Static and Moving Vehicles Stability Criteria Inside Floodwaters-A Review

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***Abstract*—Vehicles are directly affected by floods and they can be easily swept away once the flow velocity and depth exceed a certain level. Globally, around 50% of the deaths from flooding occur in vehicles each year. Therefore, understanding the vehicle's behaviors inside floodwaters are of utmost importance. Herein, a comprehensive up to date review was conducted to summarize previous studies on flooded vehicle stability. Several experimental, theoretical, and numerical studies were carried out between 1967 and 2020 using different approaches and methods. For static vehicle, it was noticed that the floating depth ranged between 0.38 m and 0.69 m. However, the sliding stability limits in terms of $depth \times velocity$ function ranged between 0.3 m^2/s and 1.09 m^2/s. For moving vehicles, the floating depth found to be 0.45 m, while the $depth \times velocity$ sliding stability function has not been developed yet. Based on literatures, stability guidelines were proposed for small and large passenger vehicles. The outcomes of this study can be used as guidelines during the planning stages of roads and parking lots to ensure the safety of vehicles during flood events.**

***Index Terms*—Floods, Hydrodynamic forces, static vehicle, moving vehicle, sliding, floating**

I. Introduction

FLOODS occurrence probabilities have been increased recently due to land urbanization and climate changes caused by global warming [1], [2], [3], [4], [5]. The statistical data showed that among the hydrological disasters, floods caused the highest average mortality [6], [7], [8], [9], [10], [11], [12]. Besides, engineers and planners who are responsible for designing flood risk management projects are facing difficulties due to the shortage of hydrological data, and properties stability limits [13]. The roads were said to be the most and first affected parts stroked by floodwaters. Thus, the risks on the parked and moving vehicles have been increased and became a global issue [14]. In the United States, 50% of the total flood-related deaths occurred for the people inside their vehicles [15]. A total of 96 vehicle-related deaths were reported during the flood events in Australia between 2001 and 2017 [16]. In the Netherlands, the drowning-related deaths inside vehicles were about 33% [17]. During the roadway floods in Texas, a total of 216 people were died inside their vehicles between 1950 and 2004 [18]. In this way, vehicles were recognized as one of the most dangerous factors that increase injuries and deaths among the people during the flood events [19].

The Boscastle flood event is a clear example of the serious effects of the urban flood on the static (parked) and moving vehicles. On 16 August 2004, a flash flood hit a small city in the United Kingdom called Boscastle. An excessive rainfall event up to 200 mm in 5 hours led to a heavy flash flood event through the town. About 116 vehicles were washed away from the streets and the parking lots. Some of these vehicles and other large debris stacked underneath a small bridge blocking the waterway, finally, the bridge was collapsed due to the high-water pressure. Moreover, few numbers of these vehicles were swept away straight to the harbor without any obstacles [20]. Fig. 1 shows an example of the flooded vehicles which were swept by flash flood event in Sana'a city ,2018 [21].

Fig. 1. Flooded vehicles after flash flood event, Sana'a 2018, [21] owned by our author.

Flooded vehicles lose their stability in two common forms, sliding or/and floating [22]. Sliding instability occurs when the traction between the road surface and the tires becomes zero or neglectable. On the other hand, floating instability takes place when the upward forces equal to or more than the vehicle weight [23], [24]. Flow characteristics (velocity, depth, Froude number), vehicle specifications (weight, length, width, hydrodynamic design, ground clearance), and hydrodynamic forces are the key factors that controlling the vehicle instability modes inside floodwaters [22], [25]. Flow velocity and depth are the main hydraulic variables that having high effects on the vehicle's stability limits. Thus, flooded vehicles easily swept away and lose their stability once the flow velocity and depth exceed a certain value [24], [26].

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In this paper, an up to date comprehensive review on the flooded vehicle stability is presented. First, a detailed discussion on the main hydrodynamic forces on the flooded vehicles is introduced for both static and moving vehicles. Second, modes of instability are explained and the main factors affecting on the stability limits are discussed. Third, previous studies are summarized and discussed in two main sections namely, i) previous studies on static flooded vehicles stability and ii) previous studies on flooded moving vehicles stability. Based on the literature, safety guidelines were proposed for small and large passenger vehicles. The proposed safety guidelines were divided into three zones representing the stability of the small, medium, and large passenger vehicles. Finally, gaps and conclusions are discussed and presented at the end of the paper.

II. Hydrodynamic Forces

Parked (static) and moving (non-static) vehicles inside floodwaters are projected to several hydrodynamic force combinations. Understanding the nature of these forces is of utmost importance to develop vehicle stability guidelines. Fig. 2a and 2b illustrates the main hydrodynamic forces on a partially submerged static and moving flooded vehicle, respectively. A detailed description of these forces was presented in Table I [22], [24], [25].

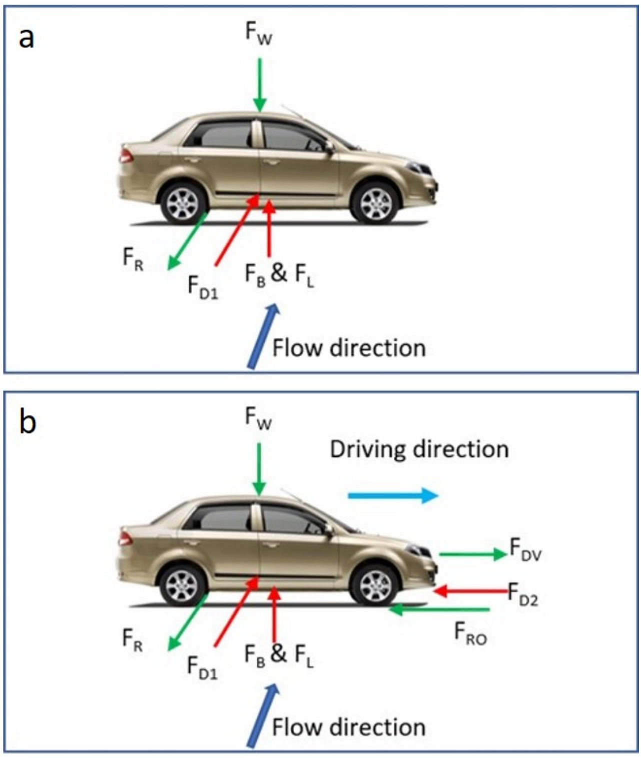

Fig. 2. Hydrodynamic forces acting on a) static vehicle b) moving vehicle, inside floodwaters [22] owned by our author.

III. Modes of Instability

Generally, flooded vehicles lose their stability in three common modes, namely floating, sliding, and toppling as shown in Fig. 3. Floating instability mode usually happens when the flow velocity is low and flow depth is high (i.e. subcritical flows). Once the vehicle under floating instability mode, the summation of buoyancy (F_B) and lift (F_L) forces is equal to or more than the vehicle weight (W) [22], [24], [25], [27]. On the other hand, sliding instability mode usually occurs at high flow velocity and low flow depth (i.e. supercritical flows). In terms of hydrodynamic forces, sliding instability mode occurs when the drag force (F_{D1}) equal to or more than the friction force (F_R) for a static vehicle, while sliding instability mode of a moving vehicle occurs when the drag forces (F_{D1}+F_{D2}) equal to or more than the summation of the friction (F_R), rolling (F_{RO}), and driving (F_{DV}) forces based on Shah et. al. (2018)[22], [24], [25].

