Australian Rainfall & Runoff

Revision Projects

PROJECT 10

Appropriate Safety Criteria for People

Literature Review

STAGE 2 REPORT

P10/S2/020

FEBRUARY 2011

AUSTRALIAN RAINFALL AND RUNOFF
PROJECT 10: APPROPRIATE SAFETY CRITERIA FOR VEHICLES
– LITERATURE REVIEW

STAGE 2

FEBRUARY, 2011

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FOREWORD

AR&R Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (AR&R) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- estimation of extreme flood levels.

However, many of the practices recommended in the 1987 edition of AR&R are now becoming outdated, no longer representing the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of AR&R. A recent and significant development has been that the revision of AR&R has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The Federal Department of Climate Change announced in June 2008 $2 million of funding to assist in updating Australian Rainfall and Runoff (AR&R). The update will be completed in three stages over four years with current funding for the first stage. Further funding is still required for Stages 2 and 3. Twenty-one revision projects will be undertaken with the aim of filling knowledge gaps. The 21 projects are to be undertaken over four years with ten projects commencing in Stage 1. The outcomes of the projects will assist the AR&R editorial team compiling and writing of the chapters of AR&R. Steering and Technical Committees have been established to assist the AR&R editorial team in guiding the projects to achieve desired outcomes.

Project 10: Appropriate Safety Criteria for People and Vehicles

Emergency management of flood situations in both urban and rural areas is directly concerned about the safety of people and vehicles in floods. Over the past two decades there has been increasing concern about these safety issues and there is a need to revisit and update the criteria currently used. The current approach is based on the results of some studies undertaken in the 1970s. A body of research has been undertaken since then and there is a need to collate this research and to develop guidelines for authorities. As a result, it is anticipated that most of the work involved in this project will be the collation of research in this field and the development of appropriate guideline information.

The aim of Project 10 is to provide guidance on pedestrian and vehicular safety and stability in floods.

Mark Babister
Chair National Committee on Water Engineering

Dr James Ball
AR&R Editor

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below :

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people & vehicles	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

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EXECUTIVE SUMMARY

The stability of vehicles exposed to flood flow on streets, causeways and bridges is of major concern in urban stormwater, road design and floodplain management. Human activity on flooded surfaces is inevitable with much development already in flood prone areas. The safety of people can be compromised when the vehicles they are travelling in are exposed to flows which cause the vehicle to become unstable by losing traction (frictional instability) or become buoyant (floating). Current design guidelines for vehicle stability on floodways (i.e. I.E.Aust, 1987) are generally based on the product of flow depth (D) and velocity (V) derived during experimental investigations of stationary vehicle stability in the late 1960's and early 1970's (Bonham and Hattersley, 1967; Stone and Gordon, 1973) and theoretical analysis in the early 1990's (Keller and Mitsch, 1993). However, substantial changes in vehicle design have occurred since these early studies, notably in vehicle planform area, vehicle weight and ground clearance. These changes in vehicle design are substantial and it is likely that the results of these earlier studies may no longer hold for contemporary vehicles. Note that an extensive literature review did not discover any further relevant research data and showed that international standards by and large referenced these same Australian research publications.

Existing guidelines and recommendations for limits of vehicle stability are compared to experimental and analytical results. With the exception of the Public Works Department (1986)/NSW Floodplain Development Manual (2005) and AusRoads (2008) criteria, all other criteria are found to be non-conservative at some flow regime when compared to experimental and computational test results. The existing Australian Rainfall and Runoff criteria (AR&R87; I.E. Aust, 1987) exceed all experimental test results in high depth, low velocity flow regimes and extend to high velocity regimes outside the limits of experimental testing. On this basis, the current Australian Rainfall and Runoff criteria require revision.

Based on the available experimental and analytical data, *Draft, interim* criteria for stationary vehicle stability are proposed for three vehicle classes: small passenger cars, large passenger cars and 4WD vehicles, with approximate dimension ranges shown within the table below. These criteria have floating limits of 0.3 m (small passenger vehicles), 0.4 m (large passenger vehicles) and 0.5 m (4WD vehicles) to remain in agreement with experimental results and all stability criteria have a limiting velocity of 3.0 ms^{-1}. This was incorporated to provide agreement with human stability criteria presented within Cox, Shand and Blacka (2010) and to ensure that, in the event of vehicle failure, safety was not compromised once people abandoned their cars. This appears to have been overlooked in all existing safety criteria except for the Public Works Department (1986)/NSW Floodplain Development Manual (2005) criteria. Between the floating and velocity limits, constant DxV relations are recommended in accordance with proposed human stability criteria. For all flow conditions in all vehicle classes, the proposed vehicle safety criteria remain below the moderate hazard criteria for adults (Cox, Shand and Blacka, 2010).

Overall, it is the author's opinion that the available experimental data is being applied beyond its limits to provide these *Draft* criteria and that they are unlikely reliable enough to be adopted permanently as safety criteria. The available data does not allow adequate assessment of:
- Appropriate coefficients of friction for use in flood flows;
- Buoyancy in modern cars;
- The effect of vehicle orientation to flow direction (including vehicle movement);
- Information for additional categories including small and large commercial vehicles and emergency service vehicles;

However, the physical parameters governing vehicle stability under flood flows is a relatively simpler

problem than for persons due to the lack of external factors which can influence stability of stationary vehicles such as experience and training. In this regard, an analytical solution (computational model) using manufacturer specifications should be suitable for determining stability if correct coefficients of friction and drag are selected and the computational model is able to be verified against experimental data.

To provide robust and accurate criterion, we propose that:
1. The draft stability criteria presented below are adopted as interim, informal values;
2. Full scale testing of the force required to initiate vehicle movement in varying water depths is undertaken to ascertain appropriate frictional coefficients. This could be carried out in a controlled laboratory environment using a variety of surface and vehicle types and tyre conditions to examine frictional coefficient sensitivity.
3. Calibration of the Keller and Mitsch (1993), or similar, computational model using the vehicles tested within (2) and then application of the model to an agreed range of modern vehicles based on a statistical distribution of car types within Australia and their geometric properties.
4. Field verification of the adopted computational model for both stationary and moving vehicles using a full scale test in flowing water at a selected venue capable of attaining the required flows and with appropriate safety equipment in place.
5. Using the results of (3), as verified during (4), produce appropriate stability criteria for specific classes of vehicle including small and large passenger cars, 4WD vehicles, small and large commercial vehicles.

Only criteria developed in such a rigorous way are suitable for presenting as true safety guidelines. Such guidelines would be a world first and likely used worldwide as the earlier experimental studies of Gordon and Stone (1973) and Foster and Cox (1973) have been.

Proposed *DRAFT INTERIM* criteria for stationary vehicle stability

Class of vehicle	Length (m)	Kerb Weight (kg)	Ground clearance (m)	Limiting still water depth[1]	Limiting high velocity flow depth[2]	Limiting velocity[3]	Equation of stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.1	3.0	$DV \le 0.3$
Large passenger	> 4.3	> 1250	> 0.12	0.4	0.15	3.0	$DV \le 0.45$
Large 4WD	> 4.5	> 2000	> 0.22	0.5	0.2	3.0	$DV \le 0.6$

[1] At velocity = 0 ms^{-1}; [2] at velocity = 3ms^{-1}; [3] at low depth

TABLE OF CONTENTS

1.   Introduction

The stability of vehicles exposed to flood flow on streets, causeways and bridges is of major concern in urban stormwater, road design and floodplain management. There were 15.7 million motor vehicles, including motor cycles, registered in Australia at 31 March 2009 (Aus Bureau of Statistics, 2009). Of these cars, 12 million were classed as passenger vehicles. Human activity on flooded surfaces is inevitable with much development already in flood prone areas. The safety of people can be compromised when the vehicles they are travelling in are exposed to flows which cause the vehicle to become unstable by losing traction or become buoyant. Current design guidelines for vehicle stability on flooded surfaces (i.e. I.E.Aust, 1987; DIPNR, 2005) are simplistic, generally based on the product of flow depth (D) and velocity (V) derived during experimental investigations in the late 1960's and early 1970's (Bonham and Hattersley, 1967; Stone and Gordon, 1973) and theoretical analysis in the early 1990's (Keller and Mitsch, 1993). However, substantial changes in vehicle design have occurred since these early studies (Figure 2), notably in vehicle planform area, vehicle weight and ground clearance and the results of these earlier studies may no longer be representative of contemporary vehicles.

