EVALUATION AND TESTING OF POLICE VEHICLES FOR ROLLOVER STABILITY

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Abstract. Following a Police vehicle rollover crash resulting in the death of the driver and front passenger, major concerns were raised by the Police Force regarding the safety and handling performance of certain Police vehicles. As a result, a study of vehicle handling and stability for different vehicle types in the Victoria Police fleet was carried out by MUARC. This Stage 1 study comprised two main tasks: (i) analysis of the Police vehicle accident database with regard to determining the incidence and rate of rollover involved crashes for each vehicle type; and (ii) determine stability and dynamic handling characteristics of a range of Police vehicles using Tilt-Table tests, and Steady State Turning and Double Lane Change Manoeuvres. The tests were carried out by the Army Engineering Agency (AEA) Mechanical Laboratories, at the Army's Monegeetta Proving Grounds. The analysis and handling tests helped identify vehicle models that had an unacceptably high rollover risk, resulting in the Victoria Police changing certain key vehicles in their fleet, and interstate Police Forces also reviewing their vehicle operational policies. Following this work, a Stage 2 project is in progress, with the aim of defining performance and evaluation criteria to be used in the specification and procurement of new Police vehicles.

INTRODUCTION

A fatal rollover crash involving a Holden Commodore Police Divisional van in May 2000, resulted in the death of two young police members. This crash was the catalyst for the Victoria Police to review the way the organisation internally selected vehicles for operational use, and also precipitated a review of the processes used for design, development and installation of equipment fitted to police vehicles.

Of particular concern was the on-going safety of the vehicle fleet, in particular the handling performance of vehicles fitted with Prisoner pods. Determining if stability was an issue was extremely important as there were 210 prisoner transport units, similar to the one involved in the accident, still in service. The 210 vehicles comprised 140 pick up vehicles ('Divisional Vans') and 70 crew cab pick up vehicles, some of which were 4 wheel drives.

The Police requested Monash University Accident Research Centre (MUARC) to assist in this urgent evaluation. The Phase 1 study (the subject of this paper) was carried out from June to September 2000, and involved an analysis of vehicle handling and stability for different vehicle types in their fleet [3]. The Phase 2 study is currently being completed and involves defining selection and performance criteria for Police vehicles.

METHOD

Two main activities were undertaken: (i) the analysis of the Police Vehicle Accident database and, (ii) carrying out the rollover stability and handling tests.

(I) Analyses of the Police Vehicle Accident Database: Determination of the Incidence of Rollover Crashes

The Police Transport Branch made the Police vehicle accident database available to MUARC. Although this database does not explicitly categorise vehicle accidents by type of crash, a search was made of the text data to identify any crashes where the descriptions identified a rollover. The accident database was searched for the 10-year period from beginning of 1990 to June 2000.

In addition measures of exposure were determined from the Transport Branch's Police Vehicle Database which contains records of all pre-delivery, active (current) and retired vehicles (sold). Fields in this database include the date vehicles are purchased, sold date, last recorded odometer reading (available for all but 850 of the 12,424 vehicles over the period) and average mileage per month (available for 70% of the 12,424 vehicles in the data set). The statistical software package SPSS was used to analyse this database for the period 1990 to June 2000, to determine for each vehicle model the exposure in 'vehicle-months'. Vehicle-months are the sum of the total number of months that particular model type was in service. For example if there were 10 Holden Divisional vans operating for a period of 12 months each, then the total "vehicle months' is 10x12=120.

The exposure value 'vehicle-months' could then be used to compare the rollover rate for each vehicle model involved in rollover crashes. In addition, as the various vehicle models have different usage, rollover crash rate based on kilometres traveled was also determined.

(ii) Stability and Handling tests

A vehicle rollover (not involving tripping) can be attributed to either of two vehicle parameters: the relationship between the centre of gravity height and the track width, and /or the handling characteristics of the vehicle. In order to establish if either vehicle parameter is causing a rollover, both must be measured and ranked within a sample group. Victoria Police identified 13 vehicles to be tested for centre of gravity height and a further 6 for handling evaluation. All the stability and handling tests were conducted at the Army Engineering Agency (AEA) Proving Ground, Monegeetta.

