A METHODOLOGY FOR ESTIMATING VEHICLE ROLLOVER PROPENSITY THAT COMBINES STABILITY FACTOR AND HANDLING METRICS

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ABSTRACT

Although vehicle rollovers represent a low percentage of all vehicle crashes, rollovers are disproportionably represented in terms of vehicle occupant injuries and fatalities. The National Highway Transport Safety Administration (NHTSA) has been consistently exploring the issues relating to rollover. NHTSA have implemented a star rating system to inform consumers of the rollover propensity of vehicles as part of the New Car Assessment Program. The NHTSA propensity rating is based on the Stability Factor. Recent work by Monash University Accident Research Centre (MUARC) for the Victorian Police Force resulted in a range of a vehicle functional performance criteria being developed and utilised. A specific criterion relating to vehicle handling and Stability Factor was proposed. There is sufficient evidence to support the contention that Stability Factor and the rate of "real world rollovers" are linked. It is the contention of the authors that the 'apparent noise' (scatter) within the Stability Factor data is due to vehicle handling. This paper proposes a methodology that allows the combination of the Stability Factor and handling characteristic to be measured for a specific vehicle and enables the probability of rollover per single vehicle crash to be estimated.

BACKGROUND

Vehicle rollovers remain one of the major crash types yet to be dealt with in terms of effective vehicle design countermeasures and performance standards. Although crash prevention is the preferred countermeasure for all crash types, this is particularly true for rollovers. Whereas for most crashes serious or fatal injury outcomes are typically related to crash severity, this is less true for rollovers where fatal or serious injuries can still occur in low energy rollover events due to partial occupant ejection.

The importance of rollover prevention has been recognized in the USA, in particular, where some 10,000 fatalities per annum occur due to rollovers. Structural requirements have been developed for the Australian Military [1], as rollover predominates as an injurious vehicle crash mode. The Victorian Police Force [2] identified an issue with vehicle rollovers and implemented various strategies to reduce the exposure of their members to injury from vehicle rollover crashes. Rollover was also identified as a significant problem at the 1999 and 2000 SAE TOPTEC's on Military and Emergency Vehicle Safety.

In the USA measures to reduce rollover risk have included the introduction of a five-star rating vehicle rating system based on rollover propensity using a vehicle Stability Factor approach. The star rating system is aimed at simultaneously, informing Consumers as well as encouraging the vehicle manufactures to improve their vehicle designs. The USA National Highway Transport Safety Administration (NHTSA) has for a prolonged period of time been evaluating and exploring the issues relating to vehicle rollover.

This paper provides a summary of recent work carried out by the authors on rollover risk reduction relating to stability and handling tests for Police and Military vehicle fleets. It then develops a new methodology for testing and rating a vehicle for rollover propensity, based on static stability factors *combined* with a vehicles dynamic handling performance. Some of the data included in this paper was presented at ICrash 2002 (Melbourne, Australia) [3] additional data points and analysis have included in this paper.

SOME ROLLOVER STATISTICS

Rechnitzer [4] et al. reported on an Australian based study of rollover, using 1988 Federal Office of Road Safety (FORS) Fatality File data that rollovers; *"constitute 19% of occupant fatalities in Australia."* The problem of rollover is magnified further when vehicles are operated in a non-urban environment. Rechnitzer et al. reported that; *"rollover crashes are a common cause of occupant injury especially on non-urban roads. They constitute to 44% of occupant fatalities in rural Western Australia and 54% in rural Northern Territory".*

Henderson [5] et al. reported on Australian based data for FORS, using 1988, 1990 and 1992 FORS Fatality File data that; *"rollover crashes, especially in the country, are usually very destructive events. About 15% of passenger cars in fatal crashes in Australia have overturned. Between about 13% and 16% of all passenger-car occupants killed in Australia died primary as a result of injuries received in a rollover".*

The Australian Transport Safety Bureau (ATSB) Crash Database for the period 1996, 1997, 1998 and 1999, examining rollovers for cars, utilities, vans, 4x4's and motor homes details that 22.78% of Australian road fatalities are linked to vehicle roll overs. As the ATSB Crash Database also shows that for the period 1996, 1997 and 1998 that 12.17% of the fatal crashes involved rolled over, this data indicates 1.87 fatalities occur for each fatal rollover event.

Herbst [6] et al. presented United States of America (USA) data and argued that; *"rollover accidents pose a serious cost to society, while they account for 10% of all passenger car accidents, rollovers cause 20% of the Harm."* The reason for the significant amount of Harm, is that rollovers produce more severe injuries to the head, neck and or spine than any other type of vehicle crash.

Rollover is also a significant problem for 4x4's and SUV's with rollover rates of up to five times that of the average passenger car, on roads (Synder [7] et al).

Howe [8] et al. presented USA Fatality Analysis Reporting System (FARS) data identifying that between 1991 to 1998 an annual average of 9,237 people were fatally injured in crashes that included rollover. Howe et al stated; *"Rollovers are the second most dangerous type of crash occurring on our nation's highways…second only to the average for people who die due to frontal collisions."* Howe et al then identified using National Automotive Sampling System General Estimates System (NASS-GES) data for 1995 to 1999 that rollovers accounted for; *"approximately only 2% of the average number of all NASS-GES crashes for these years…. due to this relatively low percentage of rollover crashes, when measured by either fatalities or incapacitating injuries per occupant involved, rollover crashes are the most dangerous type of collision for all classes of light vehicles".*

Figure 1 details the average FARS data by vehicle class and also by million registered vehicles presented by Howe et al, illustrating that the issues of rollover in the USA predominates in the Pickup and SUV classes of vehicles