The two recognised hydrodynamic mechanisms by which stability is lost include *buoyancy* or floating and *friction instability* or sliding (Figure 1). Floating instability occurs when the upward force exerted due to buoyancy exceeds the downward directed force exerted by the vehicle mass. This instability is dominant in low velocity, high depth flows. Frictional or sliding instability occurs when the horizontal force exerted on one or more car panels is greater than the vertical restoring force which is dependent on vehicle mass, buoyancy and the friction which exists between the car tyres and road surface. A further mode of instability discussed within the BC Hydro Life Safety Model Description (BC Hydro, 2005) is a toppling instability. However, this stability appears to be restricted to vehicles which are already sliding or floating and encounter uneven terrain. This form of instability is therefore excluded from further analysis.

A distinction should be made between flow-induced stability loss and stability loss induced by the interaction of a vehicle at high speed and evenly distributed water, commonly referred to as hydroplaning (Gallaway et al., 1979). This phenomenon is of concern for vehicle stability but generally occurs at high vehicle speeds and at low water depth. Hydroplaning is therefore not considered further within this study.

This report reviews and discusses previous experimental and analytical investigations of vehicle stability for stationary vehicles. Existing guidelines and recommendations for vehicle stability are compared with these study results. Conservative flow limits to ensure vehicle stability for various vehicles classes are derived and presented together with a discussion of their limitations and recommendations for future work necessary to obtain robust criterion.
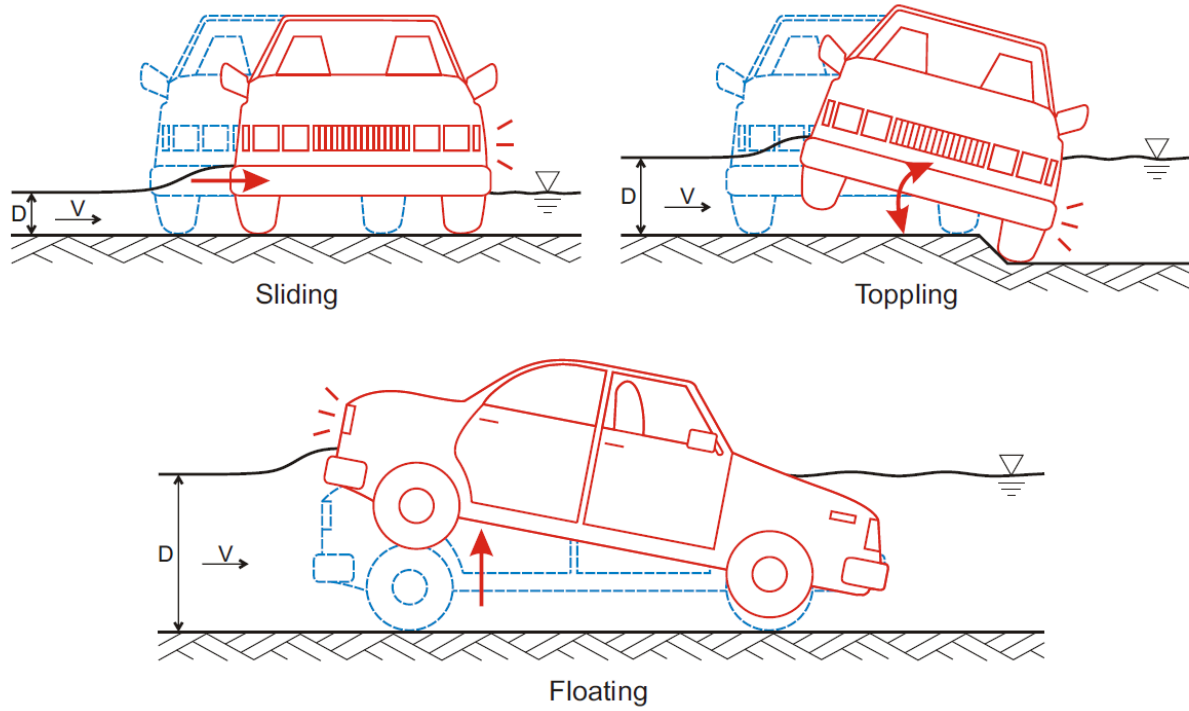
Figure 1   Typical modes of vehicle instability.

Figure 2   Typical small car of the early 1970's (A: Morris Mini) and prototype for the model testing undertaken by Stone and Gordon (1973) compared to a typical small car of 2010 (B: Toyota Corolla).

2. Review of Previous Investigations

2.1. Guideline Values and Recommendations

The current Australian Rainfall and Runoff (ARR) guidelines (I.E.Aust, 1987) stipulate that "*Where vehicles alone are affected, a higher depth-velocity product, 0.6 or 0.7 m^2s^{-1} depending on vehicle size, is appropriate*". This implies a higher flow threshold is applicable for vehicles than pedestrians where a depth-velocity product of 0.4 m^{s-1} is recommended. In contrast, the velocity-depth relationships that define vehicle instability as presented within the 1986 NSW Floodplain Development Manual (DPW, 1986) and adopted within the 2005 NSW Floodplain Development Manual (DIPNR, 2005) do not indicate constant D.V relationships (Figure 3), but do place upper bounds on both depth (0.3 m) and velocity (2.0 ms^{-1}) for vehicles to remain stable. The limiting depth for pedestrian safety is given at 0.7 m implying lower flow thresholds are applicable for vehicles than pedestrians (Figure 3). The Melbourne Water Land Development Manual (Melbourne Water, 1996) defines safety limits based on constant D.V values which vary as a function of flow depth. These values are based on the results of the Keller and Mitsch (1993) study. The Ausroads Guide to Road Design, Part 5: Drainage Design (AusRoads, 2008) state that "dependent on flow velocity and length of floodway, water depths up to 300 mm are considered to be trafficable to passenger cars". They further suggest that road closure should occur when "total head (static plus velocity) above the crest of a carriageway exceeds 300 mm". The expression for this closure limit is provided within Table 1.

Besides the safety of the general community, safety on floodways is important to rescue workers who are frequently required to operate in hazardous conditions. Emergency Management Australia (EMA) is the national government agency responsible for managing disaster situations. EMA has published a series of manuals to assist other agencies and local governments in the planning of emergency situations regarding flooding. In regard to "Flood Hazard", EMA advice is that "Small, light, low motor vehicles crossing rapidly-flowing causeways can become unstable when water depths exceed 0.3 metres. Evacuation by larger, higher sedans is generally only possible and safe when water depths are less than 0.4 metres" (EMA, 1999). A further EMA manual on four-wheel-drive vehicle operation, aimed at emergency services personnel (EMA, 1997) states that, for water crossings, "If water reaches to the bumper bar or higher, upon entering the water accelerate until a *bow wave* forms in front of the vehicle. Maintain this bow wave at all costs, to keep water out of the engine." In water depths of greater than 750 mm, it is suggested that either a snorkel extension to the engine air inlet and exhaust system is fitted or a canvas sheet or tarp is placed across the grille to prevent water entering the engine bay. This advice is clearly directed at large, four-wheel-drive emergency vehicles and not for general motorists.

A study by Moore and Power (2002) assessed previous experimental and numerical findings and presents a stability limit which changes dependent on whether the buoyant (large depth, low velocity) or drag (low depth, high velocity) forces dominate stability. This change is defined based on the transition from super to sub-critical flow, or when the Froude number equals one. A constant D.V rate is assumed in supercritical regimes (drag dominated; assumed at V > 1.81 ms^{-1}) and a linear relation in subcritical regimes (buoyant forces dominate; V < 1.81ms^{-1}).