Vehicle Static Stability Tests. Measurements selected for the assessment of the Victoria Police vehicles were axle loading, mass, wheelbase, track, centre of gravity location and Tilt-Table rollover angle. Two metrics were used to rank the rollover propensity of the supplied Police Vehicle: Tilt-table Test and the Stability Factor.

The Tilt-Table test provides a measure of the level of lateral acceleration (force) needed to lift the inside wheels off the ground and overturn a vehicle. Such lateral acceleration (i.e centripetal acceleration) may arise when the vehicle is cornering or changing direction such as during a quick lane change manoeuvre. Also the tangential function of the overturn angle is a measure of the frictional coefficient necessary to trip the vehicle if it is sliding sideways. If the vehicle overturn angle is low then it is quite possible to roll a vehicle over on a dry bitumen road, simply by sliding the back of the vehicle out (fishtail).

Vehicle Handling Tests. The Handling tests selected for the assessment of the Victoria Police vehicles were Steady State Turning and a Double Lane Change Manoeuvre. The Steady State Turning test is based on recognised International Organisation for Standardisation (ISO) test procedures. The Double Lane Change Manoeuvre was selected because it is commonly used by the automotive industry to simulate an accident avoidance manoeuvre.

The test vehicle was fitted with instrumentation that measured lateral acceleration, handwheel angle and torque, vehicle roll angle, forward velocity and lateral velocity both in the front and rear of each vehicle. For safety reasons, a limit of 0.7 of the calculated rollover lateral acceleration was used as a limit for all Handling Testing. A zero run was performed prior to all tests, which enabled instrumentation offsets to be determined.

RESULTS

(1) Police vehicle rollover rate.

A total of 39 crashes involving rollover were identified, of which 34 were relevant to the vehicles under review. The rates of vehicle crashes used two exposure measures. The first exposure measure was 'vehicle-months', representing the total time exposure of the model type in the fleet, and the second based on kilometres traveled, with results for both summarized in Table 1 and Figure 1.

Vehicle Description	Rollovers	Rate per 10,000 vehicle-months	Rate per 10 million kms
Holden Commodore Sedan	2	0.25	0.06
Ford Falcon Sedan	5	0.60	0.24
Ford Falcon Divisional Van	2	0.95	0.20
Landcruiser Wagon 105R	1	2.3	5.61
Patrol Wagon	1	2.7	1.20
Jackaroo Wagon	1	6.2	1.92
L/Cruiser Wagon 80R	3	6.6	3.46
L/Cruiser Hardtop LWB	3	10.6	6.10
Commodore Divisional Van	11	16.6	3.26
Rodeo 2x4	5	51.6	18.51
Total	**34**		

Table 1. Summary of Police Vehicle Rollovers and Rate, by Vehicle Model Type (1990-2000)