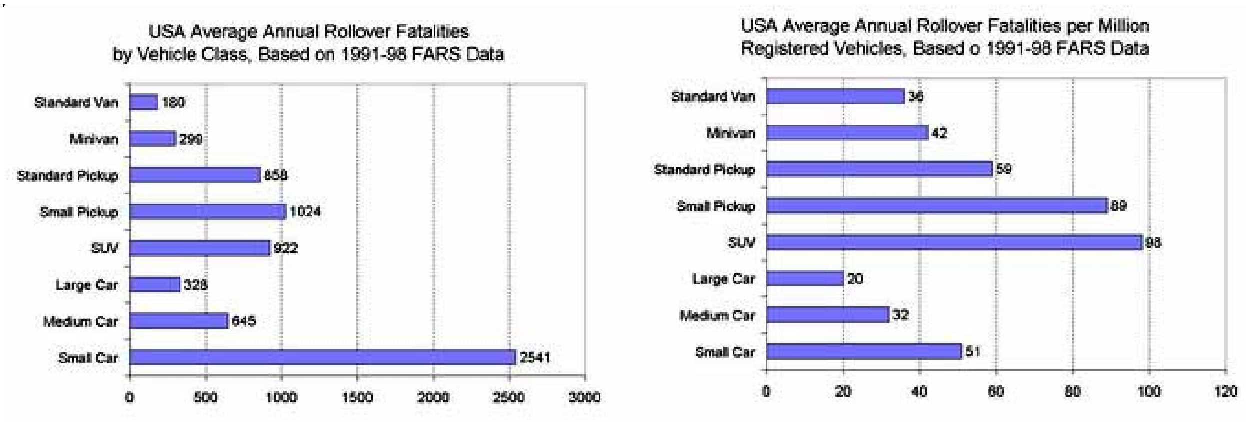

Figure 1: Average Annual Rollover Fatalities by Vehicle Class and per Million Registered Vehicles, based on 1991-1998 FARS

In Europe rollover appears to be lesser issue that either the USA or Australia for example Thollon [9] et al. presented French data; identifying rollovers represent 8% of vehicle crashes.

STABILITY FACTOR

The Stability Factor [10] is a common metric used to define light vehicle rollover propensity. The Stability Factor is defined as one half the average front and rear track width divided by the total vehicle Centre of Gravity (CofG) height. The simplifying assumption is that; the vehicle behaves as a rigid body (i.e. no suspension compliance, the tyres are rigid and there is sufficient tyre to road friction to induce a rollover). The Stability Factor relates to basic vehicle parameters of track width and CofG height to lateral stability. The Stability Factor is a rough conversion of the steady state lateral acceleration, in g's (9.81ms^{-2}) at which the vehicle will rollover on a flat road. Given that vehicles do not behave as rigid bodies, the Stability Factor is a first order predictor of a vehicles static rollover threshold

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA) WORK ON ROLLOVER PROPENSITY

In 1989 Mengert [11] et al presented a study examining 40,000 single vehicle crashes involving 40 different vehicle types to establish the probability of being involved in a rollover. In analysing the data eleven possible variables which could influence the probability of being involved in a rollover were evaluated; Stability Factor, wheel base, age of driver, alcohol/drug use, seatbelt use, rural location, urban location, road geometry, driver error, tracking v's sliding and road surface condition [dry/wet/snow]. Mengert et al determined that Stability Factor was the contributing variable with an "*excellent correlation to rollover*".

They presented the following characteristic:

Probability of being involved in a rollover = 100 / (1 + Stability Factor $^{6.9}$)

NHTSA has proposed [12] and implemented a rollover rating system into the New Car Assessment Program (NCAP) based on the Stability Factor. The rollover rating for NCAP is based on a four-year study of single vehicle crash data (1994 to 1997) from six states (Florida, Maryland, Missouri, North Carolina, Pennsylvania and Utah). The analysis is based on 226,117 single vehicle crashes of which 45,574 involved rollovers. One hundred vehicle types were identified. The data collected was presented in two forms [13]; not adjusted and adjusted for differences in road use or state reporting, as shown in Figure 2.

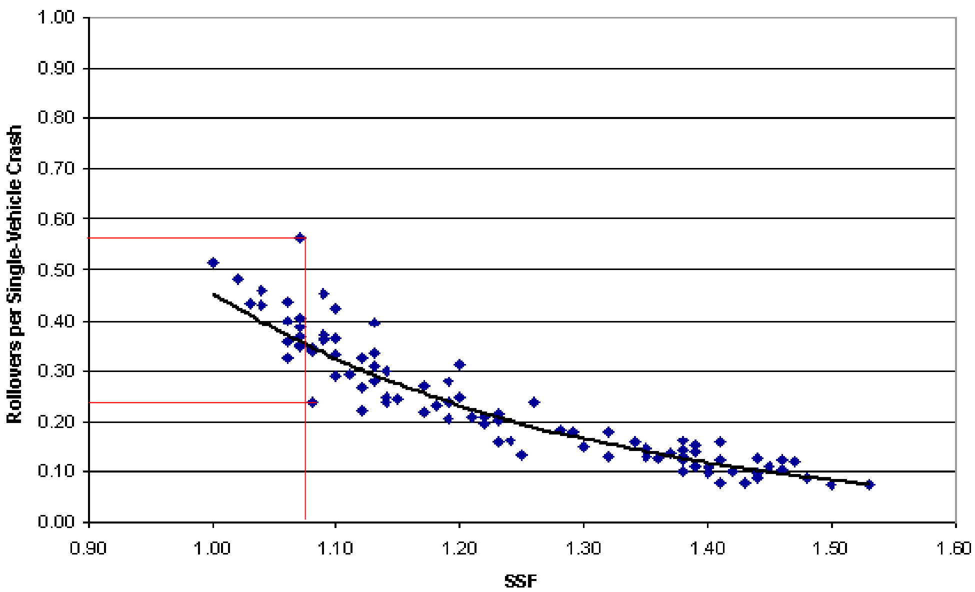

Figure 2: NHTSA data on rollovers per Single-vehicle crash estimated from Six states, adjusted for differences in road use or State reporting

The data collected shows a strong tendency for lower rollover rates for vehicles with higher Stability Factors. NHSTA have now classified vehicles using a star rating as part of the NCAP (http://www.nhtsa.dot.gov/cars/testing/NCAP/).