These documents are not specific regarding whether their criteria are intended for moving or stationary vehicles. However, given that the experimental data upon which most are based is for stationary vehicles, the derived criteria are likely applicable only under this regime. A summary of the limiting values for vehicle stability under flood flow within historic and current guidelines are presented within Table 1.
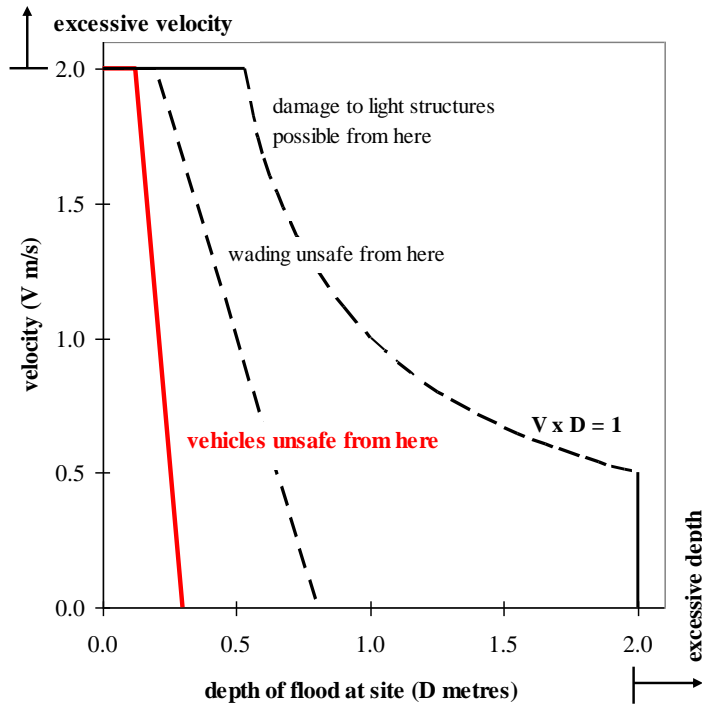
Figure 3 Depth-velocity relationships for floodway design (adapted from: Department Public Works, NSW, 1986)

Table 1
Guidelines and recommendations for limits for vehicle stability

Guideline/ Recommendation	Year	Recommended limits for vehicle stability			
		Maximum Depth (D; m)	Maximum Velocity (V; ms^{-1})	Maximum D.V	Other
Department Public Works, NSW (PWD)	1986	0.3	2.0	-	$\dfrac{-11 \times V + 3.3}{D} < 1$
Australian Rainfall and Runoff (I.E. Aust)	1987	-	-	0.6 – 0.7 depending on vehicle size	-
Melbourne Water Land Development Manual: Floodway Safety Criteria	1996	0.6	-	<= 0.60 m^{2}s^{-1} for D_{av} <= 0.1 m; <= 0.80 m$^{2-1}$ for D_{av} =0.2m; <= 0.35 m^{2}s^{-1}, for D_{av} >= 0.3 m.	-
Emergency Management Manual (EMA)	1997	-	-	-	Maintain a bow wave and outfit the vehicle in depths > 750 mm
Emergency Management Manual (EMA)	1999	0.3 (small, light low cars) 0.4 (larger, higher cars)	-	-	-
Moore and Power	2002	-	-	-	D ≤ (0.4 – 0.0376V) for [V ≤ 1.81]; DV ≤ 0.6 for [V > 1.81].
Floodplain Development Manual (DIPNR)	2005	0.3	2.0	-	$\dfrac{-11 \times V + 3.3}{D} < 1$
Ausroads Guide to Road Design - Part 5: Drainage Design	2009	-	-	-	$D + \dfrac{V^2}{2g} \le 0.3m$

Guidance documents from England, Japan, Canada and the United States reviewed within Keller and Mitsch (1993) suggest either non-quantitative limits such as "*the depth and velocity of cross-street flow should always be maintained within such limits that it will not have sufficient force to affect moving traffic*" or arbitrary limits such as "*knee-high flow, with velocity not exceeding 0.5 ms^{-1}*", with no theoretical background provided. The BC Hydro Life Safety Model (BC Hydro, 2005), developed to track individual entities such as persons, vehicles and structures during flooding, tsunami and inundation events uses criteria based on the Australian Rainfall and Runoff Guidelines (I.E.Aust, 1987) and Keller and Mitsch (1993).

2.2. Experimental and Analytical Investigations

2.2.1. Bonham and Hattersley (1967)

Bonham and Hattersley (1967) carried out laboratory testing on the stability of a model Ford Falcon (Figure 4) exposed to perpendicular flow (relative to the car length) on a causeway. A geometric length scale of 1:25 was employed and the vehicle restrained by fine threads both vertically and laterally. Horizontal and vertical loadings were obtained by measuring forces on these threads. Tests were undertaken at 46 different combinations of depth and velocity with depth ranging from 0.11 to 0.57 m and velocity from 0.48 to 3.09 ms^{-1} (both prototype scale).

Figure 4   Model Ford Falcon at 1:25 scale used by Bonham and Hattersley (1967)

The horizontal reaction force (F_H) consists of the pressure and momentum forces acting on the side of car and the vertical reaction force (F_V) consists of the weight of the car (W), floatation or buoyancy (B) less any aspiration or vacuum effects due to water passing beneath the car and any vertical component of momentum force acting on the curved shape of the car side below the car door (Figure 5). Loss of stability due to floating, presumably at the rear of the car, was found to occur at a depth of 0.57 m. Once horizontal and vertical forces were determined, a frictional coefficient (μ) which would lead to loss of frictional stability was defined. As expected, derived frictional coefficients generally increased with increasing depth and velocity. A slight increase in vertical reaction was noted at a velocity of 1.5 to 2.0 ms^1 and depth of 0.45 to 0.55 m. This infers increased stability during this flow regime and was attributed

by the authors to aspiration and a slight vacuum developing on the underside of the car.

Lines of constant friction were produced for µ = 0.3 to 0.5 (Figure 6). However, to define limiting flow values for vehicle stability, specification of an appropriate frictional coefficient was required. Correspondence with various roading experts and test laboratories (Road Research Laboratory, 1963) indicated a low-end frictional coefficient for braking on a smooth causeway surface with a worn tyre of µ = 0.5. This value was reduced by 10% to convert the coefficient to a sideway force giving µ = 0.45. As "peak" friction coefficients are greater than sustained or "slipping" coefficients, this value was further reduced to µ = 0.36. A factor of safety of 20% was then incorporated to allow for collision with slippery floating debris. A final friction coefficient of µ = 0.3 was adopted by Bonham and Hattersley and, while significant uncertainties remained, was confirmed as "almost certainly adequate for most surfaces" (Mr R.F. Jenkins, Olympic Tyre and Rubber Company, *per. comm.*, 1967). These steps indicate that adoption of µ = 0.3 is likely very conservative.
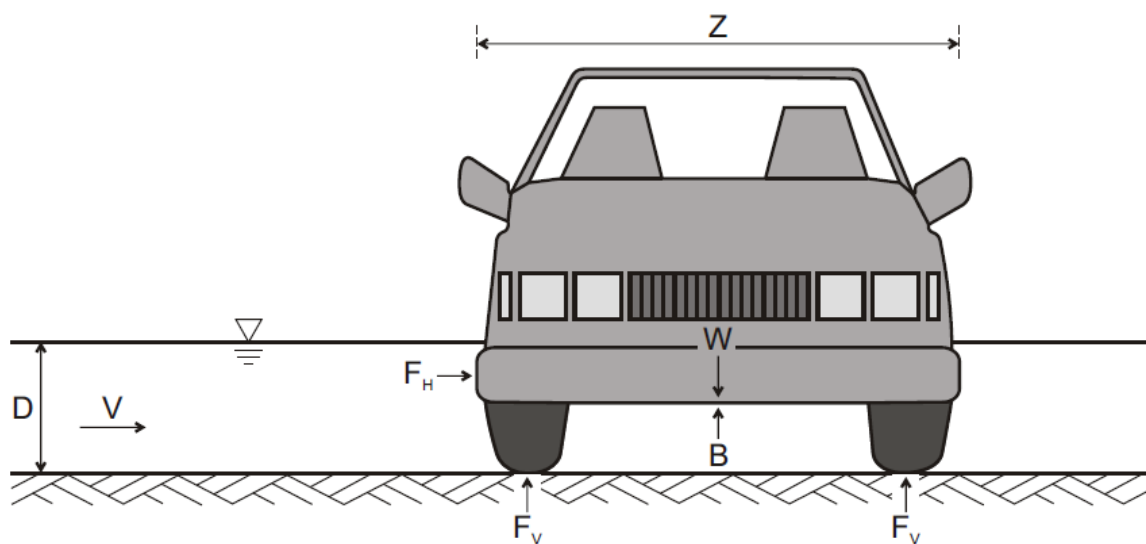

Figure 5 Vehicle Stability Nomenclature

Using principles of geometric similarity, results were used to determine limits of floating and frictional stability for a range of cars available at the time. These cars were grouped into seven categories including small, averaged and large sized cars, rear engine cars, sports cars and others. The cars were found to float at depths between 0.38 m and 0.58 m, with heavier cars floating at greater depths. Limits for other cars were found to be lower than for the tested Ford Falcon. A lower limit, as determined by the original authors assuming a friction coefficient of µ = 0.3, is indicated within Figure 6.