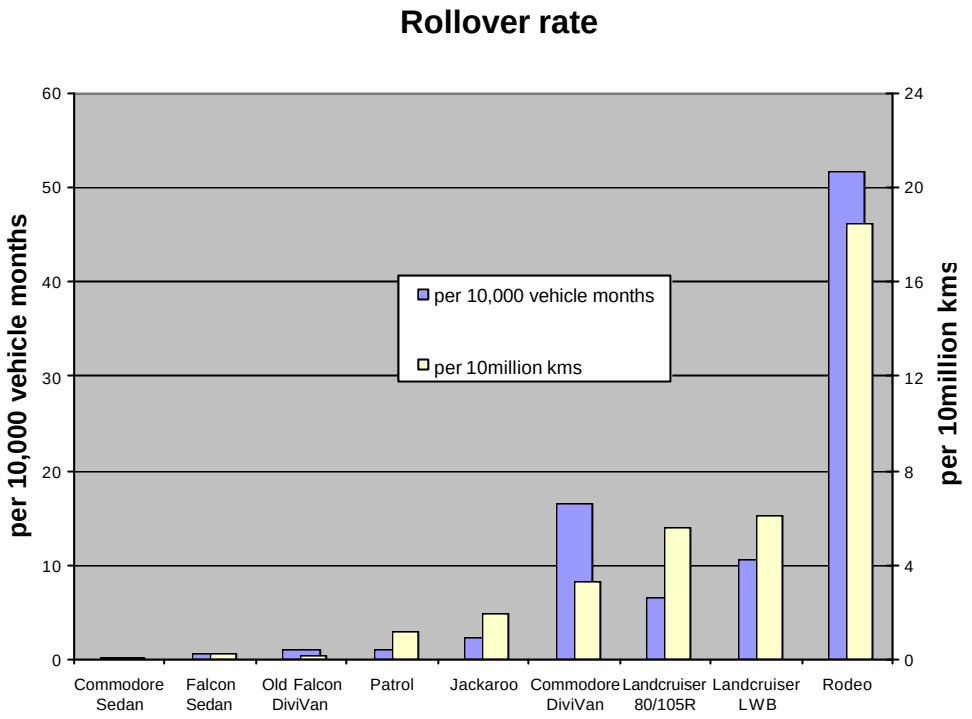

Figure 1. Victoria Police Vehicle Rollover Rate, by Vehicle Model Type (1990-2000)

Based on kilometres traveled, the lowest rollover rate is for the Holden Commodore sedan (0.06), with the highest calculated for the Rodeo 2x4 (18.2). For the Holden Commodore Divisional van, the rate of 3.26 compares unfavorably with the much lower rate of 0.20 calculated for the previous Ford Falcon Divisional van (a rate that is 16 times lower). It is important to note that the Ford Divisional van was based on a Ford Falcon panel van (a largely unmodified vehicle), whereas, in contrast, the Holden Commodore Divisional van was a utility model significantly modified by the addition of a prisoner pod weighing some 500kgs.

(2) **Tilt-Table results and Mengert Stability Factor.**

The Victoria Police identified 13 vehicles to be tested for centre of gravity height. The vehicle measurements selected for the assessment of the Victoria Police vehicles were Axle Loadings, Mass, Wheelbase, Track, Centre of Gravity location and Tilt-Table Rollover angle. Two metrics were used to rank the rollover propensity of the supplied Police Vehicle tilt-table test (see Figure 1) and the Stability Factor. The results of the Tilt-Table Tests are included in Table 2.

The Stability Factor is derived from circular motion theory, and is calculated from the track width and the centre of gravity height using equation 1.

$$\textbf{Stability Factor} = \textbf{Track Width} / (2 \times \textbf{Centre of Gravity Height}) \qquad (1)$$

In the Mengert study of rollover accidents 40,000 cases involving 40 different types of vehicle were analysed. Eleven different factors were utilised to examine rollover propensity, including; Stability Factor, wheel base, age of driver, alcohol/drug use, seatbelt use, rural location, urban location, road geometry, driver error, tracking vs sliding and road surface condition (dry/wet/snow). Stability Factor was clearly the most compelling item with an excellent correlation to rollover; further analysis resulted in a relationship between Rollover Probability and Stability Factor.

$$\textbf{Rollover Probability} = 100 / (1 + \textbf{Stability Factor}^{6.9}) \qquad (2)$$

The results for the 13 vehicles tested are presented in Table 2 and the Rollover risk based on the Mengert Study is plotted in Figure 2.

Ranking -	Vehicle	Tilt-Table Angle	Tan (angle)	Stability Factor	Rollover Risk - Mengert
13	Holden Rodeo 4x4 Divisional Van	37.0	0.754	0.901	67.23
12	Toyota Landcruiser Troop Carrier	38.9	0.807	0.896	68.01
11	Holden Rodeo 2x4 Divisional Van	39.3	0.818	0.888	69.47
10	Mazda E2000 Van	39.9	0.836	0.899	67.55
9	Toyota Landcruiser Wagon LWB	42.2	0.907	1.034	44.28
8	Holden Rodeo 4x4 Utility	43.7	0.956	1.069	38.72
7	Holden Commodore Divisional Van	42.9	0.929	1.078	37.38
6	Holden Rodeo 2x4 Utility	44.8	0.993	1.092	35.32
5	SA Ford Falcon AU Divisional Van	45.4	1.014	1.157	26.77
4	Old Ford Falcon Divisional Van	48.3	1.122	1.25	17.66
3	Holden Commodore Utility	49.2	1.159	1.271	16.02
2	Ford Falcon AU Utility	51.6	1.262	1.357	10.85
1	Holden Commodore Sedan	52.0	1.279	1.507	5.57

Table 2. Summary of the Stability tilt-table tests, and Mengert analysis results for the 13 Police vehicles. Ranking is from 'highest to lowest' rollover risk.