- One star: Risk of a single vehicle rollover crash ≥ 40%
- Two star: Risk of a single vehicle rollover crash > 30%, but <40%.
- Three star: Risk of a single vehicle rollover crash > 20%, but <30%.
- Four star: Risk of a single vehicle rollover crash > 10%, but <20%.
- Five star: Risk of a single vehicle rollover crash > 10%.

The problem with basing a rollover rating system on purely Stability Factor data is the distribution of the actual data points (defined by Garrott [14] et al. as the "*noise*"). The noise is illustrated in Figure 2, specifically at a Stability Factor of 1.07. At the maximum and minimum extremes two vehicles have a 56% and 23% probability of rollover per single vehicle crash respectively. The NHTSA rollover rating system would rank all vehicles with a Stability Factor of 1.07 as the same ie. 36% probability of rollover per single vehicle crash and would rank them as a two star vehicle, in terms of probability of rollover. This results in a 20% advantage to the 56% vehicle and a 13% disadvantage to the 23% vehicle. It is the opinion of the authors that the real disadvantage is to the consumer who uses the star rating to make an informed purchase on the probability of rollover.

In addition to the star rating NCAP Garrott et al. states that: *"NHTSA is working to develop either an information program which will make consumer's more aware of vehicle make/models with a high rollover propensity or a Federal Motor Vehicle Safety Standard (FMVSS) which would both prevent the manufacture of vehicles that have too high a rollover propensity or both".*

Garrott et al. then argues that; *"there are two reasonable ways to develop a methodology for determining a vehicles rollover propensity:*

- *<u>Actual Rollover Occurrence</u> approach,* (where) *a vehicle being tested is driven through a prescribed test procedure that may result in On-road untripped rollover.*
- *<u>Rollover Propensity Metrics</u> approach, may include dynamic driving tests. Laboratory tests or both… unfortunately, due to the 'noise' present in 'real-world' rollover crash statistics, achieving good correlations is very difficult".*

Howe et al defined rollovers into three types of events; Off-road tripped, On-road tripped and On-road untripped.

Garrott et al. reports on NHTSA research to establish a testing procedure for On-road untripped rollover (the Actual Rollover Occurrence approach). The authors are confused by the NHTSA focus on On-road untripped rollovers rather than Off-road rollovers, because in an earlier phase of the same study Howe et al. stated that:

- "*On-road, untripped rollovers due to vehicle maneuvering are responsible for only a small portion of the rollover safety problem.*
- *Perusal of the various rollover crash databases clearly shows that the Off-road rollover category contains the vast majority of all light vehicle rollover crashes.*"

Garrott et al. also states that: *"NHTSA has not yet decided whether to use the Actual Rollover Occurrence approach or the Rollover Propensity Metric approach. Therefore, work is proceeding in parallel upon both approaches."*

The work carried out by Howe et al and Garrott et al to establish a testing procedure for On-road untripped rollover has merit. The research is logical and provides a repeatable testing methodology that is based on using a steering machine and defined manoeuvres.

VICTORIAN POLICE STUDY

Subsequent to several rollovers of vehicles operated by the Victorian Police (VicPol) Monash University Accident Research Centre (MUARC) was requested to analyse the issues. MUARC was engaged and conducted a two-phase analysis. The first phase examined vehicle crash data held by VicPol, static stability and handling for a range of vehicles operated by Police Forces within Australia [2]. The second phase of the analysis was to assist in the definition, selection and specification of performance criteria for VicPol vehicles [15].

The VicPol operate essentially a lease fleet of production vehicles that are modified with police equipment. The majority of vehicles are fitted with light bars, communication equipment, etc. However, the typical VicPol first response unit was a Divisional Van (DiviVan), a standard Utility fitted with a prisoner containment system. The DiviVan's operated by the VicPol in June 2000 were based on the Commodore Utility and Rodeo 4x4 and 2x4 twin cab vehicles, illustrated in the Figure 3.

Commodore DiviVan

Rodeo 2x4 DiviVan

Figure 3: DiviVan's operated by VicPol in June 2000

VICPOL DATA

The VicPol vehicle accident database did not explicitly categorise vehicle crashes by the type of crash, a search of the data for descriptions containing "rolled" or variations thereof. The database was searched from Jan 1990 to Jun 2000. Ten vehicle types defined the fleet. Thirty-four rollovers were identified and detailed in Table 1. (The Victorian Police replaced the Old Falcon DiviVan with the Commodore DiviVan in 1995)

Five other rollovers were identified but were not included in the data. The rollover of a snowmobile was not considered while four other rollovers lacked sufficient detailed descriptions to enable identification of the vehicle involved. The rollovers per vehicle type were normalised against two fleet operational factors 10,000 vehicle months. (The calculated rollover rate is per 10,000 vehicle months of operation by VicPol. The Rollover Rate equals the ratio [number of rollovers]/[total vehicle months] multiplied by 10,000).