Even within this early study, Bonham and Hattersley (1967) recognised that there was a general trend in motor car design towards cars which will more easily float or be swept away by the flow of water over causeways. They attributed this to elimination of the separate car chassis in favour of a lower unitised body with low floor trays at the minimum acceptable road clearance level and improved dust proofing resulting in watertight interiors which more easily facilitate buoyancy and floating.
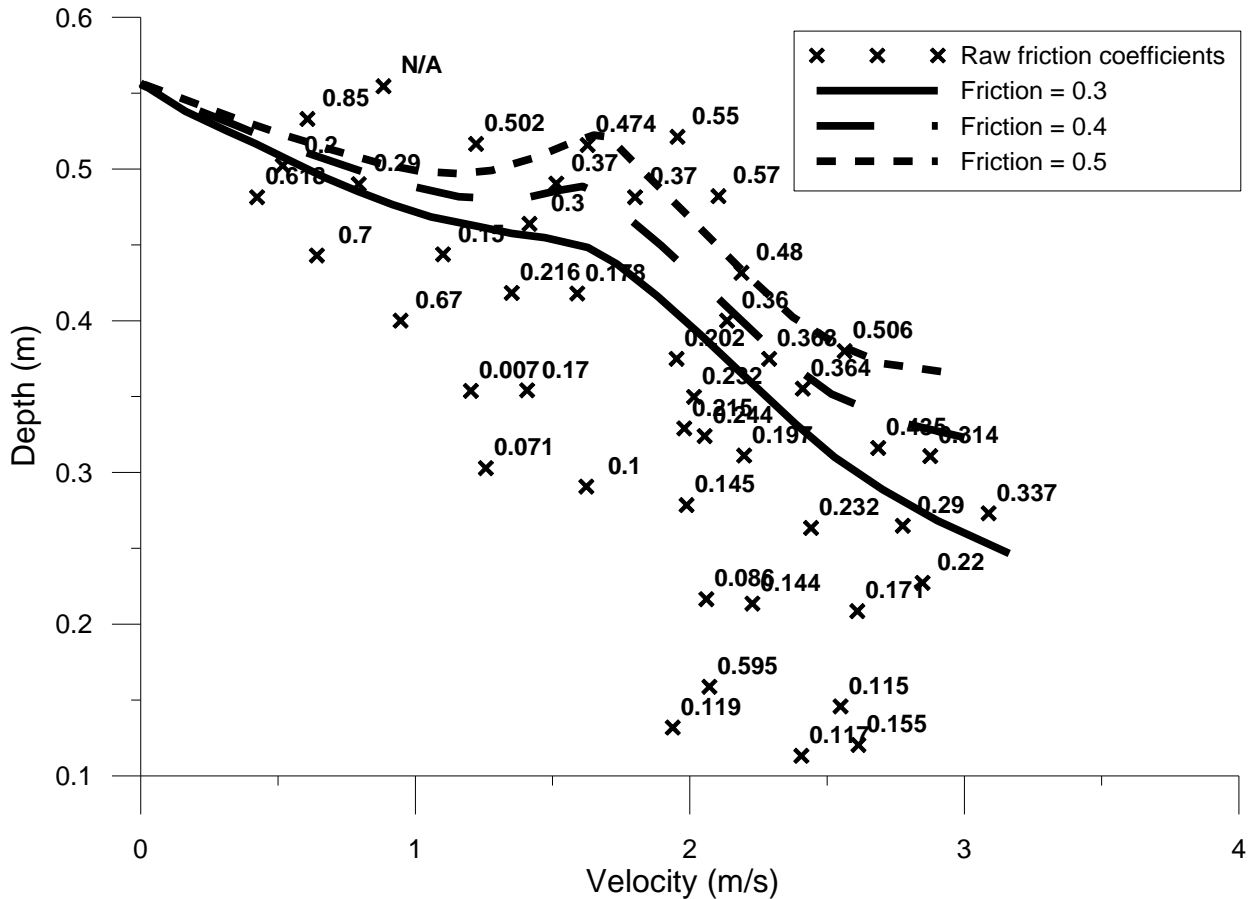
Figure 6 Raw test results of Bonham and Hattersley (1967) with the calculated coefficient of friction required to initiate sliding indicated and their assessed lines of constant friction indicated.

2.2.2. Gordon and Stone (1973)

Gordon and Stone (1973) undertook laboratory testing on the stability of a model Morris Mini sedan exposed to parallel (relative to the car length) and oncoming flow within a 1 m wide hydraulic fume. This vehicle was selected as it was deemed representative at that time of a range of motor cars most susceptible to losing stability in flood flows.

Three modes of resistance to movement were considered. These included:
1. Car parked in first gear: Front wheels locked
2. Car parked with handbrake on: Rear wheels locked
3. Both of the above: All wheels locked.

The third mode was deemed non-conservative and testing was undertaken considering the first two modes only. A geometric length scale of 1:16 was employed and the vehicle restrained by fine threads both vertically and laterally to measure total horizontal reaction force and vertical reaction forces on the front and rear wheels (Figure 7). Coefficients of friction representing the limit of stability were defined by $\dfrac{F_H}{\mu F_V} = 1$, where F_H is the measured horizontal reaction, F_V is the measured vertical reaction and μ is the coefficient of friction. Lines of constant friction to initiate vehicle movement as a function of depth and velocity were derived for the locked front wheel condition and for the locked rear wheel condition. These relationships for a range of coefficients between $\mu = 0.3$ and $\mu = 1.0$ are also shown within Figure 7. While specific advice on appropriate coefficients of friction was not provided within this report, values for

stationary tyre-flooded road coefficients of friction as measured in Canberra by UNSW (Yandell, 1973) and skidding road-tyre coefficients of friction (Woods et al., 1960) are presented. The stationary coefficients presented ranged between 0.85 and 1.15 and the skidding values (at 30 km/hr) ranged from 0.16 to 0.48. These results indicate that the stationary value of μ = 0.3 assumed by Bonham and Hattersley (1967) is likely conservative.

Overall, stability was found to be slightly higher for the front wheel locked condition than for the rear wheel locked. This is attributed to the greater vehicle weight exerted above the front wheel in the front-wheel-drive vehicle tested. It was also noted that, in some cases increased velocity for a constant depth resulted in increased vertical reaction and therefore stability. This was attributed to the formation of a bow wave at the front of the car, resulting in a hydraulic jump and accelerating flow at the back of the car. This lowered the water level in the vicinity of the rear wheels increasing stability under those flow conditions. Similarly to the earlier Bonham and Hattersley study, some aspiration or vacuum effects under the body pan were also observed, developing additional vertical forces and increasing stability.

