Stability criteria for flooded vehicles: a state-of-the-art review

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Abstract

Hazard conditions related to vehicular circulation are important in flood risk management. The knowledge of vehicles stability when those are exposed to flooding is crucial for an informed flood risk management in urban areas. After losing stability, the vehicle becomes buoyant and may be washed away with potential injuries and fatalities. Therefore, the analysis of the stability of vehicles exposed to flooding is important in order to make decisions to reduce the damages and hazards. Herein a comprehensive state-of-the-art on stability of vehicles exposed to flooding is presented. The different studies have been gathered in experimental, theoretical and guidelines proposals and all of them focusing on parked vehicles. There is a clear need to conduct more research in this field by testing a greater variety of models in order to offer a more general methodology to define stability threshold for any vehicle exposed to flooding. Nevertheless, in this work, it has been demonstrate that the most safety stability criterion for vehicles exposed to flooding up to now is the proposed in the Guide AR&R.

Introduction

After a rainfall event, only a part of the runoff is captured by the inlets, while any exceedance flow may continue over the street. An inadequate inlet spacing or insufficient capacity of the underground sewer system, combined with an increase of urbanised areas all over the world, may lead to high amounts of water on streets. In this sense, the design of drainage systems should consider the dual drainage concept (Djordjevic et al., 1999; Schmitt et al., 2004; Nasello and Tucciarelli, 2005; Concha and Gómez, 2009; Nanía et al., 2015), through which certain amount of runoff is assumed to flow on the streets because only a portion of runoff can be conveyed by the sewer system. Therefore, after a sewer network is designed, an important question should be answered: what are the consequences, in terms of flood hazard, of the water running off the streets?

The hazard produced by surface water, as many authors propose in literature, is related to a combination of the hydraulic variables – water depth and velocity. That is to say that the hazard must be understood as a part of the risk, together with the vulnerability, which may be assessed from the 'easy' to calculate water depth and velocity (Sanyal and Lu, 2006; Russo et al., 2013b; Van Drie et al., 2013). These

hydraulic variables will determine the hazard level which might affect pedestrians, vehicles and properties.

The numbers of vehicles in our cities appears to be ascending. Thus, it is essential to analyse the hazard regarding vehicles exposed to flooding in urban areas. The hazard study for vehicles exposed to water flows has to be based on the determination of their stability threshold. There are three typical modes of vehicle instability: floating, sliding and toppling (Shand et al., 2011); however, the most frequent are the first two and for the most of cases the instability occurs as a combination of both, floating and sliding. On the one hand, vehicle stability analysis is simpler than pedestrian stability studies because manoeuvrability, abilities and psychological aspects do not need to be taken into account, but on the other hand the integrity of the vehicle occupants may be compromised (i.e. intangible damages).

The vehicles instability in case of floods can generate tangible direct damages due to the physical contact of water with them, but also indirect tangible damages (like loss of production) due to traffic disruption. Moreover, after losing stability, the vehicle becomes buoyant and may be washed away colliding with urban elements with potential injuries or fatalities (intangible damage). In this way, vehicles might be considered as massive debris washed away by the flood

that could generate significant economic damages and compromising pedestrian safety. A clear illustration of these damages is the massive flash flood that occurred in Boscastle (UK) on 16 August 2004 caused by an extreme rainfall event up to 200 mm in 5 h, causing millions of pounds of damages and more than 100 vehicles washed away. Furthermore, the washed out vehicles caused the blockage of a bridge, which collapsed, aggravating notably the damages. These kinds of events are not uncommon, with greater or lesser consequences, and Spanish urban areas as well were struck by massive flash floods recently. The city of Santa Cruz de Tenerife (Spain) on 19 October 2014 was struck by a flood caused by an up to 139.2 mm and 15 h duration rainfall (Figure 1), being the highest recorded precipitation in the last 70 years. The consequences of this event were tangible and intangible damages: loss of energy supply for more than 4000 users, lots of vehicles flooded and washed away, massive material damages in properties and urban elements, two injured pedestrians and one death. The death was the result of a heart attack after a woman was washed away by the water flow and became trapped under a parked vehicle.