Serial	Vehicle type	Number of rollovers
1	Holden Commodore Sedan	2
2	Ford Falcon Sedan	5
3	Ford Falcon DiviVan (old)	2
4	Toyota Landcruiser Wagon 105R	1
5	Nissan Patrol Wagon	1
6	Holden Jackaroo Wagon	1
7	Toyota Landcruiser Wagon 80R	13
8	Toyota Landcruiser Troop Carrier	3
9	Holden Commodore DiviVan	11
10	Rodeo 4x4 DiviVan	5
	TOTAL	**34**

Table 1: VicPol rollovers January 1990 to June 2000

It can be seen from Figure 4 that the Commodore DiviVan has rollover rates similar to 4x4 vehicles and is significantly different from the Old Falcon DiviVan, which it replaced. The rates for the Rodeo DiviVan are significantly worse than all other types of vehicles operated by VicPol.

It was considered that rollovers are mainly due to the Track width to CofG height ratio, in the DiviVan vehicles the addition of the prisoner containment system was considered to have increased the rollover rates by significantly raising the CofG height of the base vehicle. This could be evaluated by measuring static factors, however to ensure that the suspension set-up of vehicles had not also contributed to the increased rollover rates handling evaluations of the vehicles was also carried out.

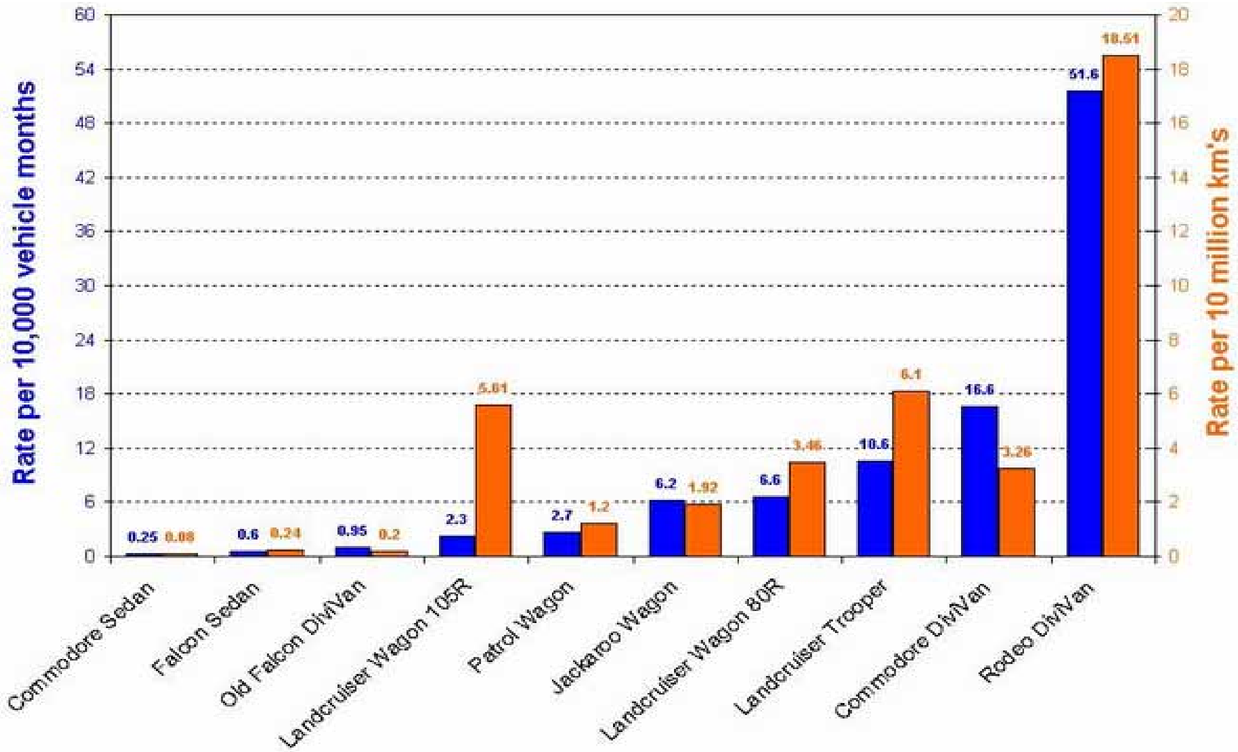

Figure 4: VicPol rollovers per vehicle months and 10 million km's travelled

Thirteen vehicles were tested for static factors [16 and 17] and the parameters measured included; Mass, Axle Loadings, Wheelbase, Track width, CofG location and Tilt table rollover angle. The Limit of Lateral Acceleration (LLA) was established from the Tilt table rollover angle at first wheel lift and the Stability Factor was calculated using the Track width and CofG location data (Table 2).

Serial	Vehicle	LLA (ms^{-2})	LLA (g's)	Stability Factor
1	Holden Rodeo 4x4 DiviVan	7.39	0.75	0.90
2	Toyota Landcruiser Troop Carrier	7.92	0.81	0.90
3	Holden Rodeo 2x4 DiviVan	8.03	0.82	0.89
4	Mazda E2000 Van	8.20	0.84	0.90
5	Toyota Landcruiser Wagon 80R	8.90	0.91	1.03
6	Holden Commodore DiviVan	9.12	0.93	1.08
7	Holden Rodeo 4x4 Utility	9.37	0.96	1.07
8	Holden Rodeo 2x4 Utility	9.74	0.99	1.09
9	Ford Falcon AU DiviVan (SA)	9.95	1.01	1.16
10	Ford Falcon DiviVan (old)	11.01	1.12	1.25
11	Holden Commodore Utility	11.36	1.16	1.27
12	Ford Falcon AU Utility	12.38	1.26	1.36
13	Holden Commodore Sedan	12.56	1.28	1.51

Table 2: Limit of Lateral Acceleration and Stability Factors for VicPol vehicles tested

Handling evaluations were conducted on eight vehicles [18]. Steady State turning tests were conducted in-accordance with ISO 4138 "Passenger Cars – Steady State Circular Driving Behaviour – Open-loop test procedure", and dynamic testing was conducted using the test track defined by ISO 3888-1 "Passenger Cars – Test Track for a Severe Lane-change Manoeuvre". All handling tests were limited to 70% of the previously defined LLA for the specific vehicle, so that testing could be carried out without outriggers.

