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Chapter

## Impact and Mitigation Strategies for Flash Floods Occurrence towards Vehicle Instabilities

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#### Abstract

This chapter presents a flood risk management system for vehicles at roadways, developed from extensive experimental and numerical studies on the impact of flash floods towards vehicle instabilities. The system, easily addressed as FLO-LOW, developed to contradict the assumptions that a vehicle would be able to protect the passengers from the flood impact. Herein the hydrodynamics of flows moving across these roads coupled with the conditions of a static car that would result in vehicle instabilities has been studied. In an attempt to prevent fatalities in commonly flooded areas, permanent structures are installed to warn users regarding water depth at the flooded areas. The existing flood monitoring system only focuses on water conditions in rivers or lake in order to determine risks associated with floods. Thus, there is a need for a better system to understand and quantify a mechanism to determine hydrodynamics instability of a vehicle in floodwaters. FLO-LOW enables the road users to input their vehicle information for a proper estimation of safety limits upon crossing the flood prone area. Preferably, the system enables road users to describe and quantify parameters that might cause their vehicles to become vulnerable to being washed away as they enter the flooded area.

**Keywords:** vehicle hydrodynamics, instability modes, static vehicle, flooded roads, flood risk assessment system

#### 1. Introduction

Recently, flood occurrence possibilities have been increased globally due to two main reasons namely, lands urbanization and climate changes [1, 2]. Climate changes caused by global worming increase the precipitation intensity and rapid lands urbanization leads to increase the flow run off process throughout the paved areas which becomes flooded during heavy rainfall events [3]. Floods can be categorized into three main types namely, riverine, coastal and flash floods [4]. However, Malaysian drainage and irrigation department (DID) classified floods into two main types namely, monsoon and flash flood [5]. Flash floods are considered the most dangerous when compared to others due to its high velocity and short time warning which causes high mortality among people [6, 7].

Floods usually sweep light and non-stable objects through their ways; vehicles are among these objects which can be swept away at certain flow velocity and depth [8]. There are three forms of vehicles failure mode during floods including sliding, floating and toppling. Sliding occurs at high flow velocities and low water depths, floating occurs at high depths and toppling which basically occurs when the vehicle slides beyond the road edge [8]. Once moved, it can be easily following the flood path and cause damages to properties and road structures. Previous studies showed that around 50% of the total deaths during flash floods occur to the people inside vehicles [9]. Recently, many vehicles swept away during Sant Lorenc des Cardassar flash flood in the Spanish Balearic island of Majorca. A total of 10 persons were killed during this event 6 of them were inside their cars [10].

Vehicles are either parked or moving on a roadway. During a flooding condition, a parked or moving vehicle expects different hydrodynamic forces which leads to three failure modes as discussed earlier. Low-lying roads are the most critical location for moving vehicles due to the existence of the highest water depth and flow velocity [11]. Many drivers judge the flooded low-lying roads by their naked eyes and intentionally drive through it believing that the flow intensity and water depth are low which will not affect their car. Unfortunately, this can be considered as the main reason of increasing deaths during flood events [12].

During 1960s several cases related to flooded vehicles were reported in Australia. In 1967 (Bonham and Hattersley) conducted the first experimental work to find out the vehicle stability limits during floods [11, 13]. Bonham and Hattersley carried out several lab tests on a scaled car model (1:25) of Ford Falcon which was the common passenger car at that time. The flow direction was perpendicular to the car's longitudinal side. Vertical and horizontal forces were measured under different flow velocities and water depths. Finally, a friction coefficient of 0.3 was proposed [13]. In 1973, Gordon and Stone conducted laboratory investigation on Morris Mini car model with scale ratio of 1:16 following the same procedure of Bonham and Hattersley. However, the orientation of the model was different, where the car front side faced the flow direction. Two cases were investigated namely, front tires and rare tires locked mode. The results showed that the stability limits (depth  $\times$  velocity) ranged between 0.3 and 1.0  $m^2/s$ . The front tires locked condition was more stable and safer due to high friction resistance caused by the vehicle engine placed above the front axle [14]. In 1993, Keller and Mitsch carried out an analytical study to investigate the limits of stability of four car models namely, Suzuki Swift, Ford Laser, Toyota Corolla and Ford LTD. Vehicle's instability suggested to occur when the drag force was equal or greater than the friction force between the tires and road surface [15]. This leads to the formulation of the threshold velocity formula which can be given as,

$$v = 2 \times \left(\frac{\mu F_G}{\rho C_D A_D}\right)^{0.5} \tag{1}$$

where, v is the incipient velocity,  $\mu$  is the coefficient of friction which was set to 0.3 as derived by Bonham and Hattersley,  $F_G$  is the axle load in wet conditions,  $\rho$  is the density of water,  $C_D$  is the drag coefficient and  $A_D$  is the submerged area projected normal to the flow.