Vehicles stability will be compromised when the hydraulic variables [i.e. flow depth (y) and velocity (v)] exceed a certain threshold, similar to the stability threshold of pedestrians exposed to water flows (Abt *et al.*, 1989; Russo *et al.*, 2013a; Xia *et al.*, 2014; Xia *et al.*, 2016; Martínez-Gomariz *et al.*, 2016; Cox, 2010). However, in the case of vehicles, their characteristics (e.g. weight, shape and design) will determine the level of stability. Car design has evolved over the years and today it is possible to find an endless variety of dimensions and designs. Thus, some of them have a hydrodynamic behaviour that may improve the stability, but probably in contrast those present smaller ground clearance that reduces the stability when they are flooded.

In this paper, a comprehensive state-of-the-art on stability of vehicles exposed to flooding is presented. The research on stability of vehicles in flooding may be classified into experimental or theoretical studies and the proposals for guidelines regarding vehicle stability. The latter are recommendations or guidelines in different countries that are rarely based on any experimental or theoretical work or otherwise the source of the proposed criterion is not provided. Most identified studies were focused on parked vehicles, possibly due to the great complexity of the stability analysis of vehicles in motion. Finally, some conclusions are presented regarding the most appropriate criterion proposed up to now and future research.

Experimental and theoretical studies

The earliest study was carried out by Bonham and Hattersley (1967) and consisted of stability analysis of a small-scale (1:25) Ford Falcon model exposed to perpendicular flow (relative to the vehicle length). The tested model was restrained by vertical and lateral threads through which forces were measured. Tests were carried out at 46 combinations of water depths ranging from 0.11 to 0.57 m and velocities from 0.48 to 3.09 m/s (prototype values). Loss of stability due to buoyancy was found to occur at a depth of 0.57 m. The obtained vertical and horizontal forces were used to calculate the friction coefficients between tyre and ground and identify lines of constant friction (in the representation of depth and velocity combinations for each instability situation) produced for friction coefficient between 0.3 and 0.5. Finally, the lower threshold of the constant friction coefficient of 0.3 was proposed as an adequate limit function. Through principles of geometric similarity, results were used to determine limits of floating and frictional stability for a range of vehicles available at the time. The buoyancy depths ranged from 0.38 to 0.58 m.

Gordon and Stone (1973) carried out experimental tests, studying the instability of a small-scale (1:16) model Morris Mini sedan exposed to parallel flow (i.e. relative to the vehicle length) in a 1 m wide flume. This vehicle was selected as representative at that time, considering it was the most susceptible to losing stability in flooding. Three modes of resistance to movement were considered (i.e. front wheels locked, rear wheels locked and all wheels locked) and as well total horizontal and vertical reaction forces were measured through fine threads in the same way as in Bonham and Hattersley (1967). Lines of constant friction coefficient (between 0.3 and 1.0) to initiate vehicle movement as a function of depth and velocity were derived for the locked front wheel condition and for the locked rear condition.
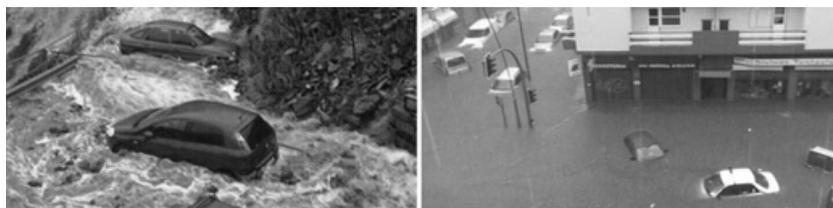

Figure 1 Flooded vehicles in the 2014 Tenerife (Spain) flood.

Keller and Mitsch (1993) undertook a theoretical study of the stability of both cars and people. Regarding vehicles, it was considered that vehicle instability occurred 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 friction coefficient and the vertical reaction force (vehicle slides). Flow depths ranged from 0.025 up to 0.4, which determined the submerged area projected normally to the flow and the water drag force (i.e. the horizontal force) was defined. Four types of cars were considered, Suzuki Swift, Ford Laser, Toyota Corolla and Ford LTD, proposing a theoretical limit of stability as a function of depth and velocity, for each one. However, the definition of these functions was dependent on the selection of friction and drag coefficients. In this study a friction coefficient of 0.3, following Gordon and Stone (1973) suggestion, and drag coefficient values of 1.1 (on the wheels) and 1.15 (on the vehicle body) were adopted.