From Figure 2 (also see Table 2), the Holden Commodore Divisional Van has a 'probability of being involved in a rollover' of about double that of the earlier Falcon Divisional van (38% vs 18%), and double that of the Holden Commodore Utility from which it is derived. The Rodeo Divisional vans have a very high rating of nearly 70%, indicating quite adverse rollover stability characteristics.

These results clearly identify the significantly increased rollover risk for the modified Police Divisional van version (with the added Prisoner Pods) compared with the base utility variants of the Holden Commodore and Rodeo vehicles.

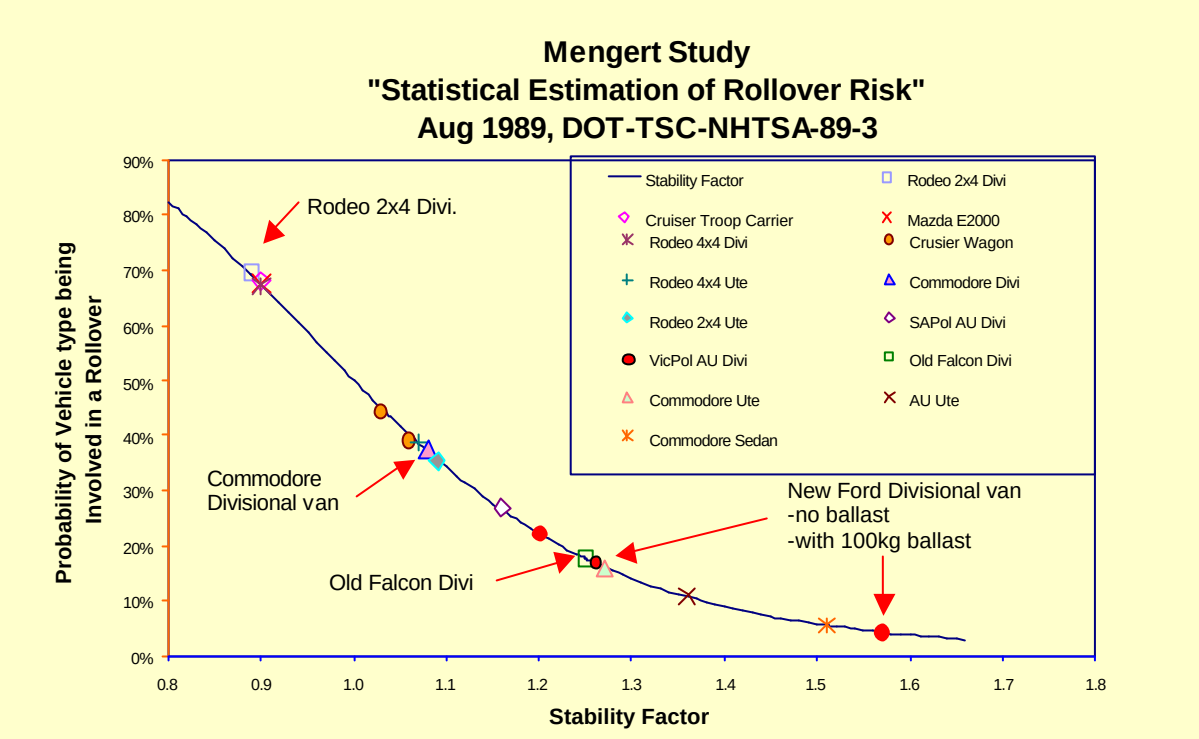

Figure 2. Mengert Study – Rollovers risk and stability factor. Plot of results for the 13 Police vehicles tested. The interim new AU Falcon Divisional van is also shown, with and without ballast. This vehicle was introduced by Victoria Police as an interim replacement for the Commodore Divisional van as result of the stability findings from this study.

Figure 3. View showing a Police vehicle undergoing Tilt-Table test at the Army's Monegeetta test facility

(3) Vehicle Handling Test results

Steady State Turning Tests. The aim of these tests was to assess the steady state understeering/oversteering characteristics of the vehicle. Normal road vehicles should possess a steady state understeering characteristic, whereby the driver is required to apply additional handwheel angle as vehicle speed increases through the turn (positive understeer gradient as shown in Figure 4 below).