Between 1993 and 2010 no studies have been reported regarding vehicle stability limits in floodwater. Australian Rainfall and Runoff the guidelines produced during this period were based on the results attained from the work of Bonham and Hattersley, Gordon and Stone, and Keller and Mitsch [16]. Between 2010 and 2019 several studies [17–28] have been published regarding flooded vehicles stability. This was due to the major changes in the vehicle design mainly due to weight, ground clearance, and hydrodynamic shape of modern cars [29].

In the past, research on vehicle instabilities have been solely dedicated to stationary vehicles which are normally translated as vehicles parked on a road surface. A vehicle exposed to floodwater gets influenced by different hydrodynamic forces and prone to various instability modes. Outcomes on such modes are somehow recognized in the work on stationary vehicles, but, the existing approaches possess a limited ability to communicate with road user with respect to complicated hydrodynamic and nature of flooding. Thus, there is a need for a better system and method to understand and quantify a mechanism to determine hydrodynamics instability of a vehicle in floodwaters. Herein the flood risk assessment system called "FLO-LOW" has been introduced that enables the road users to input their vehicle information for a proper estimation of safety limits upon crossing the flood prone area. Preferably, the system enables road users to describe and quantify parameters that might cause their vehicles to become vulnerable to being washed away as they enter the flooded area.

#### 2. Theory

The procedures of estimating hydrodynamic instability values of a static vehicle based on vehicle and flow condition information include determining the dominancy of additional forces through different combination of vehicle and water conditions. With that regards, this section covers the basic understanding on the impacts of hydrodynamic forces on a static vehicle. Further, the instability modes based on the dominancy of hydrodynamic forces are further addressed.

#### 2.1 Hydrodynamic forces

Flooded objects are influenced by several hydrodynamic forces exerted by the incoming flow in different directions. Herein the impact of hydrodynamic forces on a static flooded vehicle have been discussed. In fact, there are several forces acting on a vehicle inside floodwaters which involves, drag ( $F_D$ ), buoyancy ( $F_B$ ), lift ( $F_L$ ), friction ( $F_R$ ), and gravitational ( $F_G$ ) forces as shown in **Figure 1**. Understanding the hydrodynamic forces acting on the vehicle body is important to understand the instability modes.

#### 2.1.1 Drag force

Drag force  $(F_D)$  is the flow pressure acting on one or more sides of the flooded vehicle. The pressure magnitude is controlled by different parameters including, flow velocity magnitude, vehicle direction, flow depth, affected area and flow density. The drag force is considered as the main force leading to the sliding



**Figure 1.** *Hydrodynamic forces on a static flooded passenger car model* [28].

instability failure mode for static cars. The general drag force formula can be expressed as follow:

$$F_D = \frac{1}{2}\rho C_d A_d v^2 \tag{2}$$

where,  $\rho$  is flow density,  $C_d$  is the drag coefficient,  $A_d$  is the affected area, v is flow velocity.

#### 2.1.2 Friction force

Friction force  $(F_R)$  can be defined as the reaction between the tires and ground surface against the drag force  $(F_D)$ . Friction resistance is the main force which keep the vehicle stable against sliding. The frictional resistance is influenced by the ground surface condition (rough/smooth), tires material and vehicle weight. The friction force can be written as follow:

$$F_R = \mu F_G \tag{3}$$

where  $(F_G)$  is the net normal reaction against the vehicle weight and  $\mu$  is the friction coefficient.  $\mu$  has different values based on the vehicle orientation and tire's axles locked conditions.  $\mu$  Values ranged between 0.3 and 1.0, however the value of 0.3 has been considered conservative and effective for majority of the road condition and tire types.

#### 2.1.3 Buoyancy force

The pressure exerted by the flow in the upward direction against the object weight is called buoyancy force ( $F_B$ ). In other words, it can be defined as fluid weight which is displaced by the immersed part of the object. In general, the main parameters effecting the buoyancy force are, object density, immersed volume and fluid density. Buoyancy force ( $F_B$ ) can be written as:

$$F_B = \rho g V \tag{4}$$

where,  $\rho$  is fluid density, g is the gravity, and V is the object submerged volume. Flooded vehicles are mainly subjected to extreme  $F_B$  at low flow velocity and high flow depths that mostly leads to floating instability mode.