The research on the stability of vehicles involved in flooded was taken up by Teo (2010) and Teo et al. (2012, 2013) in the laboratory of the Cardiff School of Engineering (UK). Experimental tests were carried out based on small-scale (1:43) vehicles models; Mitsubishi Pajero, BMW M5 and Mini Cooper. The tests were undertaken in two different horizontal flumes (of width 0.3 m and 1.2 m), in order to consider the influence of flume walls on the results. A comprehensive study of several oncoming flow orientations with respect to the vehicle length was carried out in order to determine lower values of water depth and velocity that can lead to vehicle instability. It was concluded that the most influential oncoming flow orientation was perpendicular respect to the vehicle length, as expected. Moreover, four tests with 1:18 scaled models were undertaken in order to validate the results of 1:43 scaled models. Linear depth–velocity relationships were established as stability thresholds for prototypes, distinguishing two clear tendencies for each vehicle: one for water depths higher than the vehicle height and the other one for water depths lower than the vehicle height. Finally, after overlapping the threshold functions, three zones were proposed: stable zone, transition zone (i.e. zone occupied for the three overlapped threshold functions) and unstable zone.

Nevertheless, although it was stated that Froude similarity had been ensured, the fact is that the weight of the scaled models was not modified according to the Froude similarity. In this sense, three conclusions might be reached: (1) the validation of the 1:43 scaled models results

Table 1 Summary of theoretical and analytical studies [adapted from Shand et al. (2011)] (1 of 2)

Reference	Bonham and Hattersley (1967)	Gordon and Stone (1973)	Keller and Mitsch (1993)	Teo (2010)
Study type	Experimental	Experimental	Theoretical	Experimental
Vehicles tested	• Ford Falcon • Results scaled to other models	Morris Mini Sedan	• Toyota Corolla • Suzuki Swift • Ford Laser • Honda Civic • Ford LTD	• MINI Cooper • BMW M5 • Mitsubishi Pajero
Vehicle age	Mid to late 1960s	Early 1970s	Early 1990s	Actuals
Ground clearance (m)	0.18	0.15	0.155; 0.17; 0.15; 0.10; 0.16	0.149; 0.117; 0.225
Scale	1:25	1:16	–	1:43 y 1:18
Vehicle orientation	Vehicle perpendicular to flow	Vehicle parallel to flow	Vehicle perpendicular to flow	Vehicle parallel firstly. Orientation effects study. Vehicle perpendicular lastly
Range of depths tested (m) (prototype)	0.11–0.57	0.12–0.57	0.025–0.375	0.645–4.816
Range of velocities tested (m/s) (prototype)	0.48–3.09	0.5–3.69	0.6->3.5	2.37–7.94
Buoyancy depth (m) (prototype)	0.57	0.42 (rear) and 0.5 (front)	Between 0.34 and 0.4 for different	Not available
Resultant equation of stability	$\frac{F_H}{\mu F_V} = 1$	$\frac{F_H}{\mu F_V} = 1$	$U_c = 2 \cdot \left(\frac{\mu F_V}{\rho_w C_d A}\right)^{1/2}$ Note: F_v and therefore U_c are evaluated separately for the front and rear axle.	$U_c = 2 \cdot \left(\frac{\mu F_V}{\rho_w C_d A}\right)^{1/2}$ Note: Both axles were blocked. Friction is divided between four wheels.
Assumed coefficient of friction	Various, although recommends 0.3	Various	0.3	–

Table 2 Summary of theoretical and analytical studies [adapted from Shand et al. (2011)] (2 of 2)