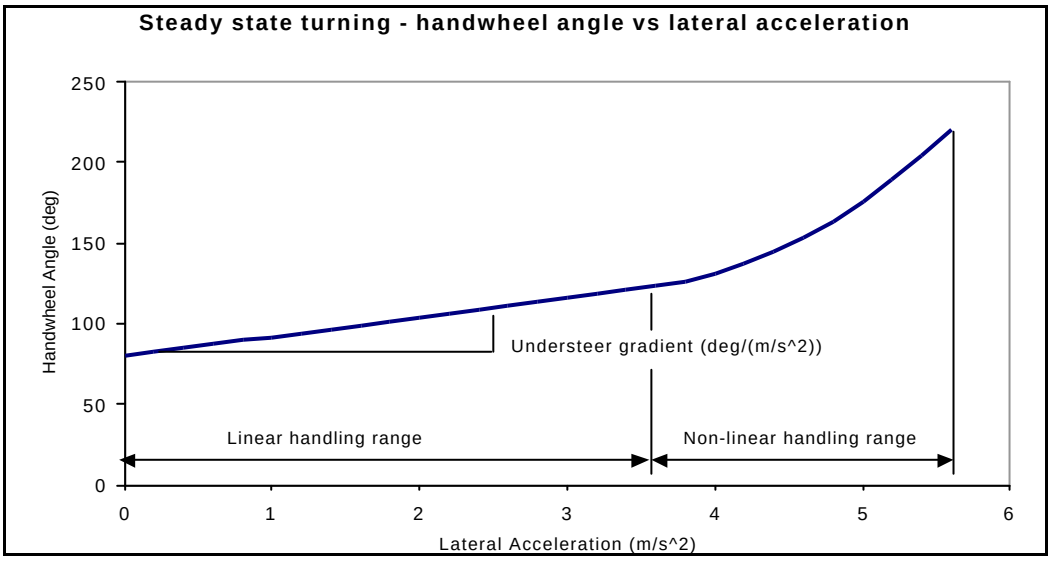

Figure 4. Steady State Turning – Understeer gradient by constant radius method

The results of the Steady State Turning Test which give the Lateral Acceleration vs the Driver's Steering Wheel Angle are shown in Figure 7, and presented in detail in [1 & 3]. The key interpretations of these handling results is that the relative order of the vehicles are in agreement with the stability ranking found in the Mengert profile.

Double Lane Change Manoeuvre. The aim of the test was to assess the handling performance while executing an emergency manoeuvre. Performance was assessed by a series of metrics calculated during the manoeuvre, and is based on those proposed in SAE Paper 780010 "Correlation and Evaluation of Driver/Vehicle Directional Handling Data". Metrics calculated included: (i) Entry speed to the course, and (ii) and Peak lateral accelerations.

The testing nominally started at a velocity of 15ms^{-1} (a speed of 54km/h) and was increased until a peak lateral acceleration of 0.7 of the rollover lateral acceleration was achieved or the vehicle could not negotiate the course. During the testing all vehicles successfully negotiated the lane change manoeuvre.

The key interpretations of these results [3] are that the trend lines are similar in shape and gradient and that the ranking profile of the Mengert Study is followed . The exception is the Landcruiser, which ranks second best and in this handling test performed significantly better than expected by the Mengert profile.

DISCUSSIONS OF FINDINGS AND OUTCOMES

Taking the relatively high rollover crash rate for the Holden Commodore Divisional van, together with its ranking in the Mengert rollover risk plots, Steady State Turning Test and the Double Lane Change manoeuvre, indicates that the rollover 'problem' was predominantly related to the height of the vehicle's centre of gravity and not the suspension set-up or handling of the vehicle. This was similarly true for the Holden Rodeo fitted with prisoner pod.

Based on these findings the Police implemented immediate steps to reduce the rollover risk with these two vehicles (210 of these vehicles were still in operation). A program of rapid replacement, as a first step, was implemented. The 70 Rodeo vehicles were immediately withdrawn from service. In regard to the 140 pick up derivative prisoner transport units, replacement was a more complex issue. In Victoria these vehicles are the first responders to incidents and are an integral part of the fleet. While driving restrictions were quickly introduced by Victoria Police, they decided that an interim replacement vehicle should be developed.