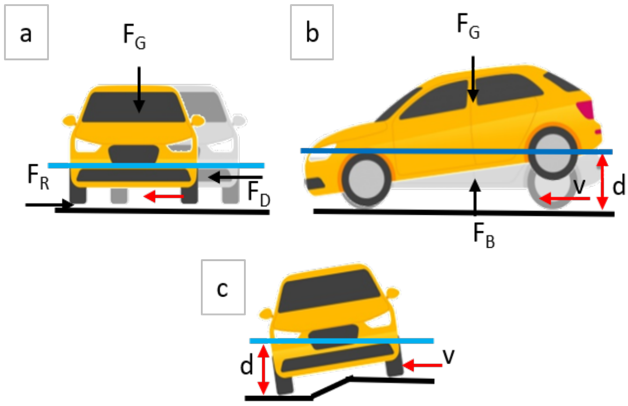

Fig. 3. Modes of vehicle instability (a) sliding, (b) floating, (c) toppling [27] owned by our author

Besides the flow velocity and depth, vehicle instability is affected by several parameters which involve, vehicle characteristics, flow orientations, road slope, tires, and road conditions. It was found out that vehicles with high ground clearance and weight are more stable. The critical vehicle orientation was found to be when the vehicleś longitudinal side facing the flow direction 90^o. Also, vehicles on a flat roads were noticed to be more stable when compared with vehicles on inclined roads. Tire's condition (new/old) and road surface roughness were recognized to have accountable effects on the stability limits of the flooded vehicles. It was observed that the vehicles with new tires and parked or moving on a rough road surface were more stable [28], [29]. Table II summarizes the main parameters which have a high effect on vehicle stability inside floodwaters.

IV. Previous Studies on Flooded Static Vehicle Stability

Several studies have been conducted since 1967 to investigate the stability of the static vehicles inside floodwaters using different approaches and methods. In this section, previous studies are summarized and discussed in three categories, experimental, theoretical, and numerical.

A. Experimental Studies

Bonham and Hattersley (1967) [30] conducted the first laboratory experimental test to investigate the hydrodynamic forces on a static vehicle inside floodwaters. A Ford Falcon vehicle model with a scale ratio of 1:25 was chosen for the experimental runs. The vehicle model was exposed to flow perpendicular to its longitudinal side (90^o). Horizontal (F_H) and vertical (F_V) forces were assessed by measuring the

TABLE I
HYDRODYNAMIC FORCES ON A FLOODED STATIC AND MOVING VEHICLE

Force	Equation	Nomenclatures	Effecting point	Description
Drag ($F_{D1,2}$)	$F_D = \frac{1}{2}\rho C_d A_d v^2$	ρ is water density, A_d is the area projected normal to the incoming flow, v is flow velocity and C_d is the drag coefficient	Projected area normal to the flow direction	It is the flow pressure and considered as the main force causing sliding instability.
Buoyancy (F_B)	$F_B = \rho g V$	V is the vehicle submerged volume; g is the gravity	Vehicles bottom plane area	It is the pressure exerted by the flow in the vertical direction against the vehicle weight. It is the main force controlling floating instability.
Lift (F_L)	$F_L = \frac{1}{2}\rho C_l A_l v^2$	C_l is the lift coefficient, and A_l is the vehicle bottom plane area	Vehicle bottom area perpendicular to the flow direction	Lift force exists when the flow is supercritical (high velocity), and it has effects on both floating and sliding instability modes.
Friction (F_R)	$F_R = \mu F_G$	F_W is the net weight of the flooded vehicle, and μ is the friction coefficient	Between the tires and ground surface	It is the reaction between the tires and the ground surface in the horizontal direction. It resists the drag force and prevents sliding instability.
Gravitational (F_W)	$F_w = F_g - (F_B - F_L)$	F_g is the vehicle weight at a dry condition, F_B and F_L are the buoyancy and lift forces	Vehicle net weight, acting against the gravity direction	It is the vehicle effective weight. It is a key parameter that resists both sliding and floating instability modes.
Rolling (F_{RO})	$F_R O = \mu_{RO} F_N$	F_W is the net weight of the vehicle and μ_{RO} is the rolling coefficient	Rolling tires and road surface	It is the force that allows the tire to roll without slipping, and it helps to keep the vehicle safe against sliding instability.
Driving (F_{DV})	$F_{DV} = (F_W(v_f - v_o))/gt$	v_f and v_o are the final and initial velocities of the vehicle, respectively and t is the time taken by the vehicle to move a certain distance	Driving directions	It is the force that exerted by the vehicle engine and it helps to keep the vehicle moving inside floodwaters.

TABLE II
MAIN PARAMETERS AFFECTING THE VEHICLE STABILITY LIMITS

Parameter	Increase stability	Decrease stability
Vehicle weight	High	Low
Ground clearance	High	Low
Road slope	Flat	Sloppy
Tires condition	New	Old
Road roughness	High	Low
Flow orientation	Other directions	90^o
Vehicle model	New	Old
Flow velocity	Low	High
Flow depth	Low	High

force on fine threads, which restrained the model in both directions. A total of 46 combinations of flow depths and velocities were applied ranging from 0.11 to 0.57 m and 0.48 to 3.09 m/s, respectively. The results showed that the floating instability occurred at the rear part of the vehicle at water depth of 0.57 m. Also, the friction coefficient between the tires and the road surface was proposed as 0.30.

Gordon and Stone (1973) [31] carried out an experimental study to investigate the stability of a Morris Mini (1: 16) vehicle model exposed to floodwaters. The vehicle model was placed inside a hydraulic flume of 1 m wide, and its longitudinal side was in parallel with the flow direction (0^o). Experimental tests were conducted under two braking modes which involved locked front wheels and locked rear wheels. The vehicle model was restrained by fine threads in both vertical and horizontal directions to measure the hydrodynamic forces. Lines of constant friction coefficient as a function in flow depth and velocity ranged between 0.3 to 1 were obtained for both braking modes. From the experimental results, it was found out that the vehicle stability was a bit higher for the front wheel locked mode when compared with the rear-wheel locked mode. This was because of the existence of the engine at the front side of the vehicle which led to increasing the weight on the front axle.

Between 1973 and 2010 no experimental studies were published regarding flooded vehicle stability [22]. However, Teo (2010) [32] restored the scientific research on flooded vehicle stability. Teo 2010[32] conducted an experimental study at the Hydraulics Laboratory of the School of Engineering at Cardiff University, UK. Three vehicle models were selected, namely Mini Cooper, Mitsubishi Pajero, and BMW M5 with two different scale ratios (1:43) and (1:18). Experimental runs were carried out inside two hydraulic flumes with different sizes (small laboratory flume, 0.3 m width) and (wide laboratory flume 1.2 m width) to find out the effects of flume width on the results. Besides, two vehicle orientations were tested, namely 0^o and 90^o. A linear velocity-depth relationship was adopted as stability thresholds for prototypes scale with two clear tendencies: one for flood depth less than vehicle height (partially submerged) and the other one for flood depth more than vehicle height (Fully submerged). It was found out that the most critical orientation was 90^o (vehicle longitudinal side facing flow direction) [32], [29],

[33].