References	Xia et al. (2010)	Shu et al. (2011)	Toda et al. (2013)	Xia et al. (2013)
Study type	Theoretical	Experimental and theoretical	Experimental	Experimental and theoretical
Vehicles tested	Validation of his derived formula based on Teo (2010) experimental results	* Ford Focus * Ford transit * Volvo XC90	* Tipo Sedan * Tipo Minivan	* Honda Accord *Audi Q7
Vehicle age	Actuals	Actuals	Actuals	Actuals
Ground clearance (m)	0.149; 0.117; 0.225	0.101; 0.166; 0.218	–	0.155; 0.206
Scale	–	1:18	1:10 (Sedan) 1:18 (Minivan)	1:14
Vehicle orientation	Vehicle parallel to flow	Vehicle parallel to flow	Vehicle parallel to flow	Vehicle parallel and perpendicular to flow
Range of depths tested (m) (prototype)	0.3–3.0	0.16–0.62	0.28–0.72	0.11–0.65
Range of velocities tested (m/s) (prototype)	4.0–0.5	0.18–6.24	0.71–5.68	0.55–8.93
Buoyancy depth (m) (prototype)	Not available	Not Available	Buoyancy variable	0.45 (Honda) 0.67 (Audi)
Resultant equation of stability	$U_c = \alpha \times \left(\frac{y}{h_c}\right)^\beta \times \sqrt{2g\left(\frac{\rho_c - \rho_w}{\rho_w}\right)h_c}$ Being, α, β: empirical parameters for each vehicle y, h_c: water depth and vehicle height ρ_c, ρ_w: vehicle and water density	$U_c = \alpha \times \left(\frac{y}{h_c}\right)^\beta \times \sqrt{2gl_c\left(\frac{\rho_c h_c}{\rho_w y} - \frac{h_c\rho_c}{h_b\rho_w}\right)}$ Being, α, β: empirical parameters for each vehicle y, h_c: water depth and vehicle height ρ_c, ρ_w: vehicle and water density h_b: buoyancy depth l_c: vehicle length	$\frac{F_D}{\mu(M_c g - F_b - F_L)} = 1$ Being, F_D: water drag force M_c: vehicle weight F_b: buoyancy force F_L: lift force	Parallel $U_c = \alpha \times \left(\frac{y}{h_c}\right)^\beta \times \sqrt{2gl_c\left(\frac{\rho_c h_c}{\rho_w y} - \frac{h_c\rho_c}{h_b\rho_w}\right)}$ Perpendicular $U_c = \alpha \times \left(\frac{y}{h_c}\right)^\beta \times \sqrt{2gb_c\left(\frac{\rho_c h_c}{\rho_w y} - \frac{h_c\rho_c}{h_b\rho_w}\right)}$ Being, α, β: empirical parameters for each vehicle y, h_c: water depth and vehicle height ρ_c, ρ_w: vehicle and water density h_b: buoyancy depth l_c, b_c: vehicle length and width
Assumed coefficient of friction	–	0.39 (Transit); 0.5 (Focus) 0.68 (Volvo)	0.26 (Sedan); 0.42 (Minivan)	0.25 (parallel) 0.75 (perpendicular)

was not adequate since the weights of both scaled models (1:43 and 1:18) were not comparable; (2) the proposed threshold for prototypes vehicles is unsafe since the velocities are consistent only for vehicles much heavier than the real ones and (3) a buoyancy depth is not considered since the density of the scaled models is greater than the water density, therefore the vehicle does not become buoyant.

A development of a formula to predict the incipient velocity of flooded vehicles according to the mechanical condition of sliding equilibrium was carried out by Xia et al. (2010). This formula was validated based on the experimental results of Teo (2010) for the three tested small-scale (1:43) vehicles models. Being aware that the weight of the scaled models was not adjusted according to the Froude

similarity, it was stated that: 'In the experiments, the density of the vehicles was significantly greater than in the prototype one. This meant that the model vehicles would be more submerged at the point of initiation of motion in the flume than in the prototype case'. Therefore, in order to fix this, a relative density term was included in the derived formula. Nevertheless, the buoyancy depth was not taken into account in this study, thus the representation of the derived formula reached depths even beyond vehicle heights.

A semi-empirical formula for critical motion conditions for partially submerged vehicles was derived by Shu et al. (2011), offering a new approach where the buoyancy depth was considered. Two main assumptions in this study were that four wheels were blocked at a time, and the vehicle

was waterproof in order to consider a specific water depth that once exceeded, the vehicle becomes buoyant. As Keller and Mitsch (1993) proposed, drag coefficients of 1.15 for water depths below ground clearance and 1.10 for higher water depths were considered. It was stated that friction coefficient between tyres and ground was a key parameter in the determination of the critical incipient velocity, thus a range of potential values (0.25–0.75) should be taken into account (Kurtus, 2005; Gerard, 2006). Experimental tests were carried out as well, in order to obtain two parameters of the derived formula (α, β) related to each tested model vehicle. The tests were based on three scaled vehicle models (1:18), Ford Focus, Ford Transit and Volvo XC90, and carried out in a horizontal flume of 1.2 m width in the laboratory of the Cardiff School of Engineering (UK). Moreover, tests to determine the friction coefficient for each model vehicle were carried out, obtaining values of 0.5 (Ford Focus), 0.39 (Ford Transit) and 0.68 (Volvo XC90).