Repeated handling tests were carried out; manoeuvring the vehicle to the left and right and using two experienced drivers.

Steady State turning was carried out to establish the steering characteristics of the vehicle and to ensure the steering characteristic was consistent either turning left or right and predictable over the 0 to 70% LLA range. The results of the Steady State testing are presented in Figure 5 as a plot of Hand-wheel Angle v's Lateral Acceleration.

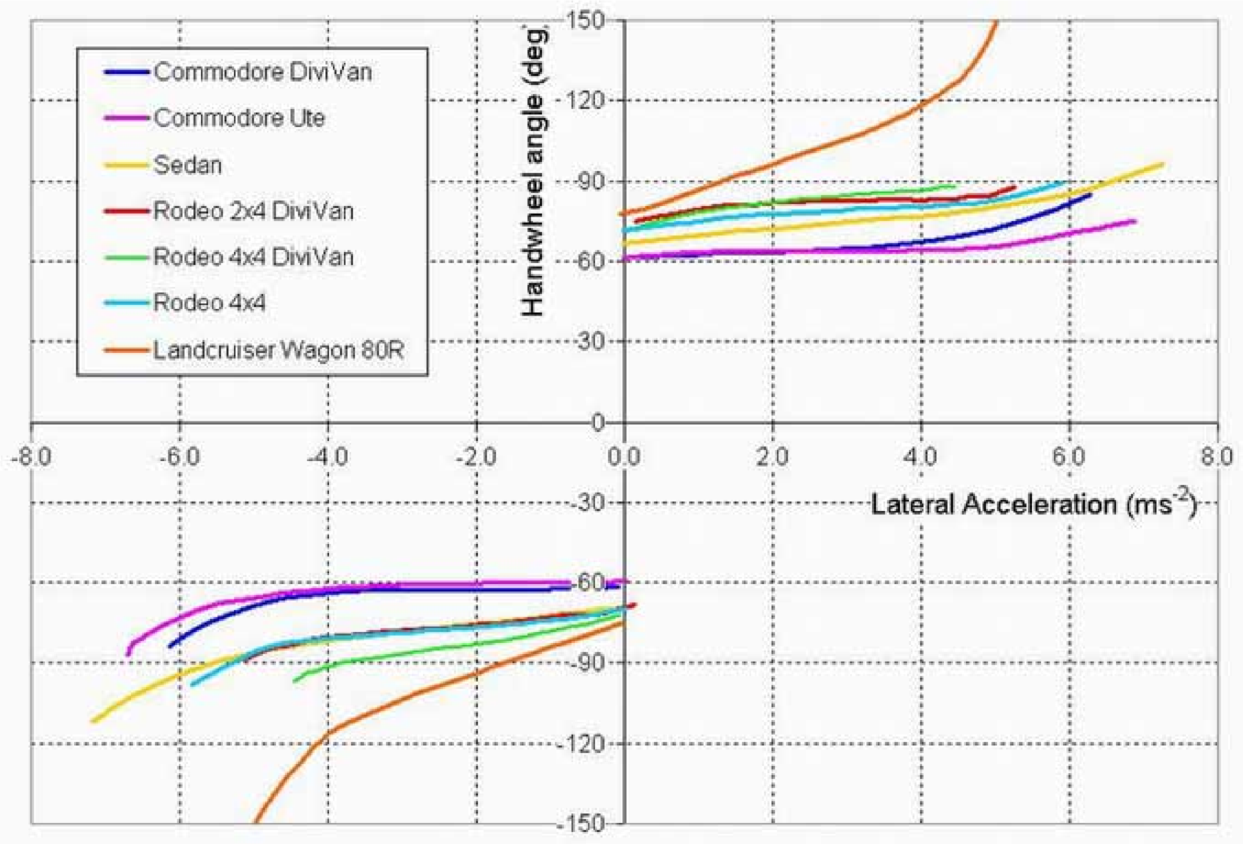

Figure 5: Plot of Hand-wheel angle v's Lateral Acceleration for vehicles tested

The Lane-change testing was carried out to determine the velocity through the Lane-change manoeuvre at which 70% LLA was achieved. Testing was initiated at a relatively low velocities and increased in small increments, until the velocity produced the required 70% LLA was achieved and successfully negotiating the test course. The 70% LLA velocity was repeated a minimum of four times, for each driver and for lane-changes to the left or right (minimum of 16 data points). A summary of the average velocity for each vehicle is presented in Table 3.

Serial	Vehicle type	Velocity (ms^{-1})
1	Holden Commodore DiviVan	21.1
2	Holden Commodore Utility	24.2
3	Holden Commodore Sedan)	26.5
4	Holden Rodeo 2x4 DiviVan	20.2
5	Holden Rodeo 4x4 DiviVan	18.2
6	Holden Rodeo 4x4 Utility	22.5
7	Toyota Landcruiser Wagon 80R	24.3
8	VicPol AU Falcon DiviVan	25.6
9	Nissan Patrol Wagon 3.0lt	24.9
10	Nissan Patrol Wagon 4.2lt	23.8

The ranking of the Lane-change handling data based on velocity correlated to the ranking of the vehicles based on Stability Factor, with the exception of the Toyota Landcruiser Wagon 80R. The Landcruiser negotiated the Lane-change manoeuvre faster than expected.

It was concluded that the cause of higher rollover rates for the Commodore DiviVan and Rodeo DiviVan's was the high Track width to CofG height due to the addition of the prisoner containment system.