#### 2.1.4 Lift force

High velocity floodwaters flowing around the lower surface of the vehicle generates a force acting on the surface perpendicular to the flow direction. This force is called lift force ( $F_L$ ) which is affected by several parameters including, flow velocity, affected area and fluid density. The general expression of the lift force can be written as:

$$F_L = \frac{1}{2}\rho C_l A_l v^2 \tag{5}$$

where,  $\rho$  is flow density,  $C_L$  is the lift coefficient, v is the flow velocity, and  $A_L$  is the affected area by the lift force (vehicle plane area).



The gravitational force  $(F_G)$  is the vehicle effective weight and it can be expressed as:

$$F_G = F_g - (F_B - F_L) \tag{6}$$

where,  $F_g$  is the curb weight of the vehicle at dry condition,  $F_B$  is the buoyancy force and  $F_L$  is the left force.

#### 2.2 Instability modes

The three modes of instability for stationary vehicles inside floodwaters are shown in **Figure 2**. In terms of hydrodynamic forces, when the drag force ( $F_D$ ) exerted by the flow exceeds the friction force ( $F_R$ ) between the tires and ground, sliding occurs. While floating takes place when the buoyancy ( $F_B$ ) and lift ( $F_L$ ) forces are equal to or more than the vehicle weight. During flood events vehicle instability is influenced by different parameters including, flow velocity, water depth, vehicle orientation against flow direction, vehicle characteristics (length, width, ground clearance, weight, tires condition, and hydrodynamic design), road slope, road roughness, and vehicle submergence level (fully or partially submerged).

The critical situation usually occurs when the vehicle's longitudinal side is perpendicular to the flow direction. At this orientation the drag force reaches to the maximum value. Further, vehicles parked on a flat road surface are more stable when compared to the vehicles on slopes. Additionally, vehicle ground clearance and weight play main rule in terms of floating instability mode. Vehicles with higher ground clearance and weight are more stable. However, road roughness and tires condition (new/old) have significant effects on the stability limits. Higher road surface roughness gives higher friction reaction against the drag force exerted by the flood.

#### 3. Flow dynamics of the vehicle linkage to flood management – FLO-LOW

The present invention generally relates to a flood risk assessment system and methods, more particularly a flood risk assessment system and a method for determining hydrodynamic instability of a stationary vehicles in a flood-prone area.

#### 3.1 The system

The present invention, FLO-LOW relates to an online decision-making tool for road users to decide the likelihood on crossing the areas that are prone to flooding. A flood risk assessment system provides a real-time monitoring of flood condition at a flood-prone area near rivers, streams, water course or lakes for determining the hydrodynamic instability of vehicles upon crossing such roads as shown in **Figure 3**. Based on complex hydrodynamics parameters, namely water depth, D and flow velocity, v associated with different types of vehicle suggest a threshold value that would lead to the possibility of a non-stationary vehicle instability in flood-prone area. The flood risk assessment system enables the road users to input their vehicle information for a proper estimation of safety limits upon crossing the flood prone area. Preferably, the system enables road users to describe and quantify parameters that might cause their vehicles to become vulnerable to being washed away as they enter the flood-prone area. The parameters may include but not limited to vehicle type, vehicle volume, vehicle location and vehicle direction.

The flood risk assessment system includes an application program that is running on a personal mobile communication device of an individual user, such that the road user is able to input vehicle and water condition information as well as to receive flood risk related data message and warning. **Figure 4** illustrates the schematic diagram of the flood risk assessment system according to an embodiment of the present invention. Generally, the flood risk assessment system comprises a plurality of sensing devices and a flood risk analysis terminal. The flood risk analysis terminal further comprises an input/output (I/O) module, a flood database and a data processing engine. The data processing engine further includes a flood analysis module and a flood warning module.

#### 3.2 Algorithm

**Figure 5** exhibits the result vehicle instability based on complex hydrodynamics parameters carried through experimental and theoretical assessments. It is observed and evident in **Figure 5**, that other than different combinations of water depth, D and flow velocity, v, vehicle information which includes vehicle type is another important parameter to estimate vehicle instability in flood.



**Figure 3.** *Flood level monitor for low-lying area (FLO-LOW).* 







Figure 5.

Compilation of previous works and validation of current research.