In this case, similarity principles were rigorously followed (geometric, kinematic and dynamic), thus the selected density of the models were close to that of the corresponding prototype. Two vehicle orientation angles were considered: 0° for vehicle front faced to the direction of the oncoming flow and 180° for the rear front faced the oncoming flow

direction. The results indicated no substantial difference in the conditions of incipient motion for both orientations and for all the tested vehicle models. Limits of stability (i.e. function of depth and velocity) for each prototype vehicle corresponding to the tested model vehicles were proposed; and validated on the basis of visual observations of real flooding events (2004 Boscastle flood, UK; and 2010 Var flood, France).

A variation of the Shu *et al.* (2011) formula was proposed by Xia *et al.* (2013) in order to include the effect of orientation, considering in addition 90° flow exposition (i.e. relative to the vehicle length). This time experimental tests were conducted as well in order to obtain α and β parameters of the new derived formula for each vehicle. The tests were based on two types of die-cast model vehicles at two model scales (1:14 and 1:24), Honda accord and Audi Q7. These experiments were conducted in a 1.2 m width flume of the Experimental Hall for Sediment and Flood Control Engineering, Wuhan University, China. After the tyre-ground friction coefficient of 0.75 was proposed for perpendicular orientation and 0.25 for parallel orientation for both vehicles. The validation of the limit function was undertaken with the smaller scale (1:24) model vehicles. The results showed no significant difference
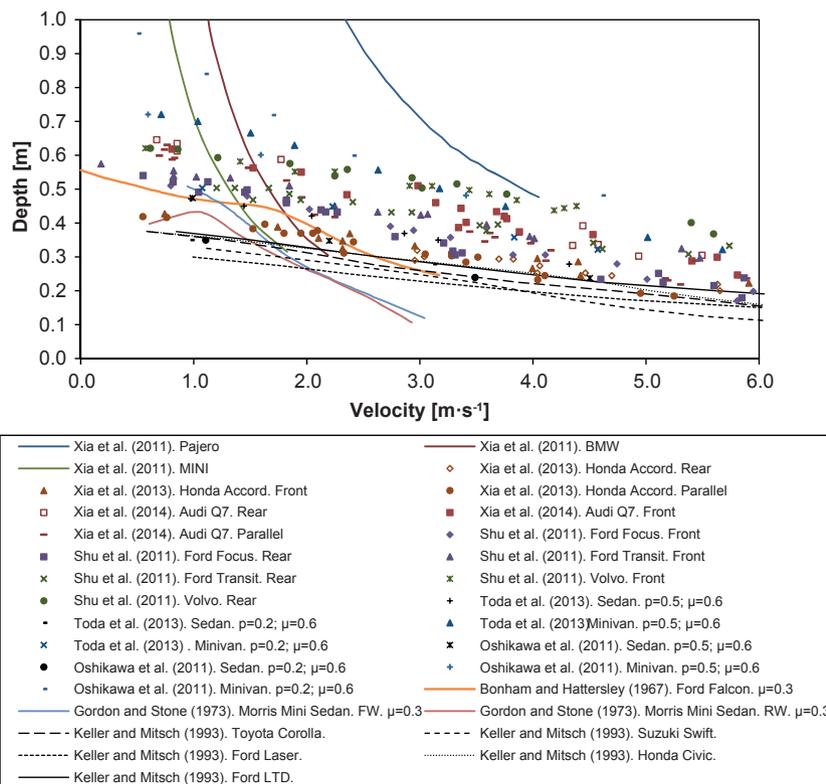

Figure 2 Representation of all the results from literature (instability points and limit functions) obtained in experimental and theoretical studies.

in instability for the two orientations when the water depth reached to the buoyancy depth.