A range of performance specifications was developed for the VicPol vehicle fleet based on a comprehensive study, including but not limited to: Literature Search; Overseas & interstate Police vehicle experience; In-vehicle data recorders; VicPol crashes & pursuits; A survey of VicPol vehicle usage, including; Demographics, Vehicle policies, Communications, Audio and visual equipment, Training, Type of vehicle use, Equipment storage; Prisoner transport; Safety features and What do VicPol officers want in a vehicle.

The following Performance criteria were developed; Vehicle classification; Tilt table testing, Stability Factor and probability of being involved in a rollover; Handling; Steady State, Lane-change, Braking and Acceleration; Crashworthiness; Internal fittings and Structural rollover protection.

One of the performance criteria developed is based on a contention presented by Kahane [19] that "rollover risk has two components: directional stability (handling) and rollover stability. A vehicle is directionally unstable if it tends to skid, spin out of control or is hard to steer on course. A directionally unstable vehicle will have many more off-road excursions into loose dirt, ditches etc., where rollovers are more likely to occur. 'Rollover Stability' is the tendency of a vehicle to remain upright given that it has come into contact with a tripping mechanism such as loose dirt, ditches etc.,". The criteria are based on the velocity at 70% LLA through the ISO 3888-1 Lane-change course (Handling) and Stability Factor (rollover stability). An interpretation has been made to distinguish between desirable/ undesirable performance, based on the collected VicPol rollover data and defines the minimum acceptable velocity at 70% LLA for a given Stability Factor. The criterion also enables comparison and selection evaluation of vehicles with similar velocities through the manoeuvre or Stability Factors. Figure 6 illustrates the desirable undesirable criteria and positions of ten vehicles that have been evaluated.

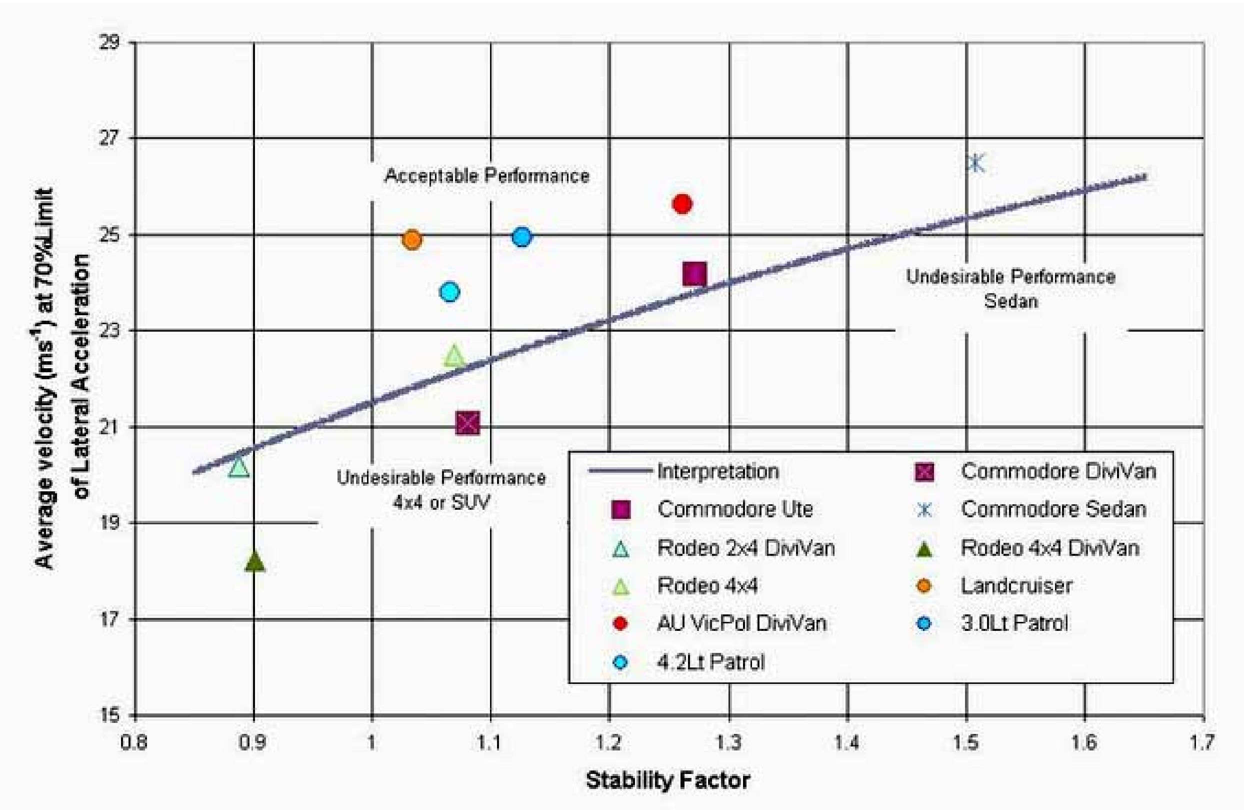

Figure 6: VicPol handling performance criteria

For vehicles that have similar velocities through the Lane-change manoeuvre (≈ 26ms^{-1}) such as the Landcruiser, AU Falcon DiviVan and Commodore Sedan the better vehicle, from a rollover perspective is the one with the highest Stability Factor, the Commodore Sedan. While vehicles with similar Stability Factors (≈ 1.06) such as the Landcruiser, Rodeo 4x4 and the Commodore DiviVan the better vehicle, from a rollover perspective is the one with the highest velocity through the manoeuvre, the Landcruiser.