Gordon and Stone note that the design curves presented have been obtained for a single car parked on a floodway with no obstructions. Factors such as other vehicles, bed slope change, floodway bends and constructions and the possibility of floating debris have not been considered.
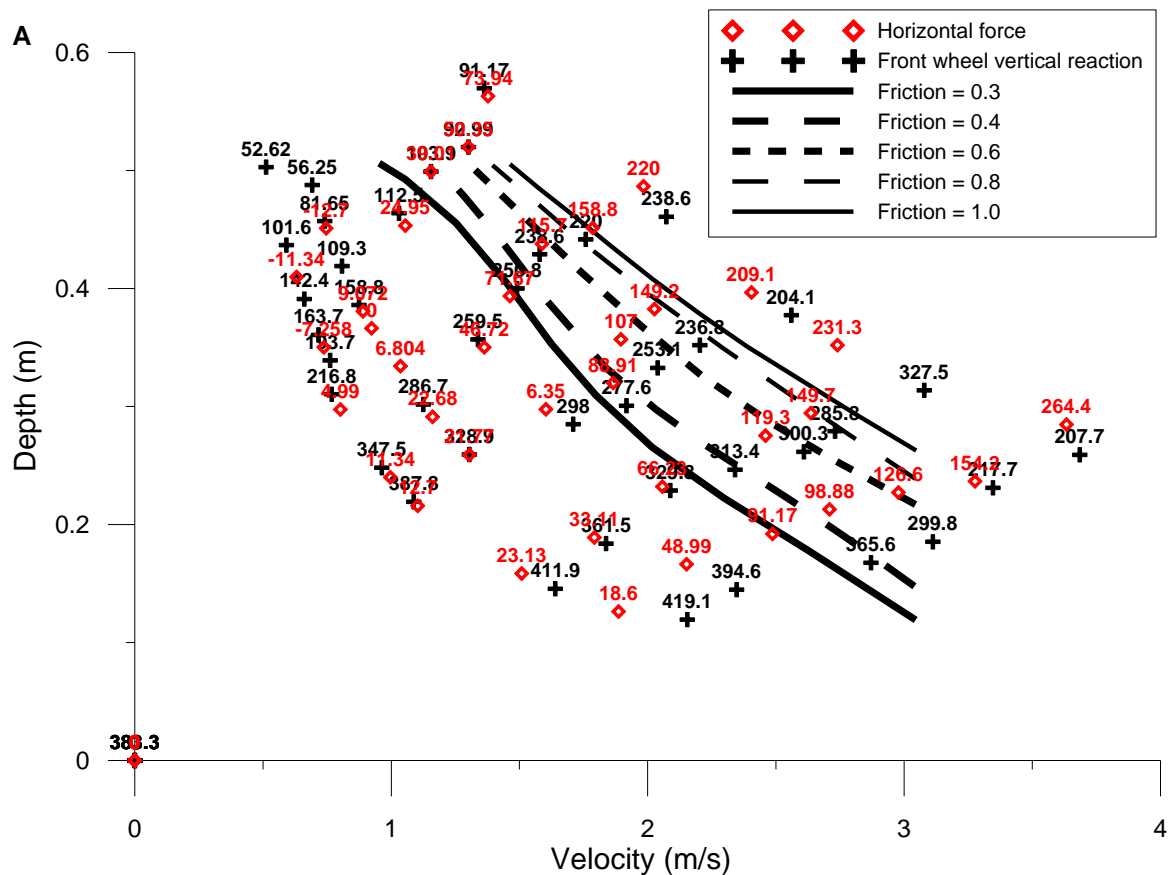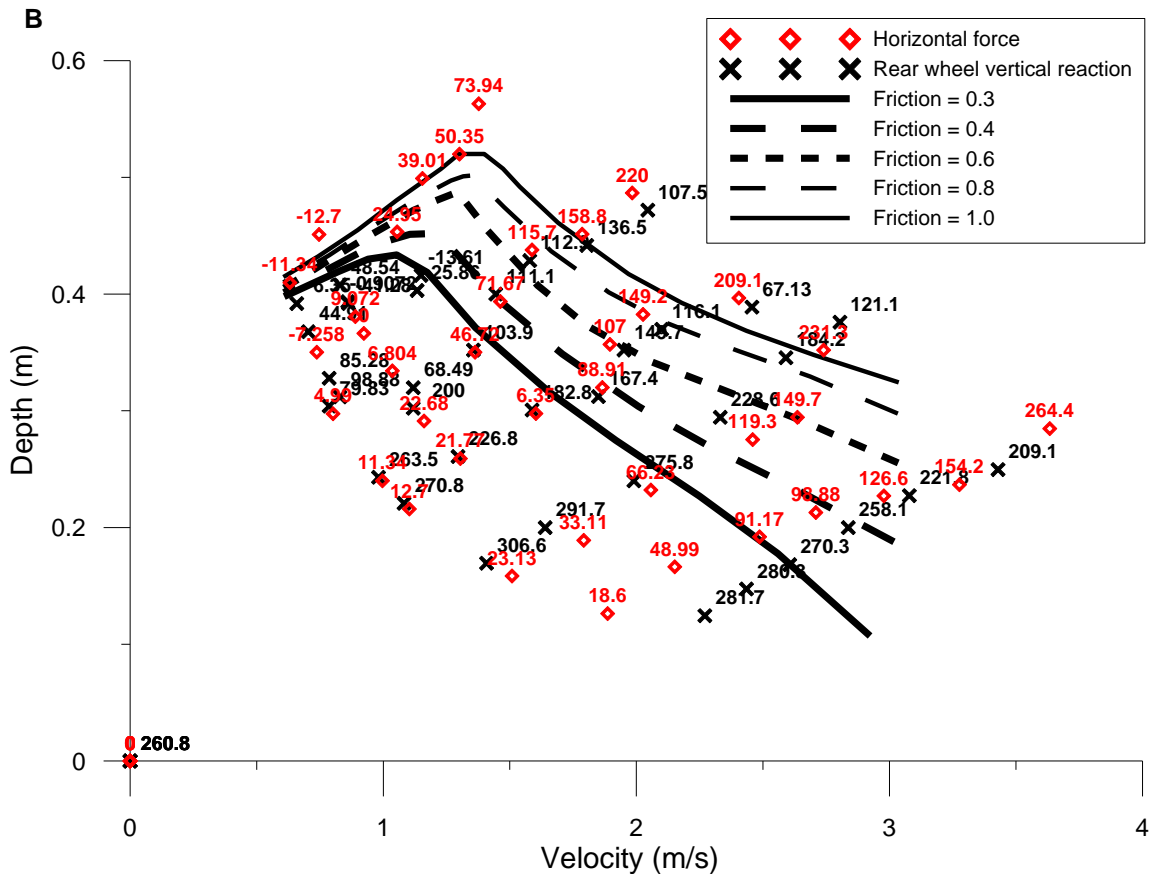
Figure 7 Raw test results of Gordon and Stone (1973) with the observed horizontal forces (kg) and front (A) and rear (B) vertical reaction forces (kg) indicated. Lines of constant friction to initiate vehicle movement as assessed during their study are overlaid.

2.2.3. Keller and Mitsch (1993)

Keller and Mitsch (1993) undertook a purely theoretical study of the stability of both cars and people. This study evaluated stability in flows perpendicular to the vehicle by comparing vertical reaction forces (F_V) at each car axle taking into account vehicle weight (W) and buoyancy (B) with horizontal reaction forces (F_H) as a result of flow velocity (V) and submerged area projected normal to the flow (A).

Manufacturer specifications were obtained for three small cars; a Suzuki Swift, Ford Laser, Toyota Corolla and a larger Ford LTD. Flow depth was incrementally increased from 0.025 m to 0.4 m. At each depth, vertical reaction forces at the front and rear axle were evaluated separately by determining a centre of buoyancy and weight distribution from manufacturer specifications. Horizontal reaction forces were then determined by evaluating the drag force acting on the submerged part of the vehicle. Instability occurs when the vertical reaction force is less than or equal to zero (vehicle floats) or when the horizontal force is equal to the vertical restoring force which is a function of the assumed coefficient of friction and the vertical reaction force. Limits of stability as presented within Keller and Mitsch (1993) within Figure 8 (A) and, as a function of depth and velocity, within Figure 8 (B). Figure 8 (A) shows that the limiting D.V value was found to not be constant but rather non-linearly dependent on flow depth with the largest flow values tolerable at 0.15 to 0.25 m depth.

The purely theoretical method described above is, however, highly dependent on the selection of friction and drag coefficients. A coefficient of friction of 0.3 was assumed following Bonham and Hattersley (1967) and drag coefficients of 1.1 on the wheels and 1.15 on the vehicle body were adopted with no sensitivity assessment evident. The coefficient of friction adopted by Bonham and Hattersley (1967) was