Other experimental studies were conducted by Toda *et al.* (2013) at Ujigawa Open Laboratory, Disaster Prevention Research Institute, Kyoto University, Japan. A new approach was adopted in this case, since the decrease of buoyancy by the water inside of the partially submerged vehicles was considered. The tests were carried out in a 1.0 m width mortar flume and two types of model vehicles were tested; a sedan-type and a minivan-type with 1:10 and 1:18 scales, respectively. The similarity principles were followed and the weight of the model vehicle was adjusted by a small steel plate until the same density as the corresponding prototype was obtained. Contrary to previous works, the lift force was also considered in the force analysis. This force together with the buoyancy force decreases the gravitational force with the water depth increase. In order to consider the decrease of buoyancy by the water leaking into the vehicle, the relations between volume and water depth were obtained by measurements. The friction coefficients were measured for $0°$ and $90°$ model vehicle orientation, obtaining values of 0.26 and 0.57, respectively, for sedan-type and values of 0.42 and 0.65 for minivan-type. Although, only tests setting the model vehicles in the same direction of flow were carried out in order to determine the instability of them.

On the other hand, the results of Oshikawa *et al.* (2011) were also represented which are corresponding to the same tests procedure but $90°$ model vehicles orientation. The final conclusion is reduced to the statement that 'if the flow velocity is higher than 2 m/s and the water depth is more than 0.5, then vehicles are likely to being to move'.

A summary of all these experimental and theoretical studies is provided in Tables 1 and 2 and the representation of those in Figure 2.

Recommendations or guidelines

The main and up to date criterion regarding stability of vehicles is the one proposed in the Australian Rainfall and Runoff (AR&R) guideline. In order to update the 1987 edition of AR&R, this guideline was revised. This revision consists of 21 projects designed to fill knowledge gaps that have arisen since the 1987 edition. The 'revision project 10: Appropriate Safety Criteria for Vehicles' (Shand *et al.*, 2011) presented a comprehensive comparison between previous guidelines and recommendations for vehicle stability and experimental and theoretical studies. Eight Australian guidelines or recommendations were considered in this review, covering Department of Public Works (1986);

Table 3 Summary of theoretical and analytical studies [adapted from Shand *et al.* (2011)]

| Guideline/Recommendation	Maximum depth (y; m)	Maximum velocity (v; m/s)	Maximum ($v \cdot y$) (m²/s)	Other
Department of Public Works (1986), NSW	0.3	2.0	–	$\frac{-11 \cdot v + 3.3}{y} < 1$
Australian Rainfall and Runoff (Institution of Engineers Australia, 1987)	–	–	0.6–0.7 depending on vehicle size	–
Melbourne Water (1996) Land Development Manual: Floodway Safety Criteria	0.6	–	≤0.6 for $y_{av} \leq 0.1$ m; ≤ 0.80 for $y_{av} = 0.2$ m; ≤ 0.35 for $y_{av} \geq 0.3$ m	–
Emergency Management Australia (EMA) (1997) Manual	–	–	–	Maintain a bow wave and outfit the vehicle in depths > 750 mm
Emergency Management Australia (EMA) (1999)	0.3 (small, light low cars); 0.4 (larger, higher cars)	–	–	–
Moore and Power (2002)	–	–	–	$y \leq (0.4 - 0.0376\ v)$ for [$v \leq 1.81$ m/s]; ($v \cdot y$) ≤ 0.6 for [$v > 1.81$ m/s]
Floodplain Development Manual (2005)	0.3	2.0	–	$\frac{-11 \cdot v + 3.3}{y} < 1$
Austroads (2008)	–	–	–	$y + \frac{v^2}{2g} \leq 0.3$
Australian Rainfall & Runoff. Project 10: appropriate safety criteria for vehicles (2011)	0.3 (small passenger); 0.4 (large passenger); 0.5 (large 4WD)	3.0	≤0.3 (small passenger); ≤0.45 (large passenger); ≤0.6 (large 4WD)	–
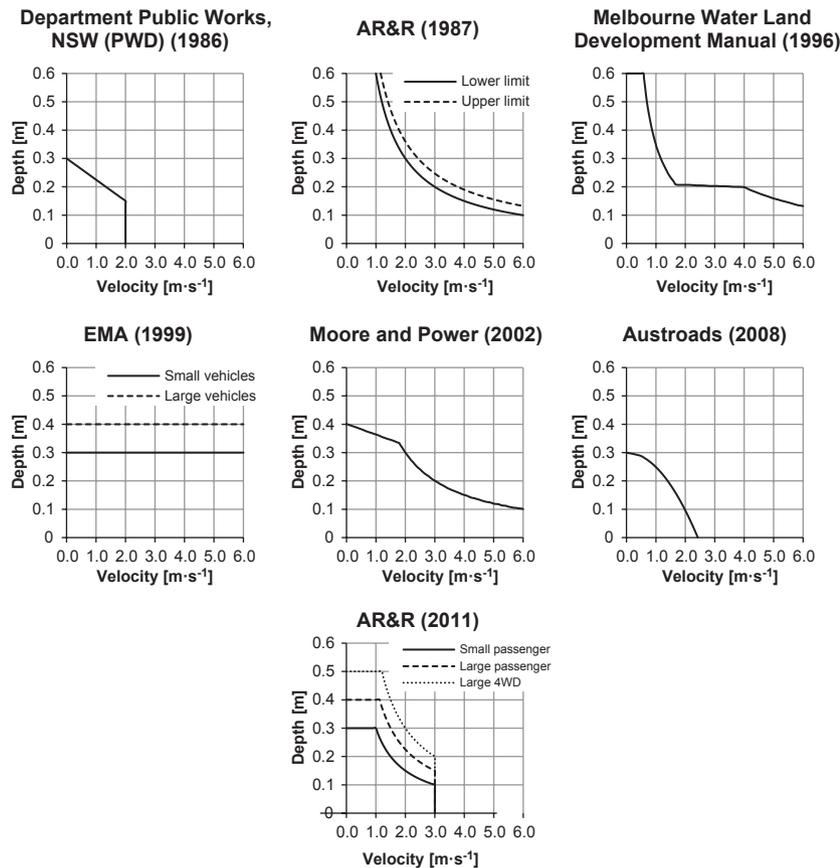
Figure 3 Representations of all the limit functions proposed in guidelines and recommendations in literature.