Shu et. al. (2011) [34] investigated the flooded vehicle stability limits experimentally and analytically. Three scaled-down vehicle models (1:18) were used, namely Ford Focus, Volvo XC90, and Ford Transit. Two vehicle orientations were tested including 0^o and 90^o, and the flow depths and velocities ranged between 0.16 and 0.62 m, and 0.18 and 6.24 ms^1, respectively. Friction coefficients were evaluated for each vehicle model, and the values of 0.39 for Ford Transit, 0.50 for Ford Focus, and 0.68 for Volvo XC90 were proposed. The incipient velocity formula developed from this study was presented as follows:

$$U = \alpha \left(\frac{h_f}{h_c}\right)^{\beta} \sqrt{2gl_c\left(\frac{h_c\rho_c}{h_f\rho_f} - R_f\right)} \tag{1}$$

Where, U is the threshold velocity of flooded vehicle, α and β are empirical coefficients for each type of vehicle, h_f, h_c and l_c are the flow depth, vehicle height and vehicle length, respectively, ρ_c and ρ_f are the car density and flow density and R_f is the ratio of car height and density to buoyancy depth and water density.

Toda et al. (2013) [35] selected two vehicle models with two different scale ratios to investigate the stability of a static vehicle inside floodwaters. The vehicle models were Tipo Sedan with a scale ratio of (1:10) and a Tipo Minivan with a scale ratio of (1:18). Experiment runs were conducted inside a 1 m wide laboratory flume under various flow depths, velocities, handbrake modes, and orientations. Similarity principles between the prototype and scaled-down models were applied in terms of shape, forces, dimensions, and weight. The friction coefficients were measured for both vehicle types at three different orientations including 0^o, 45^o, and 90^o. The results showed that the coefficients of friction for the Tipo Sedan vehicle model were 0.26 at 0^o and 0.57 at 90^o, whereas for the Tipo minivan model, friction coefficients were 0.42 at 0^o and 0.65 at 90^o. Sliding instability mode was proposed to occur when the drag force F_D equal to or more than the friction force F_R. Furthermore, the results showed that the floating instability mode could be occurred at the flow velocity of 2 m/s and flow depth more than 0.5 m for Sedan vehicle types. It was observed that the critical condition for both vehicle models was 0^o with disabled handbrake. On the other hand, the safer condition was found to be at 0^o vehicle orientation with enabled handbrake.

Xia et. al. (2014) [36] conducted another experimental and analytical studies and the results were validated with the formula proposed by Shu et. al. 2011 [34] [34]. In this study, two vehicle models were selected namely Honda Accord, Audi Q7 with two different scale ratios 1:14 and 1:24. Experiment runs were performed in a 1.2 m wide and 60 m length laboratory hydraulic flume. Three flow orientations were tested namely: 0o (vehicle front end facing flow), 180o (rear end facing flow), and 90o (longitudinal side of the vehicle facing the flow). Various combinations of flow depths and velocities were applied. It was found out that the difference between the threshold velocities of the vehicle model at 0^o and 180^o directions was small. This was due to that the submerged area projected normally to the flow direction was almost the same at both orientations. Friction coefficients were measured in both directions and the following values were proposed, 0.75 (flow perpendicular to vehicle length, 90^o) and 0.25 (flow parallel to vehicle length, 0^o). Furthermore, vehicle model stability was tested on three road slopes including flat, 1:50, and 1:100. The results showed that the incipient velocity for a vehicle on a road with slope is decreased compare with the vehicle on a flat road.

Kramer et. al. (2016) [37] conducted an experimental study to investigate the stability limits of the flooded emergency and passenger vehicles. The selected passenger vehicle was VW Golf III with scale ratios of 1:9.8 and 1:1, and the emergency vehicle was LF 10/6 with a scale ratio of 1:13.1. Different vehicle orientations were tested including 0^o, 90^o, and 45^o. The results showed that the flow angel has significant effects on the sliding stability limits. The critical orientation of both models was found to be at an angle of 45^o. It was noticed that the passenger vehicle started to float at 0.45 m, which is lower than the floating depth of the emergency vehicle model by 0.28 m. Results showed also that the buoyancy depth of the prototype was higher than the buoyancy depth of the scaled model, which was due to the sealing capacity difference between scaled-down and prototype models. Finlay, water depth of 0.3 m, and 0.6 m were recommended for the satisfy criteria of passenger vehicles and the emergency vehicle, respectively.

Smith et. al. (2017) and (2020) [38] and [39] investigated the flooded vehicle stability by conducting an experimental test on scaled-down and prototype vehicle models. To investigate the floating instability limits, two passenger cars were chosen which involves, Toyota Yaris and Nissan Patrol (4WD) at the prototype scale. On the other hand, the Toyota Yaris vehicle with scale ratio of 1:18 was selected to investigate the sliding instability limits. Experimental tests carried out under three flow conditions, namely sub-critical, super-critical, and critical flows. Velocity depth ($d \times v$) stability limit expressions were introduced for both vehicle models and the values were $v \times d \leq$ 0.3 for Toyota Yaris and $d \times v \leq$ 0.6 for Nissan Patrol (4WD).

Martinez et. al. (2017) [24] proposed a new methodology to describe the stability limits of the flooded vehicles by conducting an extensive experimental study. A total of 14 vehicle models with different scale ratios were chosen. The experiment was carried out in 0.6 m wide and 20 m length laboratory hydraulic flume. Several combinations of water depths and velocities were applied. The friction coefficients were tested for all models, and the values ranged between 0.52 to 0.62 based on the vehicle type. The buoyancy depths were measured separately for each vehicle model and a new formula was proposed to assess it (Equation 2).

$$h_b = \frac{Mc}{\rho_f l_c b_c} + GC \tag{2}$$

Where, l_c, b_c, and h_b are the vehicle length, vehicle width, and buoyancy depth, respectively, M_c is the vehicle mass, f is the water density, and GC is the ground clearance. Furthermore, stability coefficient (SC_{mod}) were developed based on three factors including ground clearance GC, vehicle plan area P_A and vehicle mass M_c (Equation 3).

$$SC_{mod} = \mu\frac{M_c GC}{P_A} \tag{3}$$

Finally, a general velocity-depth stability equation which can be used to assess the stability limit for any vehicle model was proposed (Equation 4)

$$v.y = 0.0158SC_{mod} + 0.32 \quad (4)$$

Shah et .al. (2018) [40] conducted an experimental study to investigate the stability limits of a scaled-down (1:24) Volkswagen Scirocco vehicle model inside floodwaters. The vehicle model was tested on a flat surface with the condition of rear tires locked. The novelty of this work involves that the limits thresholds for the static vehicle were assessed at all orientations. The results showed that the sliding instability occurs at high flow velocity and low flow depth, while the floating instability mode occurs when the flow velocity is near to zero and flow depth is high. Furthermore, depth x velocity ($d \times v$) factor was obtained for all orientations. Results reveled that, at 0^o and 360^o vehicle model orientations the $d \times v$ was 0.0168 m^2/s, while at 90^o the $d \times v$ was 0.0144 m^2/s.

Fig. 4 summarizes the previous experimental studies and shows the stability limits of the flooded vehicles in terms of $d \times v$ function. From the previous studies, it was found out that the minimum and maximum floating depths were 0.69 m (Mercedes G55 a MG) and 0.38 m (Mimi Cooper), respectively. On the other hand, the maximum sliding instability limit was obtained by Shu et. al. (2011) [34] for Volvo XC90 as shown in Fig. 4. The minimum sliding instability limit was found to be at the value of $d \times v$ = 0.3 m^2/s for the Toyota Yaris passenger vehicle model which examined by Smith et. al. (2017) [38]. Other experimental results were located between these limits. However, all studies showed the same pattern i.e. stability limits decreased with the increment of flow velocity as shown in Fig. 4. Based on the previous experimental results, stability limits for small and large passenger vehicles were proposed, as shown in Fig. 5.

