (#000)</td>
<td>Yes</td>
<td>80</td>
<td>260 to ROPS, 620 to A-pillar</td>
<td>10° / 10°</td>
<td>Vehicle rolled 3 ¾ revolutions and came to rest on its left side</td>
<td>Only rear glass</td>
<td>0</td>
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<tr>
<td>4</td>
<td>2000 Toyota Hilux Single Cab (#164)</td>
<td>No</td>
<td>60</td>
<td>220 to A-pillar</td>
<td>0° / 5°</td>
<td>Vehicle rolled laterally 5 ½ revolutions and came to rest on its wheels</td>
<td>All moveable glass, w/shield and rear glass</td>
<td>480</td>
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<td>5</td>
<td>2000 Toyota Hilux Single Cab (#106)</td>
<td>No</td>
<td>80</td>
<td>300 to A-pillar</td>
<td>0° / 0°</td>
<td>Vehicle rolled laterally 3 revolutions and came to rest on its roof</td>
<td>All moveable glass, w/shield and rear glass</td>
<td>480</td>
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<td>6</td>
<td>2000 Toyota Hilux Single Cab (#324)</td>
<td>No</td>
<td>40</td>
<td>190 to A-pillar</td>
<td>5° / 0°</td>
<td>Vehicle rolled laterally 3 revolutions and came to rest on its roof</td>
<td>All moveable glass, w/shield and rear glass</td>
<td>530</td>
</tr>
</tbody>
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Table 1: Summary of Dynamic Rollover Test Results

¹ Estimation based on photographs - due to the fact that the test was conducted with the doors locked and windows rolled up and there was no resulting glass breakage, post-test measurements could not be obtained
² Note: A new Nissan vehicle.
Figure 22: Dynamic rollover testing results for OEM vehicles not equipped with ROPS showing severe roof structural intrusion, compromise of occupant survival space and glazing fracture.

Vehicle dropped at 40km/h translational speed
Vehicle dropped at 60km/h translational speed
Vehicle dropped at 80km/h translational speed

Figure 23: Dynamic rollover testing results for ROPS-equipped vehicles showing virtually no structural intrusion, maintenance of survival space and glazing integrity.

Vehicle dropped at 60km/h – ROPS detached after initial ground impact
Vehicle dropped at 60km/h translational speed
Vehicle dropped at 80km/h translational speed

Figure 24: Side-by-side comparison of testing conducted at 60km/h on OEM vehicle with ROPS (left) and without ROPS (right).
In examining rollover crashes it is apparent that where the vehicle interfaces with the roadway (during the roll) the roadway wins and the vehicle structure is typically catastrophically damaged. In examining the interfaces between the Swan ROPS and the roadway it is clear that the Swan ROPS wins.

CONCLUSIONS

Based on the development work and testing conducted by the authors, the following conclusions have been reached:

1. That a strong roof is essential to protect the vehicle occupants (such requirements are presented in the following section ‘Recommendations’).
2. The authors totally reject the theory that roof crush is not a significant contributing factor to risk of serious injury in rollover.
3. Field experience along with digital and physical dynamic inverted drop and rollover testing showed that the roof structures of current OEM vehicles do not have acceptable rollover crashworthiness.
4. In response, the authors have developed acceptable performance criteria for certifying the crashworthiness of vehicle roof structures or for retrofit ROPS systems.
5. The Swan ROPS system was designed by DVE and was manufactured by DUYS Engineering Group.
6. The Swan ROPS was certified to have met the DVE performance criteria via both digital and physical dynamic rollover testing.
7. Review of field crashes involving vehicles equipped with the Swan ROPS demonstrated excellent structural performance resulting in preservation of occupant survival space and minimal consequential injuries.
8. Further full-scale dynamic rollover crash tests highlighted the inadequate crashworthiness of current OEM roofs and demonstrated that the Swan ROPS protected the vehicle cab and prevented intrusion into the occupant survival space.
RECOMMENDATIONS

DVE Requirements for effective rollover protective structures for light vehicles [OEM or retrofit] are:

1. QUASI-STATIC STRENGTH REQUIREMENT: The structure must maintain a minimum of 4 times and desirably increasing progressively up to 6 times the vehicle mass, up to a deformation of 300mm (12 inches) in a quasi-static loading environment, similar to US Standard FMVSS 216. The load should be applied consecutively to both sides of the vehicle at various angles.
   - A loading matrix should be applied, which considers multiple load directions.

2. INVERTED DROP TEST REQUIREMENT: The roof structure and related safety systems must be evaluated dynamically.
   - Digital Inverted Drop Test: A digital simulation of the vehicle and structure being dropped from at least 600mm, on both sides in turn;
   - Physical Inverted Drop Test: The vehicle and structure are dropped twice from at least 600mm, first on the near side at 5° pitch, 25° roll; then on the far side at the same angles.

3. ROLLOVER TEST REQUIREMENT: Ideally, and if economically feasible, a full-scale rollover test should be performed as an audit to validate that the system performs as desired in the real world. Such a dynamic test could be either a dolly-type rollover (e.g. the rollover test described in US standard FMVSS 208) at 50 mph (80km/h) velocity, a dynamic inverted drop test at 50 mph translational velocity, or dynamic tests using the Jordan Rollover System of at least 2 rolls. The author’s recognise the significant potential for using the Jordan Rollovers System (developed by Don Friedman and Acen Jordan of CFIR and XPRTS [5 & 9]) as a reliable, repeatable dynamic rollover test suitable for both vehicle rollover protection design validation and NCAP type star rating for rollover.

4. PERFORMANCE CRITERIA: The performance criteria for the roof and supporting structure for each of the above tests is as follows:
   - No structural failures, including joints, welds and members (thereby maintaining high load capacity and multiple rollover impact protection).
   - No intrusion into the occupant survival space of a 95th percentile male occupant.
   - High buckling load capacity for both longitudinal buckling and local buckling.
   - High structural stiffness.
   - Maintain the structures ductility.
   - No reliance upon the glazing (e.g. windshield) as a structural member.

5. AUDIT and FIELD ANALYSIS: Field analysis of real-world rollover crashes involving the subject vehicle to validate and verify that the structural system performed at a high level as designed and to identify possible areas for improvement of subsequent design iterations.

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REFERENCES


14. IIHS; Rollover in your SUV, and you want your roof to hold up so you’re protected, Status Report, Vol 43, No. 2 , March 15 2008