PROPOSED METHODOLOGY FOR COMBINED HANDLING AND STABILITY METRIC

There is sufficient evidence to support the contention that Stability Factor and the rate of 'real world rollovers' are linked. However there is a lack of correlation due to noise, probably due to the differences in vehicle handling. Hence, a methodology that allows the combination of the Stability Factor and handling characteristic could also allow discrimination of the probability of rollover per single vehicle crash and therefore provide a Rollover Propensity Metric.

This concept is illustrated using both NHTSA 'real world rollover' data (Figure 2) and VicPol data (Figure 6) are presented comparing results against Stability Factor. In both cases the limits of the data sets can be estimated, allowing the upper limit (blue) and lower limit (red) to be interpreted (Figure 7). The banded limits are similar for both data sets, in that for lower Stability Factor values (ie 1.0 – 1.1) the band is wide while for higher Stability Factor values (ie 1.4 – 1.5) the band is narrow. Using the banded limits NHTSA real world rollover data the upper limit (blue dotted) and lower limit (red solid) for specific Stability Factor values (0.90, 1.00, etc) the probability of rollover per single vehicle crash can be estimated.

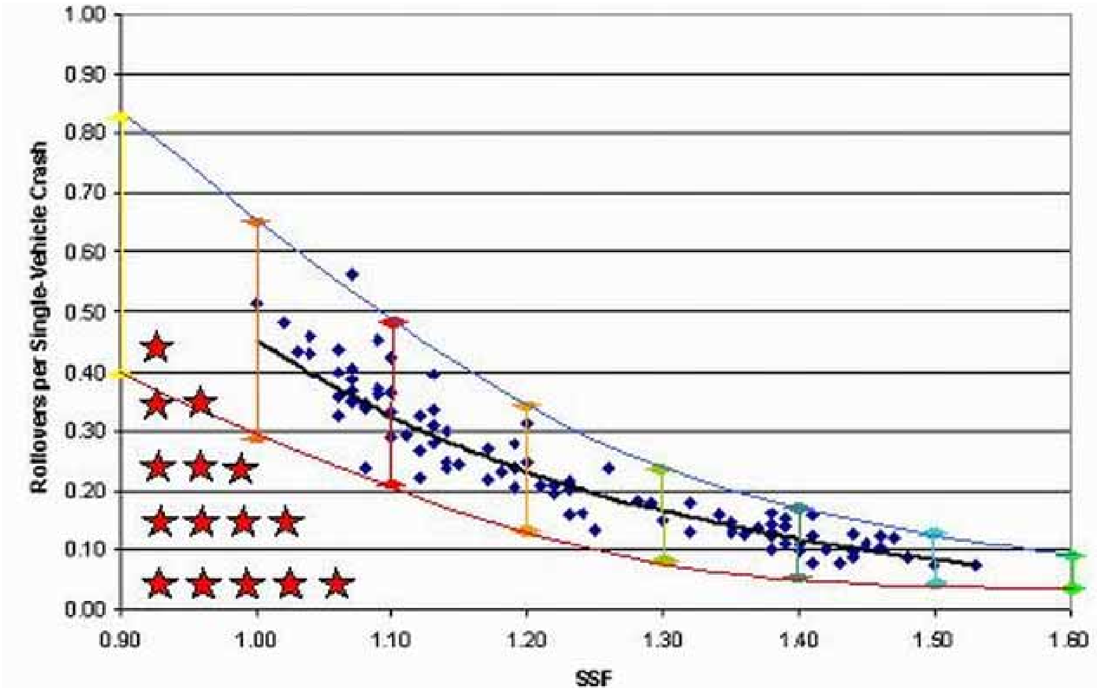

Figure 7: NHTSA real world rollover showing limit bands and NCAP star rating

The NHTSA banded probability of rollover per single vehicle crash can be transposed on the VicPol data. [Note: The position of the upper and lower limits are swapped when transposed, because the worst performing NHTSA vehicles have higher probabilities of rolling over while the worst performing VicPol vehicles manoeuvre at lower speeds. The VicPol data can then have lines of best fit for values of 10%, 20%, 30% and 40% probability of rollover per single vehicle crash and assigned stars as per the NHTSA rating system, Figure 8.

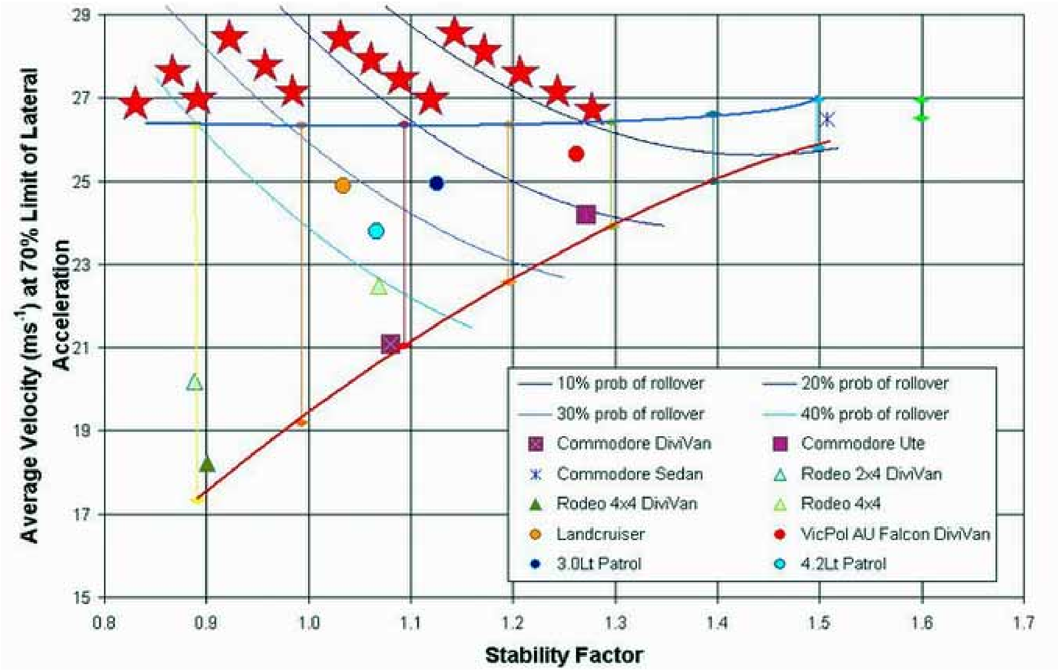

Figure 8: Rollover probability bands and NCAP star ratings transposed onto VicPol data

The hypothesis proposed is that by testing for rollover stability (Stability Factor) and directional control (handling) the probability of rollover per single vehicle crash can be predicted (i.e. a Rollover Propensity Metric).