It was found that the Ford Falcon cab-chassis utility vehicle could be used as a base with a modified prisoner pod fitted (developed in conjunction with Able Engineering Pty Ltd, AEA and Victoria Police Transport Branch). This vehicle combination resulted in a much-reduced centre of gravity height (100kg of 'ballast' was also added) that was little different to that of a sedan, hence with a low rollover risk. The fleet of 140 of these vehicles was modified and replaced over a 4-month period. Since the introduction of this new vehicle 10 months ago there have been no further rollovers.

Figure 5. The Interim Ford Falcon AU Divisional van with much improved rollover stability characteristics, based on a Ford Falcon utility fitted with a modified prisoner pod from the previous Commodore van.

NHTSA Rollover stability star ratings [5]

It is interesting to compare the findings for the Police Vehicles using the Mengert rollover risk ratings with the rollover risk star rating system recently developed by the US National Highway and Traffic Safety Administration (NHTSA). This star rating system is intended to provide consumer information on rollover risk for passenger cars and light multipurpose passenger vehicles and trucks to help reduce the number of rollover crashes and the number of injuries and fatalities from rollover crashes. The agency uses the Static Stability Factor [see Equation 1 in this paper] to indicate rollover risk in single-vehicle crashes and to incorporate the new rating into NHTSA's New Car Assessment Program (NCAP). Figures 6 and Table 3 set out the basis for the NHTSA Star Rating system for rollover risk.

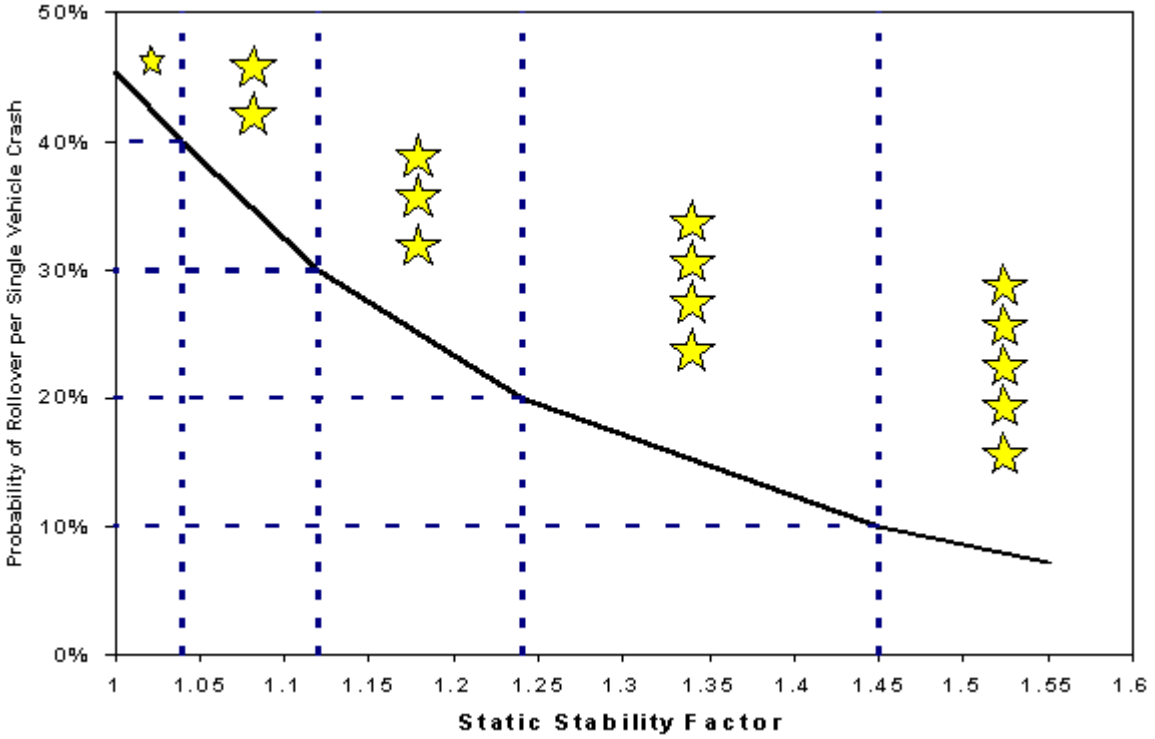

Figure 6 – NHTSA's Star rating intervals (variation in Probability of rollover vs Static Stability Factor)