B. Theoretical Studies

Previous theoretical studies on the vehicleś stability inside floodwaters were assessed based on the equilibrium of the hydrodynamic forces and vehicle characteristics. The earliest theoretical study related to flooded vehicle stability was conducted by Keller and Mitch (1993) [41] in 1993. The flood assumed to hit the vehicle body in the longitudinal side (90^o). With that regard, five-passenger vehicle models, namely Suzuki Swift, Ford Laser, Toyota Corolla, Honda Civic, and Ford LTD were tested. The flow depth ranged between 0.025 m and 0.375 m and the friction coefficient was assumed to be 0.30. The vertical and horizontal forces were evaluated at both front and rear tireś axles at different flow depths. Horizontal forces were evaluated by determining the drag force acting on the submerged part of the vehicle, while the vertical forces were evaluated by determining the center of buoyancy and weight distribution obtained from the manufacturer specifications. Floating instability mode was proposed to have occurred when the vertical reactions less than or equal to zero and sliding failure mode was proposed to occur when the horizontal force was greater than or equal to the restoring force. In addition, the drag coefficient was proposed to be 1.1 and 1.15 for flow depth below and above the vehicle chassis, respectively [41]. Finally, the stability velocity threshold formula was introduced (Equation 5).

$$U = \sqrt{\frac{2\mu F_v}{\rho C_D A_D)}} \quad (5)$$

Xia et. al. 2011 [42] developed a formula of incipient velocity to describe vehicleś stability limits in floodwaters based on the sliding hydrodynamic forces equilibrium (Equation 6). The developed equation was validated using the experiment results of Teo et. al. (2011) [33]. One flow direction was taken into consideration in this study, namely the rear of the vehicle facing the incoming flow (360^o).

$$U = \alpha \left(\frac{h}{h_c}\right)^{\beta} \sqrt{2g\left(\frac{\rho_c - \rho_f}{\rho_f}\right) h_c} \quad (6)$$

Where U is the threshold velocity of the flooded vehicles, and are empirical parameters for each vehicle h, hc are the water depth, and vehicle height ρ_c and ρ_f are the vehicle and water densities.

Table III summaries previous theoretical studies on flooded vehicles. Fig. 6 presents the flooded vehicle stability limits which were obtained from the previous theoretical studies in terms of $d \times v$ diagram. It was found out that the stability limits obtained by Keller and Mitsch (1993) [41] were lower than Xia et. al. (2011) [42] stability limits for all vehicle models. This was due to the huge improvement in the vehicle design between the time period of 1993 and 2010. Furthermore, it was observed that the maximum sliding instability limit was found to be for the Volvo XC90 vehicle model which obtained by Shu et. al. (2011) [34], while the minimum sliding instability limit was for the Ford Laser vehicle model which was investigated by Keller and Mitch (1993) [41]. Base on the previous theoretical studies outcomes, stability limits for the small and large flooded passenger vehicles were proposed as shown in Fig. 7.

The proposed stability limits from both experimental and theoretical studies showed a good agreement as shown in Fig. 8. Later, the proposed stability limits were categorized into three zones (a, b, and c). At zone (a) all vehicle sizes are considered to be safe against sliding and floating instability modes. At zone (b), small passenger vehicles may lose their stability, while large passenger vehicles are considered to be safe. At zone (c) all passenger vehicle sizes may lose their stability either by floating or sliding. The stability limits of the medium-size passenger vehicles located at zone (b) and the value depends on the vehicle size. For medium-sized passenger vehicles, it is recommended to apply the stability limit of the small passenger vehicles.

C. Numerical Studies

Using numerical approaches in investigating the flooded vehicle stability helps to capture the results in detail. This allows a deep understanding of the different hydrodynamic forces acting on the vehicle body as well as gives a detailed description of the flow behavior at the vehicle vicinity. The earliest numerical study on flooded vehicle stability was conducted by Xia et. al. (2011) [43]. This study focused on the flood hazard risk on both vehicles and people in floodwaters. An existing 2D hydrodynamic model solved

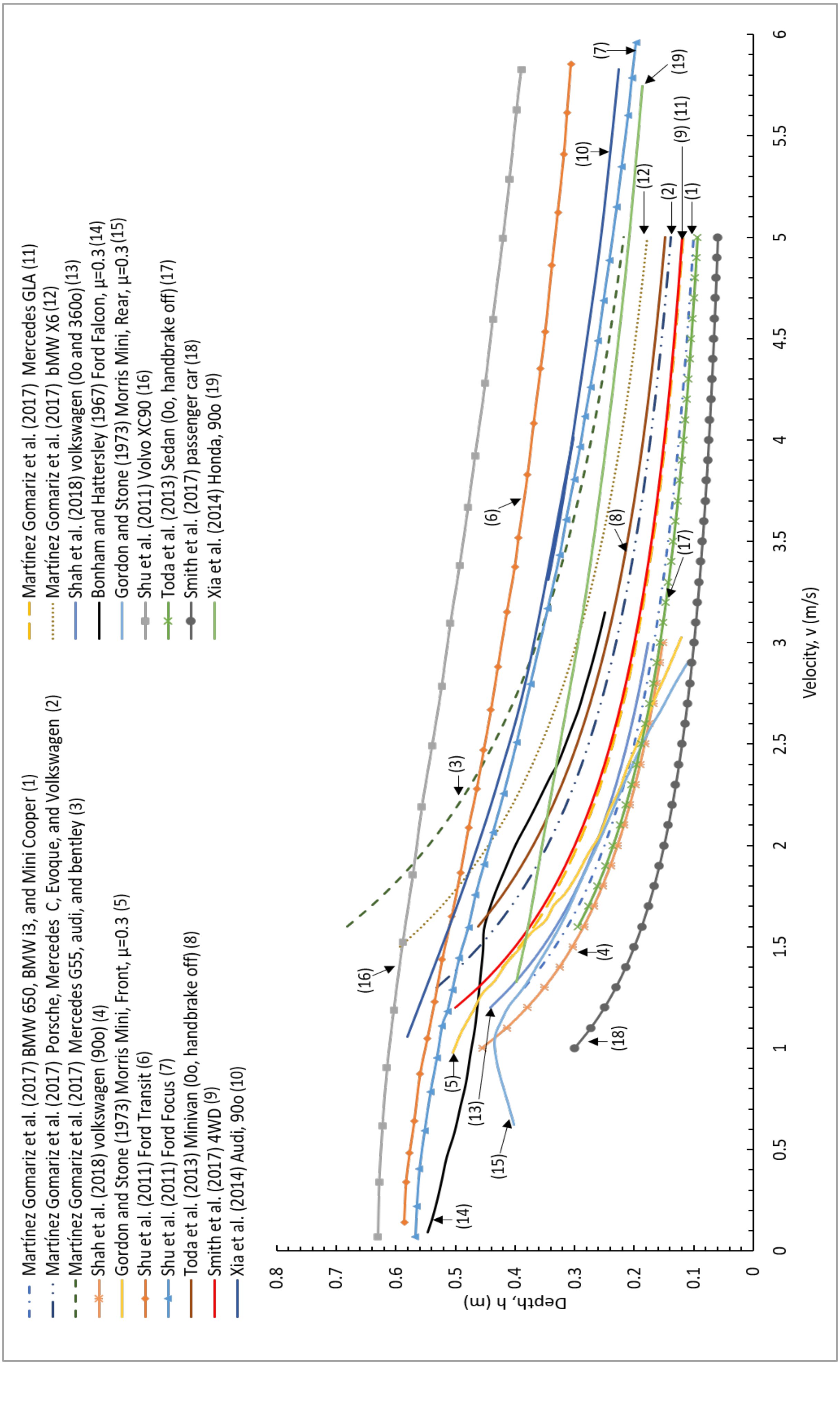

Fig. 4. Comparison between the previous experimental studies on the stability limits of the flooded vehicles between 1967 and 2020