In accordance with an embodiment of the present invention and referring to Figure 6, a method for determining hydrodynamic instability risks of a vehicle comprises the step of detecting water conditions including water depth and water velocity data by a plurality of sensing device. The technique for detecting water conditions may include implementing a plurality of sensors and at least one communication device. The communication device may include but not limited to a rain

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**Figure 6.** Process flowchart.

fall meter, a flood level meter and a visual display. The information related to water conditions that is obtained by the plurality of sensing device is displayed on a visual display screen which is visible to the road user. The flood analysis module then receives vehicle and water conditions information provided by the road user.

#### 4. Experimental investigation

To assess the hydrodynamics of a static vehicle under partial submergence and sub-critical flow conditions, a modern vehicle Volkswagen Scirocco was used with the scale ratio of 1:24 ensuring the similarity laws. Prior to perform the experiments following conditions were considered, namely (i) the rear tires of the vehicle were restricted to move, (ii) sealing capacity of the car was taken into consideration and (iii) to reduce the inconsistency in the data, the vehicle was placed at the same domain with different orientation angles [30].

#### 4.1 Experimental setup

Experimental investigation were performed in the hydraulic flume of Universiti Teknologi PETRONAS, Malaysia as shown in **Figure 7**. The instability failure modes, namely sliding and floating instability of the vehicle were assessed by adjusting the discharge in the flume. The average flow velocity and the water depth were then recorded using the point gauge and Nixon Streamflo 430. To reduce the human error while assessing the failure modes, a monitoring laser was used to profound observe the vehicle movement in any direction. Proper procedures to enable assessment of flood hazard related to vehicles have been developed based on the studies performed earlier. To ensure similar conditions to that of actual road, the surface roughness of the platform where the experiments were conducted was determined which was found to be 0.017. This value nearly matched to the coefficient roughness of asphalt pavement, which is stated to be 0.016 for rough texture [30].



4.2 Results and discussion

A varying combination of flow velocities and water depths were tested to investigate the threshold of vehicle instability. It was noticed that a static vehicle could become unstable or start to slide at two conditions, namely high flow velocity and low water depth or vice versa under the partial submergence and sub-critical flow conditions. Further, it was assumed that the lift coefficient (CL), drag coefficient (CD) and friction coefficient ( $\mu$ ) were set to a constant value. The study was limited to the partial submergence only and the vehicle behavior under full submergence was not taken into consideration. While preforming the experimental runs, the impact of buoyancy force was found dominant when the water depth exceeded 0.042 m. On the other hand, the impact of lift force was theoretically estimated. The assessment of lift force involved the assessment of planform area, theoretically, whereas the value of lift coefficient was obtained from a numerical study performed on a similar city car under partial submergence. Since the shear of the flow was mild as the study was performed under the sub-critical flow conditions, therefore the impact of the lift force was found insignificant when compared to the buoyancy force. Among the horizontal pushing forces, namely friction and drag force, the friction force was assessed by considering the friction coefficient value of 0.3, whereas the net weight of the vehicle was obtained by deducting the buoyancy force when the vehicle weight. On the other hand, to assess the drag force, the drag coefficient was taken 1.1 or 1.15 depending on flood water depth with respect to the chassis height. Similarly, the submerged area projected normal to the flow was determined for every water depth. Lastly, the velocity of the flow determined through the use of velocity meter. The impact of hydrodynamic forces, namely buoyancy, lift, friction and drag forces at varying combination of floodwater depth and velocity are shown in **Figures 8–11** respectively [30].

Referring to the lift force as highlighted in **Figure 9**, it can be seen that its impact varied between 0.030 N and 0.303 N, whereas for the similar conditions, the impact of buoyancy force was found to be between 2.379 N and 4.596 N. Based on this observation it can be stated that the impact of lift force was insignificant to support the vertical pushing force and so does the floating instability when the flow condition is sub-critical. Basically, water provides best medium to develop drag rather than the lift force [30].

It has been stated that floating instability occurs when the vertical pushing force that is composed of both buoyancy and lift forces exceeds the vehicle weight of the immersed object. Under the sub-critical flow conditions, the flow velocities were found to be moderate as the range of Froude number ranged between 0.308 and 0.91. Thus, it is assumed that the flow shear was low and therefore the impact of lift force was disregarded. On that justification, it could be stated that when the flow

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conditions are sub-critical, floating instability occurs only when the buoyancy force exceed the vehicle weight. On the other hand, sliding instability was validated based on the condition, i.e.,  $F_D$  more than  $F_R$ . The vehicle was found stable when the frictional force was greater than the drag force [30].



**Figure 8.** Influence of buoyancy on the model vehicle [30].



Figure 10. Influence of friction force on model vehicle [30].