Star rating (the higher the better)		Risk of Rollover in a single-vehicle crash	Static Stability Factor (SSF)
ONE STAR	★	40 % or greater	1.03 or less
TWO STARS	★★	30 % to 40 %	1.04 to 1.12
THREE STARS	★★★	20 % to 30 %	1.13 to 1.24
FOUR STARS	★★★★	10% to 20%	1.25 to 1.44.
FIVE STARS	★★★★★	< 10 %	1.45 or more

Table 3. NHTSA Star Rating For Rollover Risk Vs Static Stability Factor (SFF)

Ranking	Vehicle	Stability Factor	Rollover Risk - Mengert	NHTSA Star rating
13	Holden Rodeo 4x4 Divisional Van	0.901	67.23	*
12	Toyota Landcruiser Troop Carrier	0.896	68.01	*
11	Holden Rodeo 2x4 Divisional Van	0.888	69.47	*
10	Mazda E2000 Van	0.899	67.55	*
9	Toyota Landcruiser Wagon	1.034	44.28	*
8	Holden Rodeo 4x4 Utility	1.069	38.72	**
7	Holden Commodore Divisional Van	1.078	37.38	**
6	Holden Rodeo 2x4 Utility	1.092	35.32	**
5	SA Ford Falcon AU Divisional Van	1.157	26.77	***
4	Old Ford Falcon Divisional Van	1.25	17.66	****
*****	New Falcon AU Divisional van (no ballast)	1.262	16.71	****
3	Holden Commodore Utility	1.271	16.02	****
2	Ford Falcon AU Utility	1.357	10.85	****
1	Holden Commodore Sedan	1.507	5.57	*****
******	New Falcon AU Divisional van (ballasted)	1.568	4.3	*****

Table 4. Equivalent NHTSA Rollover risk Star Ratings for the 13 Police vehicles originally tested, and the interim Ford Falcon AU Divisional van (**with 100kgs ballast, * no ballast). SA= South Australia.

Based on this NHTSA star rating (see Table 4), the Holden Rodeo Divisional van has a 1- star rating; the Holden Commodore Divisional van a 2-star rating; the earlier model Ford Divisional van (panel van) a 4 star rating; the new interim Ford AU Divisional van (with ballast) a 5-star rating. Without the added ballast, the interim Ford AU Divisional van has a 4-star rating, similar to the earlier (and acceptable) Ford Falcon Divisional van (panel van). This categorization of the tested Police vehicles into these star ratings, clearly supports the Victoria Police decision with regard to implementing the changes to their vehicle fleet and restrictions on operational policies, as described previously.

CONCLUSIONS

The analysis of the Victoria Police accident data for rollover crashes clearly identified certain vehicles as being significantly over-represented in rollover crashes. These included the Holden Commodore Divisional van and Holden Rodeo Divisional van, both vehicles being substantially modified from the manufacturer's base vehicle by the addition of prisoner pods. This initial analysis supported the concerns raised by the Police regarding the rollover stability of the Holden Commodore Divisional van, following the death of two Police officers in a rollover crash. Based on these concerns and the vehicle rollover history, the need for stability and handling evaluation and testing of operational vehicles in the fleet was required.

In light of the relatively high rollover crash rate for the Holden Commodore Divisional van, together with its high risk ranking in the Mengert rollover risk plots, and its consistent ranking found in the handling tests, indicated that the rollover 'problem' was predominantly related to the height of the vehicle's center of gravity, not the suspension set-up or handling of the vehicle. This was similarly true for the Holden Rodeo fitted with prisoner pod.

As a result of this work, Victoria Police were able to identify the 'at-risk' vehicles and the reasons for the unacceptably high rollover rate, and take prompt action to reduce the rollover risk of their vehicle fleet.

Further work is currently being conducted for Victoria Police by MUARC to help develop safety and performance specifications for the procurement of new Police vehicles.