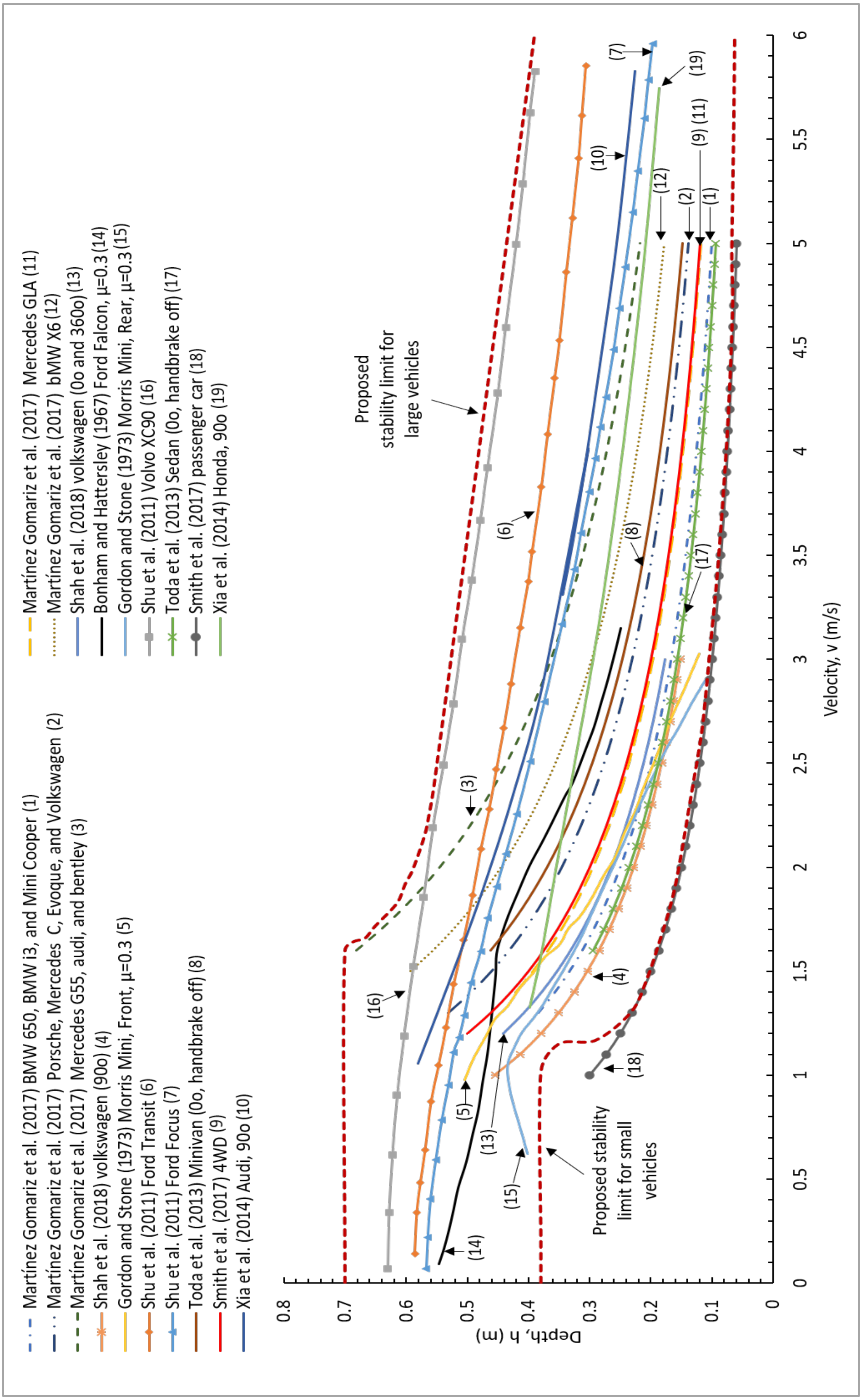

Fig. 5. Proposed stability limits based on the previous experimental studies (1967 -2020)

TABLE III
SUMMARY OF THE THEORETICAL STUDIES ON STATIC FLOODED VEHICLES

Parameters \ Reference	[41]	[42]
Vehicle models	Suzuki Swift, Ford Laser, Toyota Corolla, Honda Civic, and Ford LTD	Mini Cooper, Mitsubishi Pajero, BMW M5
Method	Hydrodynamic forces equilibrium and buoyancy center	Sliding hydrodynamic forces equilibrium
Velocity threshold equation	$U=\sqrt{\frac{2\mu F_v}{\rho C_D A_D}}$	$U=\alpha\frac{h}{h_c}\beta\sqrt{(2g((\rho_c-\rho_f)/\rho_f)h_c)}$
Validation	-	[29] experimental study
Floating depth (m)	0.34 to 0.4	-
Friction coefficient		-
Vehicle orientations	90^o	0^o and 180^o

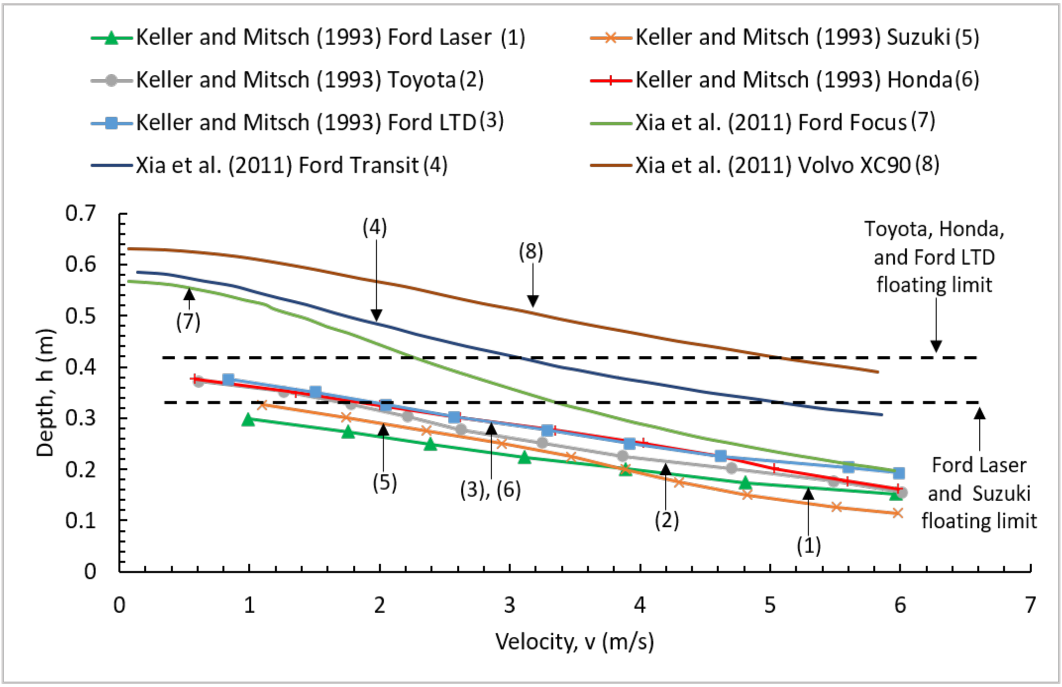

Fig. 6. Comparison between the previous theoretical studies on the stability limits of the flooded vehicles between 1993 and 2020