Institution of Engineers Australia (1987); Melbourne Water (1996); Emergency Management Australia and Queensland Government (2002); Moore and Power (2002); Department of Infraestructure Planning and Natural Resouces (New South Wales Goverment) (2005), and Austroads (2008). Others guidance documents from England, Japan, Canada and the United States reviewed within Keller and Mitsch (1993) suggest either non-quantitative limits or arbitrary limits with no theoretical background provided. A summary of the proposed criteria in each guideline is provided in Table 3 and the representation of those in Figure 3. There were only three experimental and theoretical studies assessed in the AR&R project (Bonham and Hattersley, 1967; Gordon and Stone, 1973; Keller and Mitsch, 1993), being impossible the assessment of subsequent studies (Xia *et al.*, 2010; Shu *et al.*, 2011; Toda *et al.*, 2013; Xia *et al.*, 2013) which were published very close or after new AR&R Guideline was. The final proposed draft stability criteria for stationary vehicles distinguish among three class of vehicles; small passenger, large passenger and large 4WD.

For each one, a stability limit function [i.e. product velocity times water depth ($v \cdot y$)] is offered and defining a maximum velocity and a maximum water depth (buoyancy depth). The characteristics for each type of vehicle and the proposed limit function are represented in Table 4.

AR&R criterion verification

A verification of the AR&R criterion has been carried out herein, by comparing the proposed limits with the subsequent theoretical and experimental studies which were not considered to define these safety thresholds. This criterion remains valid according to the graph presented in Figure 4, where the results of subsequent studies are presented together with the three limit stability functions. Only two instability points are found below large passenger limit, corresponding to a sedan vehicle type of Toda *et al.* (2013) and Oshikawa *et al.* (2011) studies. No instability points corresponding to large 4WD are found below the limit for those. Therefore, the AR&R criterion appears to be the best reference to date on the stability of these three types of vehicles.