based on limited advice and appears conservative when compared with stationary tyre-flooded road coefficient presented within Gordon and Stone (1973) after Yandell (1973). Additionally, results were not verified against experimental or field data, although this data was available from earlier experimental studies.
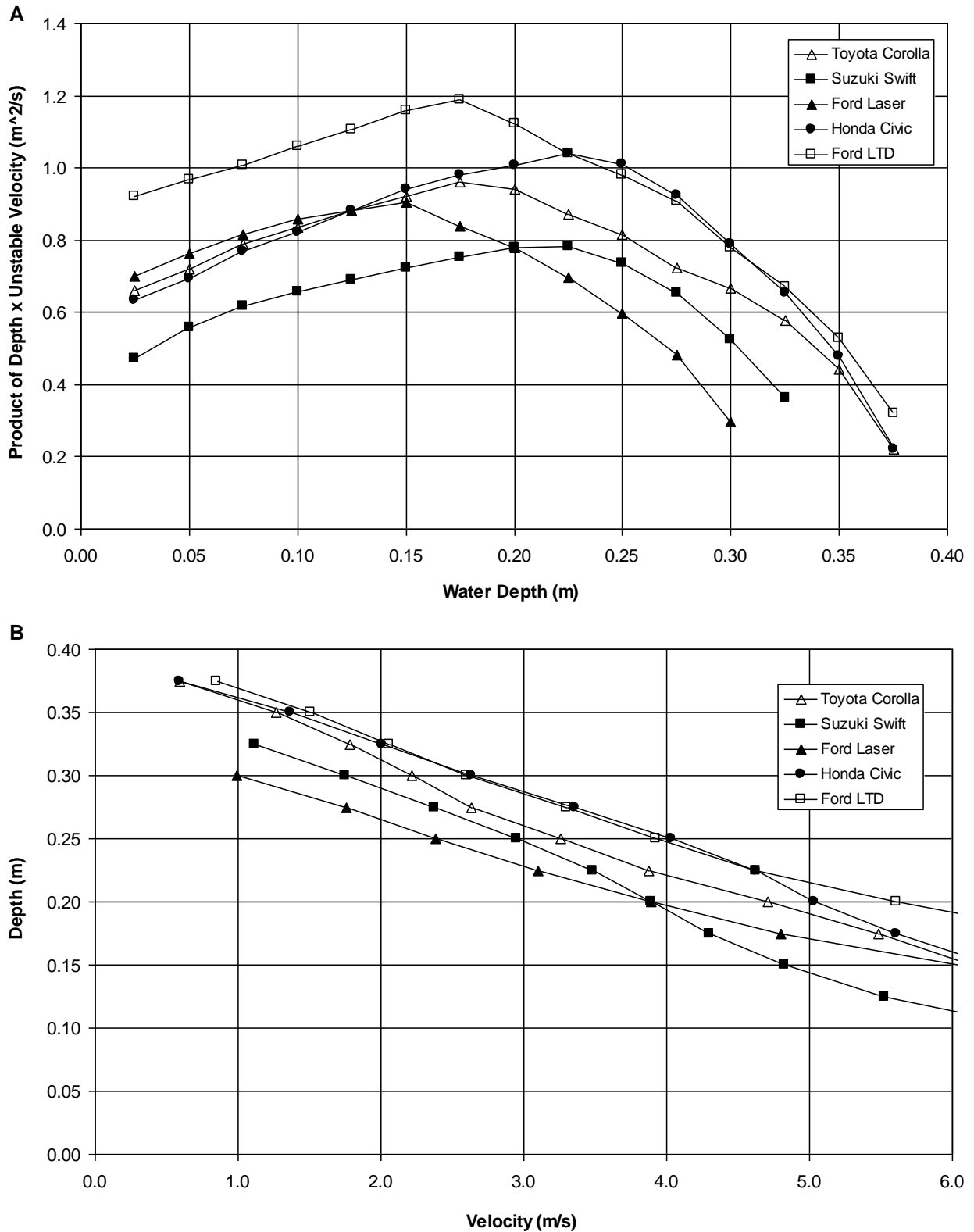

Figure 8 Theoretical unstable flow rates for range of vehicle types assessed by Keller and Mitsch (1993) assuming a frictional coefficient of 0.3 and drag coefficient of 1.1 to 1.15

2.2.4. Summary

A summary of experimental and analytical study parameters are presented within Table 2 and resultant limits of stability for an assumed coefficient of friction of μ = 0.3 is presented within Figure 9. A floating threshold of 0.57 m for the Ford Falcon tested by Bonham and Hattersley (1967) is indicated and inferred floating thresholds of 0.42 m (rear) and 0.5 m (front) for the Morris Mini tested by Gordon and Stone (1973). Floating limits for the vehicles tested by Keller and Mitsch (1993) were inferred at between 0.34 and 0.42 m by linear extrapolation.

The stability limits found by Gordon and Stone (1973) differed in that they apply to a vehicle facing parallel to the flow with only one set of wheels at a time resisting movement. Thus, while horizontal forces would be expected to be lower due to the smaller area projected normal to the flow, restoring forces would similarly be lower as friction is only being applied through one set of tyres.

While no stability limits follow the constant D.V. shape indicated by some guidelines, the experimental values by Bonham and Hattersley (1967) and Gordon and Stone (1973) are observed to slope more steeply (indicating less stability in low depth, high velocity flows) than indicated by the Keller and Mitsch (1993) results which asymptote to very high velocities at low depths. A review of international literature did not reveal any additional laboratory or full scale model testing of vehicle stability above those studies carried out in Australia.

Table 2
Summary of Experimental and Analytical Studies

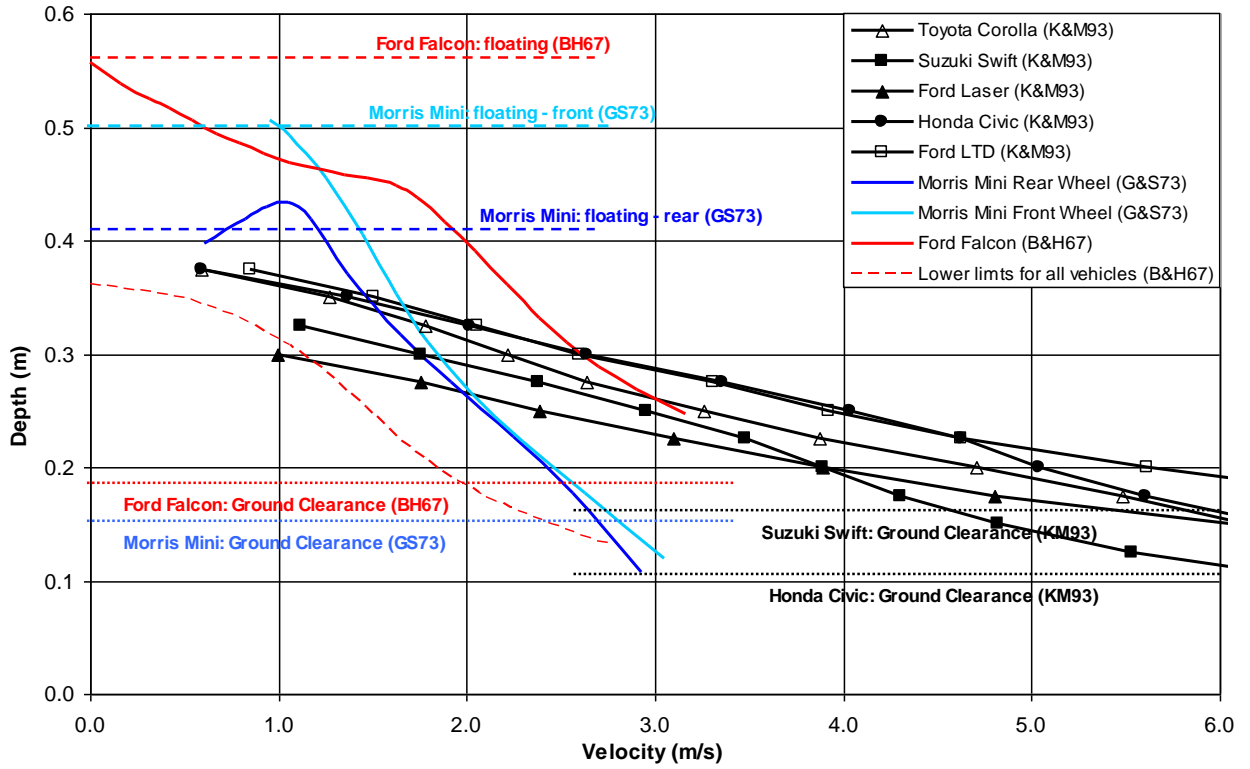| Reference	Bonham and Hattersley (1967)	Gordon and Stone (1973)	Keller and Mitsch (1993)
Study Type	Experimental	Experimental	Theoretical
Vehicles Tested	• Ford Falcon • + results scaled to other models	• Morris Mini Sedan	• Toyota Corolla • Suzuki Swift • Ford Laser • Honda Civic • Ford LTD
Vehicle Age	Mid to late 1960s	Early 1970s	Early 1990s
Ground Clearance (m)	0.18	0.15	0.155; 0.17; 0.15; 0.10; 0.16
Scale	1:25	1:16	-
Vehicle Orientation	Vehicle perpendicular to flow	Vehicle parallel to flow	Vehicle perpendicular to flow
Range of depths tested (m)	0.11 to 0.55	0.12 to 0.57	0.025 to 0.375
Range of velocities tested (m/s)	0.42 to 3.09	0.5 to 3.69	0.6 to >35
Car floats (depth, m)	0.57	Inferred: 0.42 (rear) and 0.5 (front)	Inferred: Between 0.34 and 0.40 for different models
Resultant equation of stability	$\dfrac{F_H}{\mu F_V} = 1$	$\dfrac{F_H}{\mu F_V} = 1$	$V = 2\left(\dfrac{\mu F_V}{\rho C_D A}\right)^{\frac{1}{2}}$ Note: F_V and therefore V are evaluated separately for the front and rear axel
Assumed coefficient of friction	Various, although recommends 0.3	Various	0.3

Figure 9 Comparison of the values of limiting stability assuming a frictional coefficient of μ = 0.3 derived experimentally for a Ford Falcon by Bonham and Hattersley (1967) and a Morris Mini by Gordon and Stone (1973) and analytically for a range of cars by Keller and Mitsch (1993).