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(4) NHTSA Rollover Resistance Ratings Information: http://www.nhtsa.dot.gov/hot/rollover/; and http://www.nhtsa.dot.gov/cars/rules/rulings/roll_resistance /

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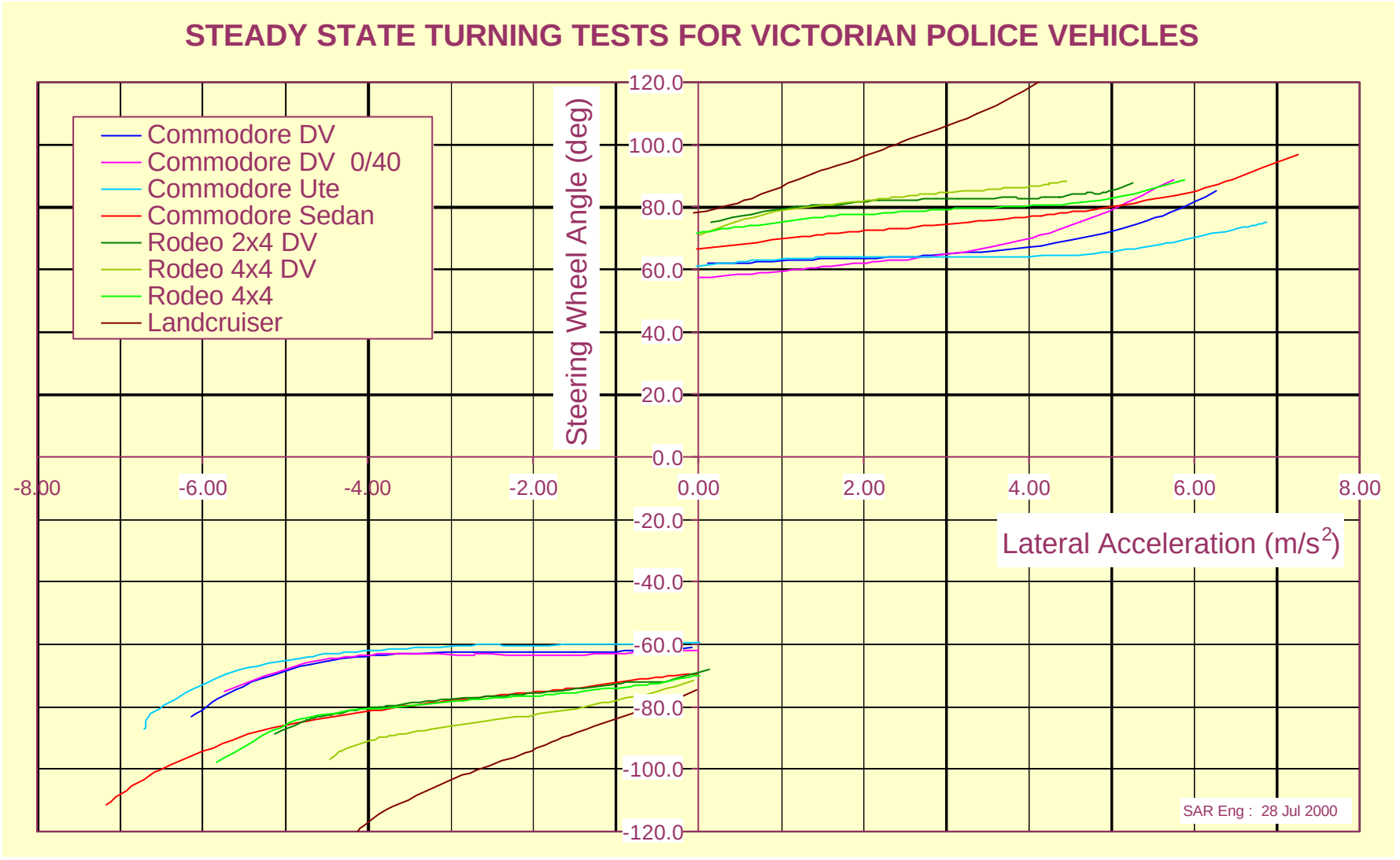

Figure 7. Steady State turning test for Victoria Police vehicles. Steering wheel angle vs lateral acceleration.