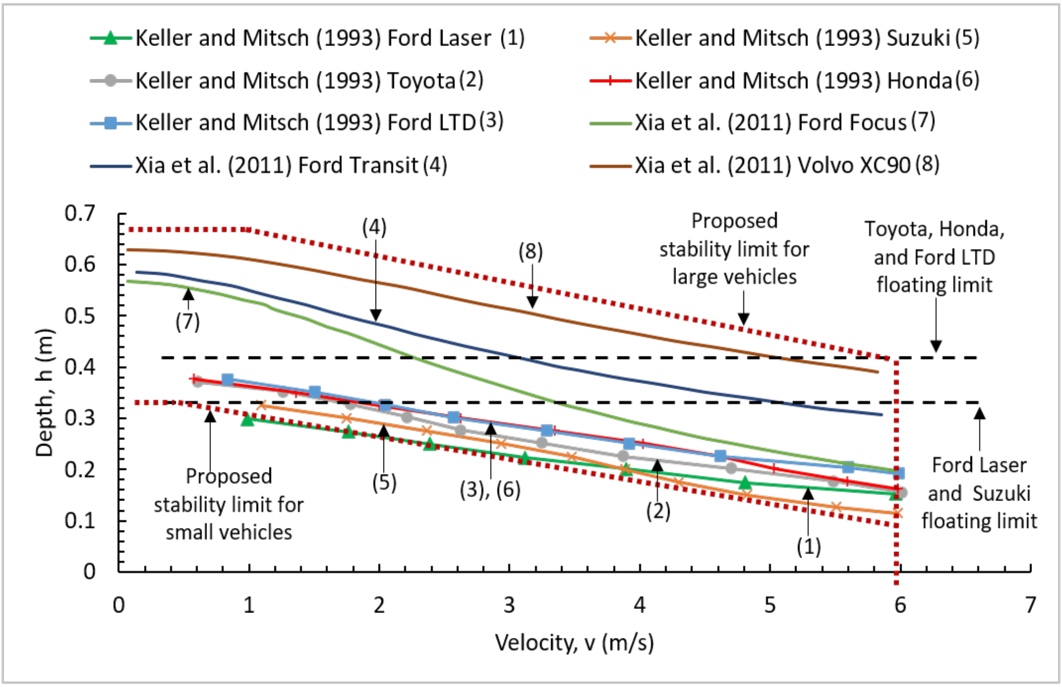

Fig. 7. Proposed stability limits of the flooded vehicles (small and large) based on the previous theoretical studies between 1993 and 2020

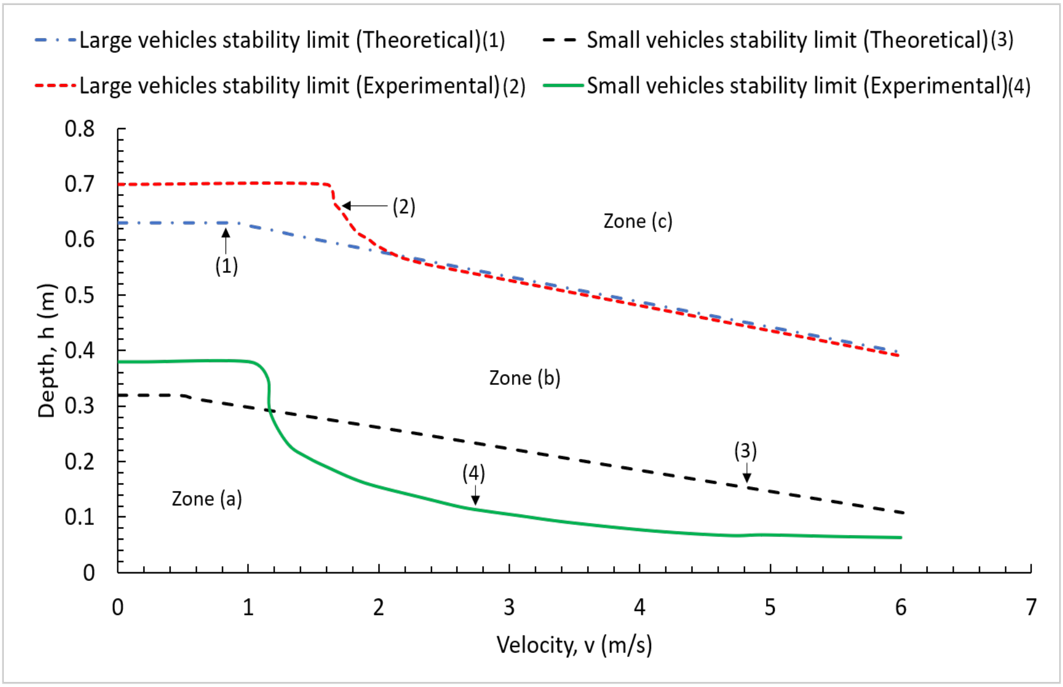

Fig. 8. Comparison between the proposed experimental and theoretical flooded vehicle stability limits

by the finite volume method (FVM) was chosen to conduct the numerical runs. The depth-averaged 2D shallow water equation (Equation 7) was used to solve the fluid flow based on an unstructured triangular mesh.

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial G}{\partial y} = \frac{\partial e}{\partial x} + \frac{\partial g}{\partial y} + s \tag{7}$$

Where U is the vector of conserved variables, S is the bed friction, bed slope, and the Coriolis force source term, E and G are the flow convective flux vectors in the x-axis and y-axis, respectively, and e and g are the turbulent stresses diffusive vectors in the x-axis and y-axis, respectively. Numerical simulation results were validated with Xia et. al. (2011) [42] incipient velocity formula, and a good agreement was noticed. In this study hazard degree (HD) expression (Equation 8) was introduced and used to evaluate the hazard corresponding degree.

$$HD = Min(1.0, U/U_c) \tag{8}$$

Where U_c is,

$$U = \alpha \left(\frac{h}{h_c}\right)^{\beta} \sqrt{2g\left(\frac{\rho_c - \rho_f}{\rho_f}\right) h_c} \tag{9}$$

Where U and Uc are the flow and critical velocity, respectively. Based on HD, the vehicle will be safe if HD=0 ($U << Uc$), while vehicles will be unsafe if HD approaches 1.0 ($U >= Uc$). For validation purposes, three real flood events were stimulated by the developed model to assess the corresponding hazard degrees related to vehicles and people. A good agreement between the predicted results from the developed algorithm and the real flood conditions was observed.

Arrighi et. al. (2015) [44] investigated vehicle stability numerically using the Computational Fluid Dynamics (CFD) toolbox in OpenFOAM. A Ford Focus vehicle model was used for the numerical simulation runs which were experimentally tested by Shu et. al. (2011) [34]. Different combinations of flow depths and velocities were applied with two different vehicle orientations, 0^o and 360^o. For 0^o vehicle orientation, 13 different combinations of flow depth and velocity were applied, while 10 combinations were tested for 360^o vehicle orientation. At each combination drag and lift coefficients were calculated. The numerical simulation results were validated with Shu et. al. (2011) [34] experimental results, and a good agreement between both studies was noticed. Finally. a mobility parameter θ_v was introduced to describe the flooded vehicle's stability as a function of Froudes number (Equation 10).

$$\theta_v = \frac{2L}{H_v - h_c} \cdot \left(\frac{\rho_c(H_v - h_c)}{\rho(H_v - h_c)} - 1\right) \tag{10}$$

Where, H_v, h_c, and L are the vehicle height, ground clearance, and length of the vehicle, respectively, ρ_c and ρ are the vehicle density and the water density, respectively.