3.   Discussion and Reassessment of Stability Criterion

Existing guidelines and recommendations for limits of vehicle stability are compared to experimental and analytical results (assuming a coefficient of friction of μ = 0.3) within Figure 10. The Public Works Department criteria (PWD, 1986), which has also been adopted within the 2005 NSW Floodplain Development Manual (DIPNR, 2005), is shown to be very conservative with an upper water level threshold of 0.3 m and upper velocity of 2.0 ms^{-1} regardless of depth. The Ausroads (2008) criteria for road closure is similarly conservative. These values are below all test results and below the Bonham and Hattersley (1967) lower limit line. The 1987 Australian Rainfall and Runoff criteria (AR&R87; I.E. Aust, 1987) exceed all test results in high depth, low velocity flows and extends to low depth, high velocity regimes outside the limits of experimental testing. Moore and Power (2002) address this by changing the form of the D.V relationship at low velocities and their criteria better matches test data, although still exceeds the Bonham and Hattersley (1967) lower limit and exceeds the Gordon and Stone (1973) data at velocities greater than around 1.5 ms^{-1}. The Melbourne Water Land Development Manual (MWLDM, 1996) criteria encapsulate the Keller and Mitsch (1993) data at low water levels but exceeds all test results at high depth, low velocity flows. The EMA (1999) criteria agree reasonably well with data at low velocity flows but exceed all test data at high velocity flows.

Overall, with the exception of the Public Works Department (1986)/ NSW Floodplain Development Manual (2005) and AusRoads (2008) criteria, all other criteria are non-conservative at some flow regime when compared to experimental and analytical test results. The Public Works Department (1986) and AusRoads (2008) criteria may be overconservative for larger vehicles and certainly for high clearance 4WD vehicles. While the assumed coefficient of friction of μ = 0.3 is likely conservative, the present lack of suitable data and wide range of road surfaces and tyre tread conditions prohibits the refinement of the coefficient.
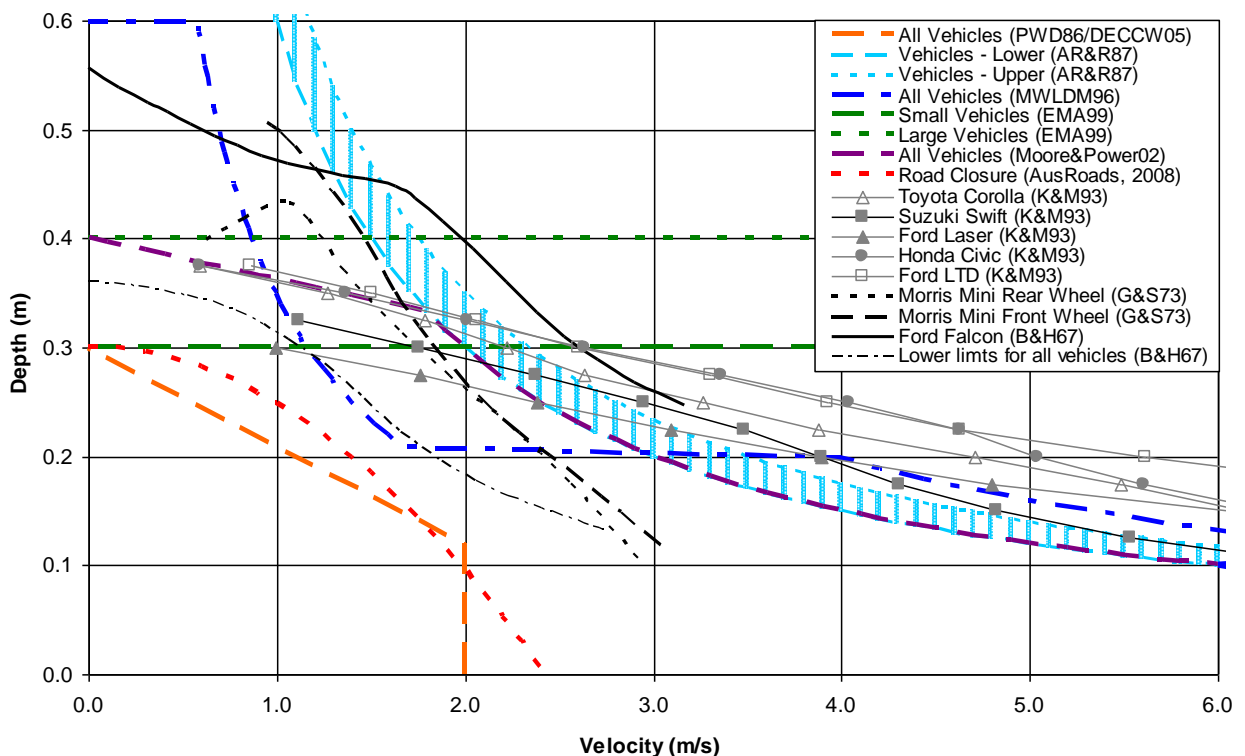

Figure 10 Comparison of guidelines and recommendations for vehicle stability limits compared to experimental and computational results

While a complete dataset on the distribution of vehicles within Australia has not been available for the present study and a comprehensive study of vehicle trends through time has not been undertaken, a cursory assessment of changes in popular car models through time, namely the Toyota Corolla, Ford Falcon and Toyota Landcruiser reveals a trend of increasing height, length, width and weight and decreasing ground clearance. Vehicle Standard information published in Victoria (VicRoads, 2003) and New South Wales (RTA, 2009) specify minimum vehicle ground clearance of 100 mm after Australian Vehicle Standards (Federal Office of Road Safety, 2006) requirements.

On the basis of changes in modern vehicle design, the limited nature of the earlier experimental work and the lack of calibration in computational studies, it is unlikely that the earlier results are directly applicable and conservative when applied to modern vehicles. A series of recommendations for further testing to address these deficiencies are presented within the following section. In the interim, however, the existing AR&R guidelines are clearly non-conservative and revision of the criteria should be considered until further testing is undertaken. Such a revision to provide **_Draft interim_** criteria for stationary vehicle stability is suggested below.

The experimental and analytical data can be reasonably represented by either a linear relationship between D and V or a constant D.V value. Lines of draft stability for stationary small and large passenger cars and large 4WD vehicles have been provided for assumed linear and constant DV relationships in Figures 11A and 11B. These draft stability criteria all have limiting depths and a limiting velocity of 3.0 ms^{-1}. This was incorporated to provide agreement with human stability criteria presented within Cox, Shand and Blacka (2010) and to ensure that, in the event of vehicle failure, safety was not compromised once people abandoned their cars. This appears to have been overlooked in all existing safety criteria except for the Public Works Department (1986)/NSW Floodplain Development Manual (2005) criteria.

For consistency with the proposed human stability criteria, the constant DV relationships for small and large passenger cars and large 4WD vehicles, as shown within Figure 11B, is preferred. These **_Draft_** criteria and approximate dimension ranges for the various vehicle classes are shown within Table 3. Under these constant D.V relationships, the proposed draft vehicle safety criteria remain below the low hazard criteria for adults (Cox, Shand and Blacka, 2010) for all flow conditions in all vehicle classes.

Upper limits of depth within still water (floating limits) are provided. The depth for small passenger vehicles, 0.3 m, is below the lower limit indicated within Bonham and Hattersley (1967) and in agreement with that proposed by Public Works Department (1986) and AusRoads (2008). The depth for large passenger vehicles of 0.4 m is within the floating limits inferred from Keller and Mitsch (1993). The floating depth for 4WD vehicles of 0.5 m remains within the limits of the large ford falcon tested by Bonham and Hattersley (1967). While specifically equipped vehicles would likely remain stable in water of greater depth, this is outside the intention of the present criteria.