Examination of the NHTSA data enables nineteen vehicles to be identified by make, model and probability of rollover per single vehicle crash. These vehicles can be plotted using the Stability Factor and probabilities of rollover per single vehicle. The data points can be interpreted to estimate the velocity through the Lane-change manoeuvre for specific vehicles to be made, figure 9.

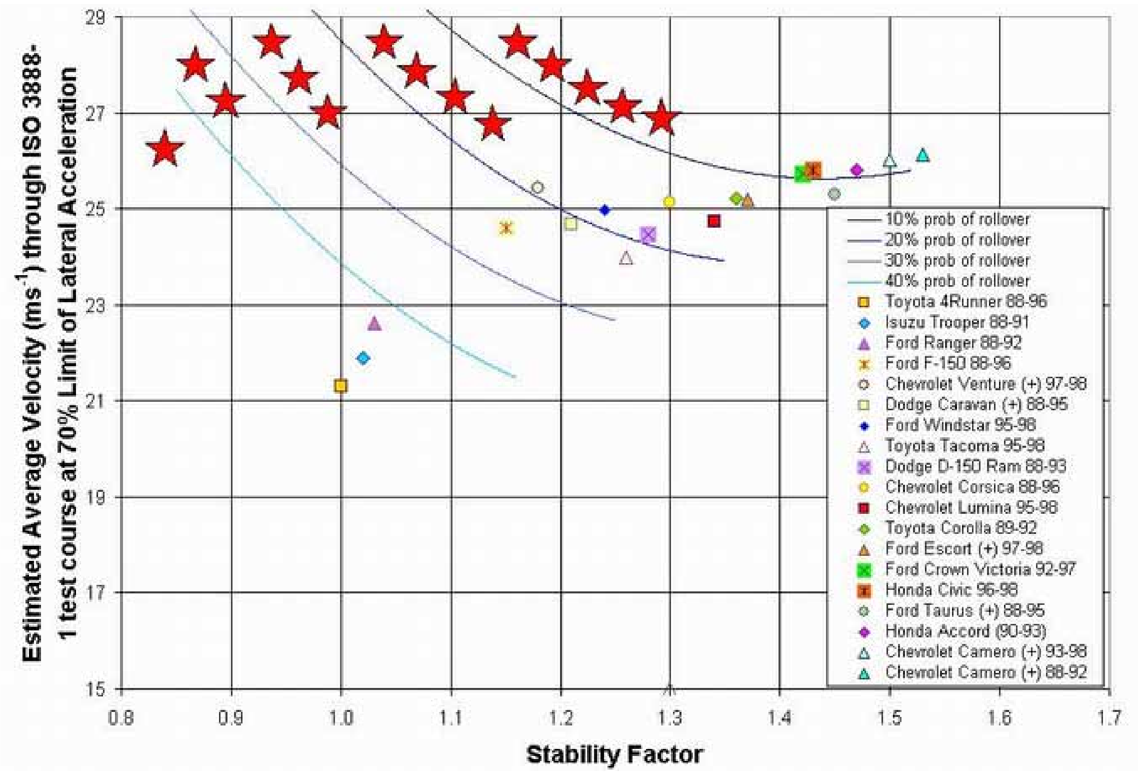

Figure 9: Estimated velocity of nineteen vehicles through ISO 3888-1 Lane-change manoeuvre

If proved valid, this method would enable the probability of a vehicle being involved in a single vehicle rollover crash to be estimated based on two measurable vehicle parameters; Stability Factor and a handling manoeuvre. The probability of a vehicle being involved in a rollover could be estimated during vehicle development via modelling and validated by testing.

One criticism of this paper could be the use of the ISO 3888-1 Severe Lane-change manoeuvre; this is an open loop test, which can be driver dependent. Howe et al identified with respect to the lane change that: *"the 'technique' one driver chooses to employ may be very different than another driver, yet both may complete the manoeuvre successfully."*

Garrott et al. overcame this problem by developing a Programmable Steering Machine, which applies a repeatable steering input to any vehicle tested. It is the author's opinion that if handling testing was conducted using other methods, such as a Programmable Steering Machine, the values to measure handling performance may change from those presented in this paper but the relative ranking between vehicles would be similar. The ISO 3888-1 Severe Lane-change manoeuvre provide the authors with a cost effective methodology to enable a distinction between vehicle handling characteristics, alternative and improved methodologies to evaluated handling would further segregate and define different vehicles, in terms of handling.

A Steering Machine is being developed by Grzebieta et al [20, 21], which can control a test vehicle remotely, be programmed to provide a steering input or follow a path on the road surface. It is proposed that any future lane change testing be carried by the authors will utilise the Steering Machine developed by Grzebieta et al to eliminate the driver to driver variability.

It is recommended that this methodology be considered for incorporation into a New Car Assessment Program using a start rating system, to provide consumers with a improved information on the probability of rollover per single vehicle crash.

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