Albano et. al. (2016) [45] conducted three dimensional (3D) numerical simulation to investigate the effects of groynes on the washed debris including vehicles during urban flash floods. A Smoothed Particle Hydrodynamics (SPH) model developed by Amicarelli et. al. (2015) [46] was used. SPH shows the hydrodynamics movement and forces of the bodies which swept away by the free-surface flow in 3D view. The results concluded that the upstream and downstream groynes can be considered as an effective solution to decrease the risk due to the washed debris movement. Further, it was found out that different groynes geometry shapes had different effects on the washed bodies' position during the flood events. Later, the numerical results were validated experimentally and a good agreement between both results was obtained.

Gómez et. al. (2018) [47] carried out a numerical study to assess the flooded vehicle stability using a 3D commercial software (Flow-3D). FLOW-3D employs the Finite Volume Method (FVM) to solve the turbulent models and the governing equations, while the Volume of Fluid (VOF) approach was used to define the free surface flow [48]. In this study, the $K - \epsilon$ turbulence model was selected, and a Mercedes Class C vehicle model was tested at 90^o vehicle orientation. Finlay, numerical simulation results were compared with the experimental results, and a good agreement between both results was noticed.

Al-Qadami et. al. (2020) and (2021) [21], [49] investigated the floating stability limits of a small size passenger vehicle numerically. Computational fluid dynamic commercial code (FLOW-3D) was chosen to solve the fluid flow equations and turbulence models. The numerical simulation was conducted under six degree of freedom and coupled motion conditions. The boundary conditions and numerical setups is shown in Fig. 9 The results should that the floating depth was 0.0127 m and the buoyancy force was 0.593 N (for scaled-down vehicle model). Later, numerical results were compared with the previous experimental study and the variation was around 1.94% and 0.50% in terms of flow depth and buoyancy force, respectively. Table IV summarizes the previous numerical studies regarding vehicle instability inside floodwaters.

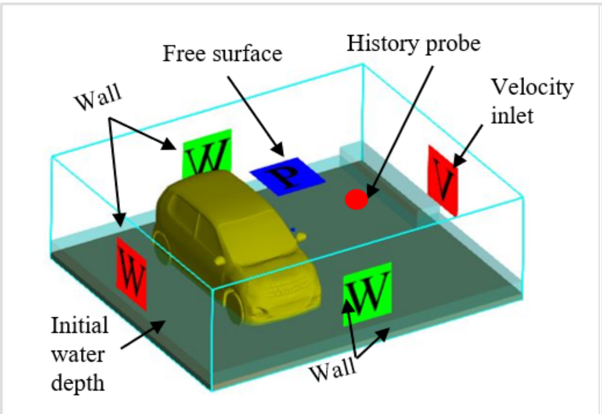

Fig. 9. Boundary conditions and numerical setups [49] owned by our author

V. Previous Studies on the Flooded Moving Vehicle Stability

Driving through flooded roadways is accounted as a high potential cause for deaths among the people during flood events. However, the previous studies investigated the flooded moving vehicles stability limits are insufficient, only one experimental study was published in this regard. That study was conducted by Shah et. al. (2018) and (2020) [50], [51] on a medium size passenger vehicle (Perodua Viva) with a scale ratio of 1:10. The vehicle model was selected because it was represented the typical size of the Malaysian passenger vehicles. To ensure that the experimental results on the scaled model can be applied on the prototype model, the scaled model was following Froudes similarity criteria in all aspects including dynamic, geometric, and kinematic similarities. A series of experimental tests were carried out in the hydraulics laboratory, Universiti Teknologi PETRONAS, Malaysia. The experiments were carried out inside a water-retaining pond with dimensions of 5 m x 4.25 m. Flow velocity (v), flow depth (y), and the time taken by the vehicle model to pass certain distance (t) were recorded and measured. To observe the vehicle model movement in x and y direction accurately, a monitoring laser beam was used. Different combinations of water depth and velocity were applied. The flow velocity values ranged between 0.25 and 0.60 m/s, while the flow depth ranged between 0.039 and 0.083 m (subcritical flow). It was observed that the vehicle started to float at 0.0457 m (scaled-down model), and below this depth sliding instability mode was noticed [50]. Figures 10a and 10b show sliding and floating instability modes , respectively.

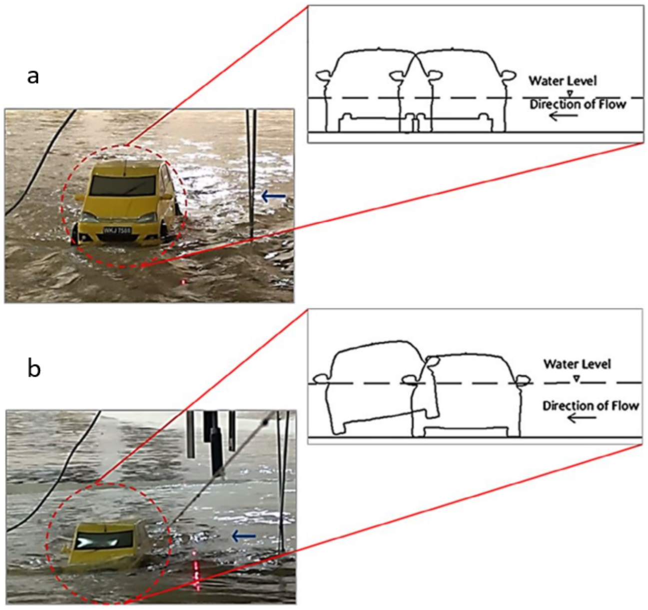

Fig. 10. Instability modes during lab tests (a) sliding, (b)Floating [51] owned by our author

The friction coefficient between the road surface and the tires were tested experimentally in the direction of floodwaters streamlines and it was about 0.52. Also, rolling friction which keeps the vehicle moving and in touch with the ground was tested and it was about 0.092. Finally, the instability threshold equation was proposed (Equation 11).

$$v = \sqrt{\frac{2 * (\frac{(W-F_B)*(v_f - v_o)}{gt} + \mu F_N + \frac{Wb}{\sqrt{r^2-b^2}})}{\rho C_d A_d}} \qquad (11)$$

Where v is the vehicle threshold velocity, W is the vehicle curb weight, g is the gravity, ρ is the water density, F_B is the buoyancy force, t is the time, v_f and v_o are the final and initial velocity of the vehicle respectively, μ is the friction coefficient, F_N is the net vehicle weight, r is the tire radius, b is the distance from the middle of the center of the axle toward the tire no longer touching the ground, C_D is the drag coefficient, and A_D is the submerged area of the vehicle projected normally to the flow direction [50]. Table V summarizes the experimental studies on the flooded moving vehicle.