Table 4 Proposed AR&R draft stability criteria for stationary vehicles (Shand et al. (2011)

Class of vehicle	Length (m)	Kerb weight (kg)	Ground clearance (m)	Limiting still water depth (m)	Limiting high velocity flow depth (m)	Limiting velocity	Equation of stability (m²/s)
Small passenger	<4.3	<1250	<0.12	0.3	0.10	3.0	$(v \cdot y) \leq 0.30$
Large passenger	>4.3	>1250	>0.12	0.4	0.15	3.0	$(v \cdot y) \leq 0.45$
Large 4WD	>4.5	>2000	>0.22	0.5	0.20	3.0	$(v \cdot y) \leq 0.60$
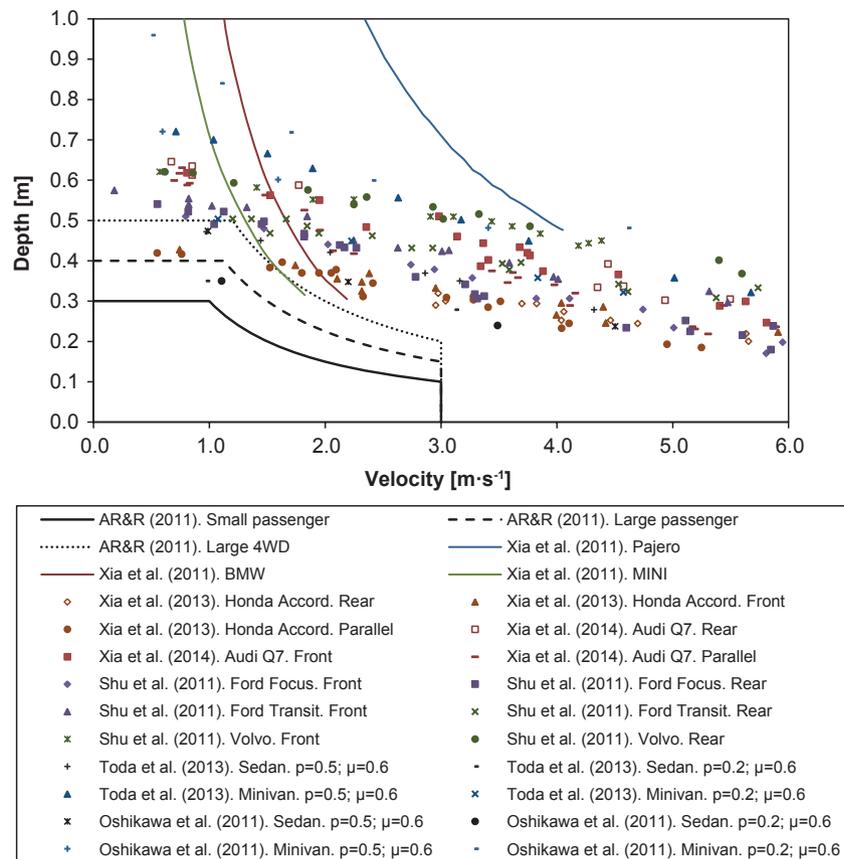
Figure 4 Verification of the AR&R criterion by comparison with results of subsequent theoretical and experimental studies.

Conclusions

Previous experimental studies regarding stability of vehicles exposed to flooding have been reviewed and it appeared that no study included a test with more than two or three scale model vehicles; therefore it was not possible to develop a general methodology for any real vehicle. The AR&R criterion was the best reference up to now to guarantee the stability of vehicles according to three types of vehicles, which has been updated and validated herein with the results of subsequent studies. Nevertheless, the proposed criterion is not flexible enough to consider any vehicle with different characteristics.

In any case, it is necessary to carry out a comprehensive experimental campaign by testing a great sample of scale vehicles in order to obtain a general method to define the stable area in the flow depth–velocity domain for any vehicle. This experimental campaign should consider a representative sample of scale models. The analysis of the most influential parameters of vehicles (ground clearance, weight, shape, etc.) regarding their stability in floods would let to us to derive a proper coefficient to sort vehicles according their stability. Therefore, a representative sample of scale models would include different types of vehicles ranged from the lowest to the highest stability. All scale models should be tested for flow conditions (i.e. sub and

supercritical flows) according to the depth–velocity domain analysed by the previous authors. Frictional and buoyancy tests must be involved in the experimental campaign in order to offer the most accurate results. Frictional tests will offer adequate frictional coefficients to ensure that those are realistic according prototype real values. Buoyancy tests will offer buoyancy depths for each tested vehicle where no flow velocity is considered. No longer be said that in order to validate the results real prototype vehicles would be able to be tested in large-scale flume.

The last objective would be to provide a tool that decision-makers in the field of urban flood risk management can employ to obtain for any design vehicle its corresponding stability threshold.

Acknowledgements

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