Influence of drag force on the model vehicle [30].

#### 5. Numerical investigation

Numerical investigation of the flooded vehicles could assist to evaluate the instability failure modes for both scaled down and prototype models. At the same time the results and measured forces are more detailed. In this section, numerical simulation of a stationary flooded passenger car model have been discussed.

#### 5.1 Computational fluid dynamic model

In this study, FLOW-3D software was used for numerical simulation purpose. FLOW-3D uses an orthogonal mesh defined in terms of either Cartesian or cylindrical coordinates. Three different types of mesh can be used (uniform meshes, non-uniform mesh, and multi-block mesh). In this case uniform single block mesh was used. However, mass continuity and momentum equations were solved to simulate 3D fluid flow. These equations can be written for incompressible flow as follows:

$$V_{F}\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x}(uA_{x}) + \frac{\partial}{\partial y}(vA_{y}) + \frac{\partial}{\partial z}(wA_{z}) = R_{SOR}$$
(7)  
$$\frac{\partial u}{\partial t} + \frac{1}{V_{F}}\left\{uA_{x}\frac{\partial u}{\partial x} + vA_{y}\frac{\partial u}{\partial y} + wA_{z}\frac{\partial u}{\partial z}\right\} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_{x} + f_{x}$$
(8)

$$\frac{\partial v}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + G_y + f_y$$
(9)

$$\frac{\partial w}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial w}{\partial x} + v A_y R \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + G_z + f_z$$
(10)

where VF is the fraction of open volume,  $\rho$  is the density, (v, u, w) and  $(A_x, A_y, A_z)$  are the velocity and the fractional areas components in the (x, y, z) directions,  $R_{SOR}$  is the source term of density, p is the pressure,  $(G_x, G_y, G_z)$  are the body accelarations in the coordinate direction (x, y, z), and  $(f_x, f_y, f_z)$  are viscous accelerations in the coordinate direction (x, y, z).

#### 5.2 Methodology

FLOW-3D is a commercial code which uses finite volume method (FVM) and turbulence models to solve continuity and Navier stokes equations [31, 32]. The FLOW-3D software also allow the numerical simulation under six degree of freedom which can represent the real experiment condition [28]. To study vehicles stability limits, small passenger car (Perodua Viva) was used to investigate the floating and sliding instability modes under different flow conditions. Two different setup modes were constructed for both floating and sliding as follows.

#### 5.2.1 Floating condition

Car model was tested in two scale ratios (prototype and 1:10) to find out the difference in terms of hydrodynamic forces as well as find out the floating depth and buoyancy force. The stability limits were investigated under sub-critical flow condition, this was because of that the main force causing floating failure mode is the buoyancy force which exerted by the flow depth. The car models were placed inside close boxes with dimensions of (900 cm  $\times$  500 cm  $\times$  220 cm, for prototype) and (90 cm  $\times$  50 cm  $\times$  22 cm for sealed down model-1:10) then the waters flowed into the box gradually. **Figure 12** shows the setup and boundary conditions for both cases. The car model was tested under six degree of freedom, where the model movement in all directions can be noticed and measured. One history probe was placed beside the car model to measure the hydraulic parameters (flow velocity, Froude's number, and water depth). Car models were defined as coupled motion object, this definition allow the code to calculate the hydrodynamic forces exerted by the flow on the models outer surfaces in all directions (X, Y, and Z).

#### 5.2.2 Sliding condition

To investigate sliding instability limits under different flow conditions, the car model with scaled ratio of 1:10 was placed inside a flume with dimensions of (300 cm × 90 cm × 22 cm), and the longitudinal side faced the flow direction. This orientation was selected because it was considered as the most critical case compared to th other orientations [29]. The numerical runs were conducted under 6 degree of freedoms condition, and coupled motion definition between flow and car model was selected. The friction coefficient was set to 0.52 based on the previous experimental tests [11]. **Figure 13** shows the numerical setups and the boundary condition definitions. One history probe was placed in front of the car model with a distance equal to the car length to measure flow velocity, water depth, and Froude's



**Figure 12.** Numerical simulation setup for floating testing (a) 1:10 and (b) prototype.



number. Four combinations of flow velocities and water depths were simulated as shown in **Table 1**.