VI. Gaps and Recommendations

From the literature, it was observed that between 1967 and 2021 a total of 17 studies were published regarding vehicle stability inside floodwaters. Among them, 16 (94%)

TABLE IV
SUMMARY OF THE NUMERICAL STUDIES ON STATIC FLOODED VEHICLES

Vehicle model	Software	Six degrees of freedom	Output guidelines
–	2D hydrodynamic model	Yes	$HD = Min(1.0, U/Uc)$
Ford Focus	OpenFOAM	No	$\theta_v = \frac{2L}{H_v - h_c} \cdot \left(\frac{\rho_c (H_v - h_c)}{\rho (H_v - h_c)} - 1 \right)$
–	(HPS) Smoothed Particle Hydrodynamics	Yes	–
Mercedes Class C	FLOW-3D	No	–
Basic vehicle model	FLOW-3D	Yes	hb = 0.0127 m, Fb = 0.593 N (for scaled down model)

TABLE V
SUMMARY OF THE EXPERIMENTAL STUDIES ON THE FLOODED MOVING VEHICLE

Parameters	Values
model	Perodua Viva
Scale ratio	1:10
Vehicle mode	Non-stationary
Vehicle orientation	90^o
Road slope	Flat
Flow condition	Subcritical
Floating depth (scaled model), (m)	0.0457
μ_R	0.52
μ_{RO}	0.09
Threshold velocity equation	Equation 11

studies were totally focused on the stability of the static flooded vehicles, while only one (6%) study was conducted to investigate the stability limits of the vehicles in movement as shown in Fig. 11 [50]. Furthermore, that one study was carried out using a scaled-down model under subcritical flows only, while the vehicle response under supercritical flows was not considered. Besides, there is no such numerical or theoretical studies were published regarding stability limits of vehicles in movement. This indicates the stability limits of the flooded vehicles in movement are not sufficient and more investigations are needed.

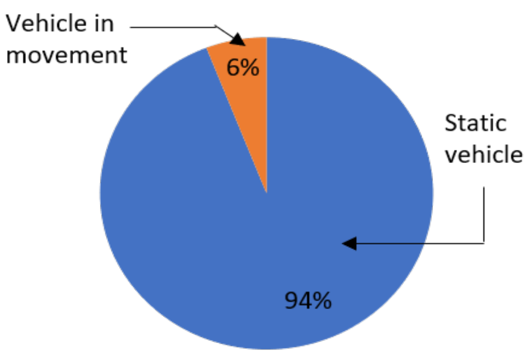

Fig. 11. Previous published studies regarding vehicle stability in floodwaters between 1967 and 2021

Previous studies were conducted using different approaches, namely i) experimental, ii) numerical, and iii) theoretical. The experimental approach was the common method being used with a percentage of 62% (11 studies), while 25% (5 studies) and 13% (2 studies) for numerical and theoretical approaches, respectively as shown in Fig. 12. In terms of numerical studies, only two of them directly explained the hydrodynamic forces on the flooded vehicle body which were conducted by Alrighi et al. (2015) [44] and Gómez et. al. (2018) [47]. Furthermore, these two studies were conducted on vehicles at static mode at which the vehicles were considered as a fixed object and the six degrees of freedom and coupled motion condition was disabled. Therefore, the sliding and floating instability modes could not be recognized in numerical simulation. However, Al-Qadami et. al. (2020) and (2021) [21], [49] investigated only the floating instability mode under six degrees of freedom and coupled motion condition, while sliding instability was not considered.

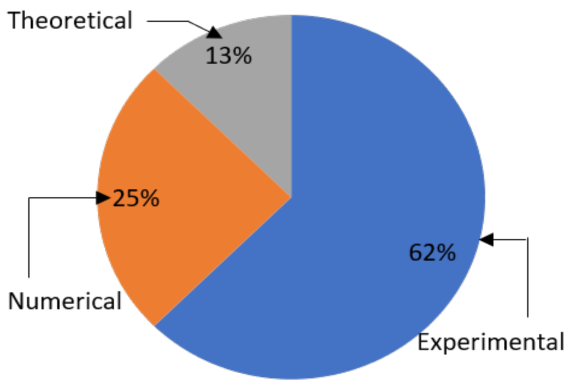

Fig. 12. Approaches distribution that being used between 1967 and 2021

Regarding the total number of vehicles being tested, it was found that a total of 40 vehicles were considered in all approaches between 1967 and 2021. Among the total number, 39 vehicles were tested under the static mode, while one only was examined under movement mode. Figure 13 shows the distribution of vehicles number being used in each approach, at which 30 (74%) in experimental, 8 (21%) in theoretical, and 3 (4%) in numerical. On the other hand, it was noted that all previous studies regarding sliding instability limits were conducted using scaled models, while only two studies were used full-scale vehicles to investigate the floating instability limits. Table VI shows the distribution of the model sizes being used in the previous experimental, numerical, and theoretical studies. From Table VI it is clear that sliding stability limits of flooded vehicles at full-scale have not been tested yet experimentally and numerically.

From the previous discussion, it is clear that the static vehicle instability limits inside floodwaters have been investigated extensively when compared with the vehicle in movement. Vehicles at static mode have been tested in different sizes (small, medium, large, and four wheels driving) as well as at different orientations ($0^o, 45^o, 90^o$ and 180^o). Also,

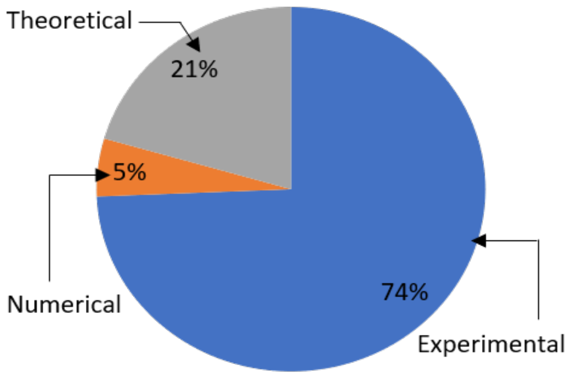

Fig. 13. Vehicles number that being used in each approaches between 1967 and 2021

TABLE VI
NUMBER OF VEHICLE MODELS THAT WERE BEING USED PREVIOUSLY

Approach	Floating test		Sliding test	
	Scaled	Prototype	Scaled	Prototype
Experimental	30	3	30	0
Numerical	2	0	2	0
Theoretical	8	8	8	8

static vehicle at different submergence conditions (fully and partially submerged) have been investigated under subcritical and supercritical flows. The stability limit functions ($v \times d$) for static vehicle were introduced for several vehicle models [29-47]. However, 97% of these studies were conducted using scaled-down models to study floating stability limits and 100% to study sliding stability limits. Furthermore, all hydrodynamic forces on the vehicle sides were not measured directly instead, basic equations were used. On the other hand, previous studies on the stability limits of the flooded vehicle in movement are insufficient. As previously mentioned, there is only one experimental study investigated the stability of moving vehicle inside floodwaters. In that study, one scaled-down vehicle model was tested with one flow orientation (90^o) and under subcritical flows. In terms of numerical simulation under six degrees of freedom and coupled motion conditions, there is no such study was published. Therefore, more experimental, numerical, and theoretical investigations are required regarding vehicle in movement stability inside floodwaters to come up with more accurate and suitable safety guidelines.

VII. CONCLUSIONS

In this paper, a comprehensive review was conducted to summarize the previous studies related to the vehicles' stability inside floodwaters. It was observed that almost all published works were focused on the stability limits of the static vehicle, while the investigations on the stability of the flooded moving vehicle were not sufficient. Also, the literature showed that no such study investigated the sliding instability mode using a full-scale model (prototype) instead, all studies were conducted using scaled-down models. For static passenger vehicle, it was found out that the minimum floating depth was 0.38 m, and the maximum was 0.69 m, while the highest $depth \times velocity$ ($d \times v$) sliding instability function was 1.09 m^2/s and the lowest was 0.3 m^2/s, depend on the vehicle size. For the vehicle in movement, the floating depth was found to be 0.45 m, and the $d \times v$ sliding instability function has not been developed yet. Based on the literature, safety guidelines were proposed for small and large static passenger vehicles. Finally, it is recommended that more studies and investigations on flooded moving vehicles are required to come out with more accurate and useful guidelines.

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