Table 3
Proposed DRAFT Stability Criteria for Stationary Vehicles

Class of vehicle	Length (m)	Kerb Weight (kg)	Ground clearance (m)	Limiting still water depth[1]	Limiting high velocity flow depth[2]	Limiting velocity[3]	Equation of stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.1	3.0	$DV \leq 0.3$
Large passenger	> 4.3	> 1250	> 0.12	0.4	0.15	3.0	$DV \leq 0.45$
Large 4WD	> 4.5	> 2000	> 0.22	0.5	0.2	3.0	$DV \leq 0.6$

¹ At velocity = 0 ms⁻¹; ² at velocity = 3ms⁻¹; ³ at low depth
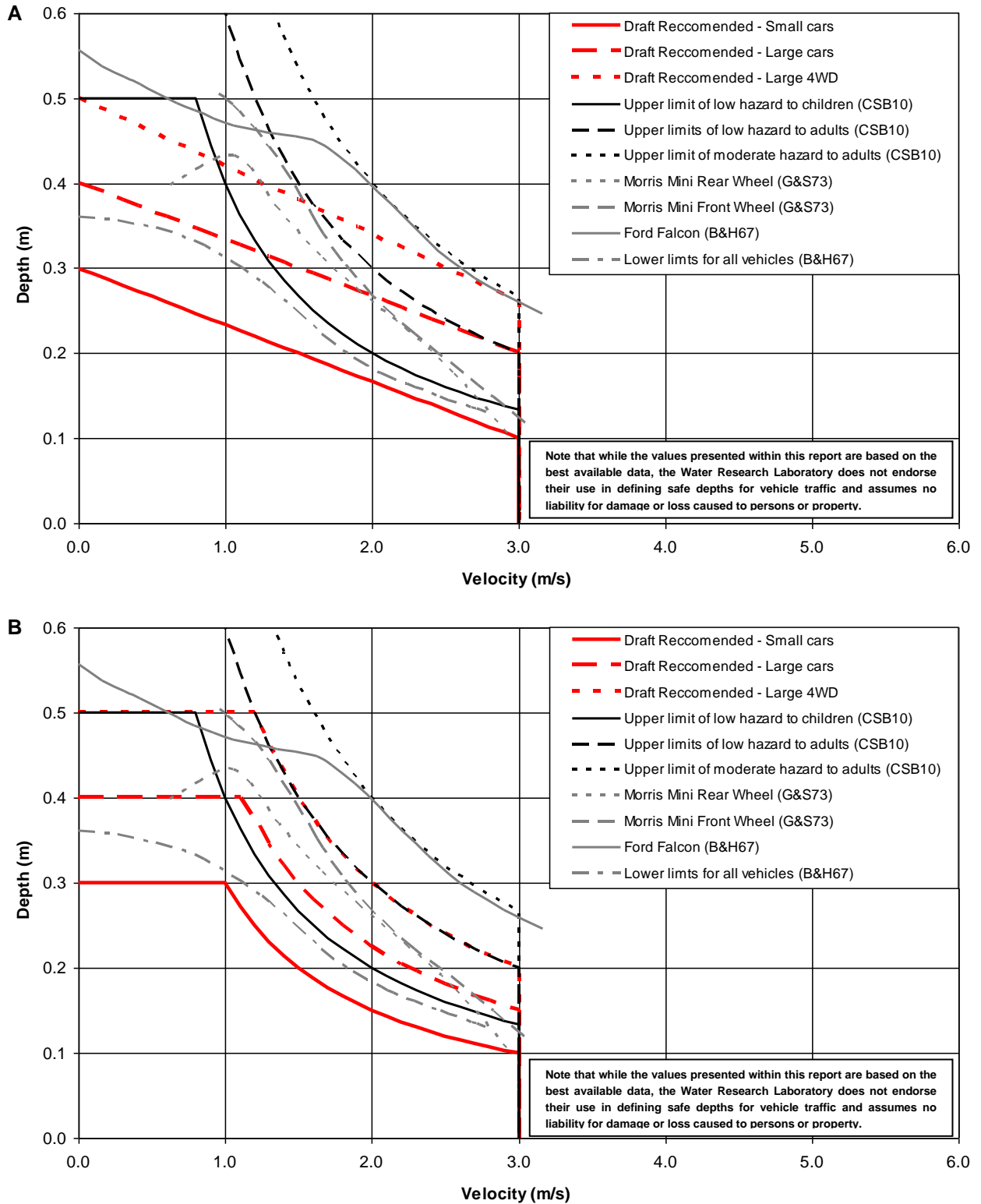

Figure 11 Possible (A) and proposed (B) *Draft* stability criteria for stationary vehicles compared to experimental and computational results.

4.   Conclusions and Recommendations

Since the early experimental studies of Bonham and Hattersley (1967) and Gordon and Stone (1973) and, to a lesser extent, the Keller and Mitsch computational study in 1993, substantial changes have occurred in car design, notably in the planform area, weight and ground clearance. Longer, wider and lower cars with better dust seals are more buoyant and more susceptible to flow-induced drag. As a result, limits of stability for contemporary vehicles are likely to be lower than the presented test results. It is therefore unlikely that the earlier results are directly applicable and conservative when applied to modern vehicles. A similar conclusion was reached by Walsh et al. (1998) who suggest that due to the changes in car design and the preliminary and limited nature of the experimental testing programs, "original data has been applied well beyond its limits and highlights the very real need for additional research," and that "practitioners should bear this in mind when applying the procedures".

Since the mid 1980s, a number of guidelines and recommendations for limits of vehicle stability have been produced.   These criteria are compared to experimental and analytical results and, with the exception of the Public Works Department (1986)/NSW Floodplain Development Manual (2005) and AusRoads (2008) criteria, are found to be non-conservative during some flow regimes. The existing Australian Rainfall and Runoff criteria (AR&R87; I.E. Aust, 1987) exceeds all experimental test results in high depth, low velocity flow regimes and extends to low depth, high velocity regimes outside the limits of experimental testing. This is of particular concern given the previous hypothesis that early tests are likely non-conservative for modern cars. While a coefficient of friction of $\mu = 0.3$, assumed when comparing experimental and analytical results, is likely conservative, the present lack of suitable data and wide range of road surfaces and tyre tread conditions prohibits the refinement of the coefficient.

Based on the available experimental and analytical data, *Draft interim* stability criteria are proposed for stationary small passenger cars, large passenger cars and large 4WD vehicles. Values are selected to provide conservative agreement with earlier experimental and analytical results, agreement where possible with existing guidelines and, most importantly, to remain within the limiting criteria for human stability under flood flow. This is important to ensure that, in the event of vehicle failure, safety was not compromised once people abandoned their cars.

Overall, we feel that the available experimental data is being applied beyond its limits to provide these *Draft interim* criteria and that they are unlikely reliable enough to be adopted as permanent safety criterion. We feel that the available data does not allow adequate assessment of:
   o   Appropriate coefficients of friction for use in flood flows;
   o   Buoyancy in modern cars;
   o   The effect of vehicle orientation to flow direction;
   o   Vehicle movement through flood waters;
   o   Information for additional categories including small and large commercial vehicles and emergency service vehicles;

However, the physical parameters governing stationary vehicle stability under flood flows is a relatively simpler problem than for persons due to the lack of external factors which can influence stability such as experience and training. In this regard, an analytical solution (computational model) using manufacturer specifications should be suitable for determining stability if correct coefficients of friction and drag are selected and the computational model is able to be verified against experimental data.

To provide robust criterion, we propose that:
   1.   The draft stability criteria presented above are adopted as interim, informal values;

2. Full scale testing of the force required to initiate vehicle movement in varying water depths is undertaken to ascertain appropriate frictional coefficients. This could be carried out in a controlled laboratory environment using a variety of surface and vehicle types and tyre conditions to examine frictional coefficient sensitivity.

3. Calibration of the Keller and Mitsch (1993), or similar, computational model using the vehicles tested within (2) and then application of the model to an agreed range of modern vehicles based on a statistical distribution of car types within Australia and their geometric properties.

4. Field verification of the adopted computational model for both stationary and moving vehicles using a full scale test in flowing water at a selected venue capable of attaining the required flows and with appropriate safety equipment in place.

5. Using the results of (3), as verified during (4), produce appropriate stability criteria for specific classes of vehicle including small and large passenger cars, 4WD vehicles, small and large commercial vehicles.

Only criteria developed in such a rigorous way are suitable for presenting as true safety guidelines. Such guidelines would be a world first and likely used worldwide just as the earlier experimental studies of Gordon and Stone (1973) and Foster and Cox (1973) have been.

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