#### 5.3 Results and discussion

In terms of floating instability mode, both scale ratios showed the same pattern and values (floating depths and buoyancy forces). **Figures 14** and **15** show the relationship between the model center of mass (COM) and the buoyancy forces for scaled down and prototype models respectively. For scaled down model, the buoyancy force at fully floating condition was 8.9797 N which can be scaled up to 8979 N. While it was 9155 N for prototype model. When compared, the buoyancy forces numerically simulated and the value from Eq. (4) the differences were 1.94 and 0.21% for scaled and prototype models respectively. In addition, form **Figures 14** and **15** it is clear that the high and sudden changes in models COM occurred once bouncy force exceeded the model weight.



**Figure 14.** *Relationship between the buoyancy force and car center of mass with time (1:10).* 

**Figures 16** and **17** show the relationship between water depth and buoyancy force with respect to the time for scaled and prototype models, respectively. The buoyancy force increased gradually with the depth increment and the values of floating depths were 3.7 cm (which can be scaled up to 37 cm) and 37.5 cm for scaled and prototype models, respectively. From both simulated parameters (buoyancy force and floating depth) it can be concluded that the numerical modeling by using FLOW-3D software gave accurate results and allowed to test vehicles in real scale.



**Figure 15.** *Relationship between the buoyancy force and car center of mass with time (prototype).* 



**Figure 17.** *Relationship between the buoyancy force and water depth with time (prototype).* 



**Figure 18.** *Numerical results validated with previous experimental study* [33].

In terms of sliding, the results showed that the car model at the  $D \times v$  value less than of 0.35 m<sup>2</sup>/s was safe. At subcritical flow condition, the car tended to be float, while the sliding condition occurred at supercritical flow condition. Car model remained at its original location in cases no. 1, 2, and 3 where the values of  $D \times v$ were less then 0.35 m<sup>2</sup>/s. In case no. 4 the car model dragged from its original location and sliding failure mode was noticed. The numerical results were compared with Australiana rainfall and runoff guidelines (2011) [32] and good agreement was noticed as shown in **Figure 18**. From the results it can be concluded that, numerical simulation using FLOW-3D can give good predictions and results related to vehicle instability limits. Several car models can be tested numerically flowing same steps under different road slops as well as under different orientations.

#### 6. Conclusions

In the past, research on vehicle instabilities have been solely dedicated to stationary vehicles which are normally translated as vehicles parked on a road surface. A vehicle exposed to floodwater gets influenced by different hydrodynamic forces and prone to various instability modes. Outcomes on such modes are somehow recognized in the work on stationary vehicles, but the existing approaches possess a limited ability to communicate with road user with respect to complicated hydrodynamic and nature of flooding. In an attempt to prevent fatalities in commonly flooded or flood-prone areas, permanent structures are installed to warn users regarding the depth of the water at the flooded area. The existing flood monitoring system only focuses on water conditions in rivers or lake in order to determine risks associated with floods. The present invention, FLO-LOW relates to an online decision-making tool for road users to decide the likelihood on crossing low-lying areas that are prone to flooding. The flood risk assessment system provides a realtime monitoring of flood condition at flood-prone area for determining the hydrodynamic instability of a vehicle.

#### 7. Recognition

FLO-LOW different individual component as well as the whole complete system have been submitted for Intellectual Property under three categories, namely Patent (PI 2017702574), Patent (PI 2019001397), Industrial Design (17-E0208-0101) and

Trademark (2019012521). FLO-LOW has won different international and national awards, namely ITEX'18, MRCIIE'18, INTEX'19, MIIEX'19, PECIPTA'19 and **IDE4TE'19**.

#### Acknowledgements

The authors gratefully acknowledge the supports provided by Universiti Teknologi PETRONAS through Prototype Fund (015PBA-008) and hydraulic laboratory equipment utilized for this research.

#### Abbreviations and nomenclature

ty

- $F_G$ gravitational force
- friction coefficient μ
- water density ρ
- $C_D$ drag coefficient
- normal projected area to the flow direction  $A_D$
- friction force  $F_R$
- $F_B$ buoyancy force
- gravity
- g V volume
- $F_L$ left force
- left coefficient  $C_L$
- area affected by lift force  $A_L$
- $F_{g}$ vehicle curb weight
- rolling resistance  $F_{RO}$
- resultant reaction R
- θ angle between the tire vertical axes and the point where the tire no more touching the ground
- horizontal distance between the tire vertical axes and the point where the b tire no more touching the ground
- tire reduce r
- vehicle net weight w
- rolling coefficient  $\mu_{RO}$
- driving force  $F_{DV}$
- vehicle mass т
- acceleration а
- time t
- flow depth d
- CFD computational fluid dynamics
- finite element method FAM

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