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# Safety criteria for the trafficability of inundated roads in urban floodings

M. Kramer, K. Terheiden, S. Wieprecht *

*Institute for Modelling Hydraulic and Environmental Systems, University of Stuttgart, Germany*

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ABSTRACT

The probability of unexpected urban flood hazards is steadily increasing due to global warming and climate change. Consequently, there is a growing need for safety criteria determining the trafficability of inundated roads to ensure a fast and safe evacuation of people in case of such events. In order to determine those criteria, experimental investigations on the stability of two scaled watertight vehicle models and of one prototype passenger car are conducted in a laboratory flume and a steel tank.

The conducted flume experiments clearly show a dependency of vehicle stability on the flow angle, whereas the prototype experiments indicate that floating water depths are higher in prototype than in model scale, which is due to the use of a watertight vehicle model. Based on both experiments, a constant total head is proposed as decisive parameter for determining trafficability. This parameter approximates the measured stability curves and can be easily adopted in practice. Furthermore, it is in accordance with fording depths evaluated from relevant literature or by means of manufacturer inquiry. The recommended safety criteria for passenger cars and emergency vehicles are total heads of $h_E = 0.3\ \text{m} = const.$ and $h_E = 0.6\ \text{m} = const.$, respectively.



## 1. Introduction

In the case of unexpected flood hazards such as flash floods or dam failure, the trafficability of flooded streets is a key aspect of the evacuation of urban areas and is investigated within the framework of the research project “EvaSim” (*Eva*cuation *Sim*ulation). With the aim of providing an effective and holistic approach for the development of evacuation plans in case of urban flooding events, hydrologic, hydrodynamic and traffic models are coupled. Furthermore, safety criteria concerning the trafficability of inundated streets represent the linkage between hydraulic and traffic models and therefore deliver a key parameter in flood event management.

In the present study, experimental investigations on vehicle stability and incipient velocity are undertaken. A distinction between *stability* and *roadworthiness* of vehicles is proposed for the definition of safety criteria concerning the trafficibility. Vehicle stability comprises stability in terms of floating and sliding, whereas the roadworthiness of vehicles takes additional parameters into account such as the height of air inlets or the tightness of electrical devices.

* Corresponding author.
*E-mail address:* silke.wieprecht@iws.uni-stuttgart.de (S. Wieprecht).
*URL:* http://www.iws.uni-stuttgart.de (S. Wieprecht).

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### 1.1. Instability mechanisms

In the past, two main hydrodynamic instability mechanisms, comprising floating and sliding, have been identified. Floating occurs as soon as the upward buoyancy force exceeds the downward directed submerged weight force of the vehicle. Sliding occurs when the horizontal force on the car is larger than the horizontal counteracting force, which is dependent on vehicle mass, buoyancy and the friction between vehicle tyres and road surface [1]. Both mechanisms are illustrated in Figs. 1 and 2.

### 1.2. Incipient velocity

When a vehicle is exposed to water flow, different forces act simultaneously on the partially submerged body of the car. Within the following equations, it is assumed that the exposed vehicle is not moving and has locked tyres. The acting forces include buoyancy force $F_B$, drag force $F_D$, weight force $F_G$ and friction force $F_R$. The buoyancy force is given by:

$$F_B = \rho g V \tag{1}$$

where $\rho$ is the water density, $g$ the gravitational acceleration and $V$ the immersed volume. The drag force acts on the vehicle body due to the relative motion of the vehicle with respect to the surrounding water and can be described with the following equation:

**Nomenclature**

| | |
|---|---|
| $\alpha$ | flow angle [deg] |
| $A$ | cross sectional area [$m^2$] |
| $\beta$ | inclination angle of the tilting flume [deg] |
| $C_D$ | drag coefficient [dimensionless] |
| $F$ | force [$N$] |
| $F_B$ | buoyancy force [$N$] |
| $F_D$ | drag force [$N$] |
| $F_G$ | weight force [$N$] |
| $F_N$ | normal force [$N$] |
| $Fr$ | Froude number [dimensionless] |
| $F_R$ | friction force [$N$] |
| $g$ | gravitational acceleration [$m/s^2$] |
| $h$ | water depth [$m$] |
| $h_f$ | fording depth [$m$] |
| $h_E$ | total head [$m$] |
| $h_{Si}$ | safety distance (road surface - water level) [$m$] |
| $L$ | length [$m$] |
| $L_r$ | length scale ratio [dimensionless] |
| $\mu$ | friction factor [dimensionless] |
| $m$ | model |
| $max$ | maximum |
| $n$ | prototype |
| $Q$ | flow rate [$m^3/s$] |
| $r$ | relative quantity = prototype/model quantity |
| $Re$ | Reynolds number [dimensionless] |
| $\rho$ | density [$kg/m^3$] |
| $t$ | time [$s$] |
| $v$ | velocity [$m/s$] |
| $V$ | immersed volume [$m^3$] |

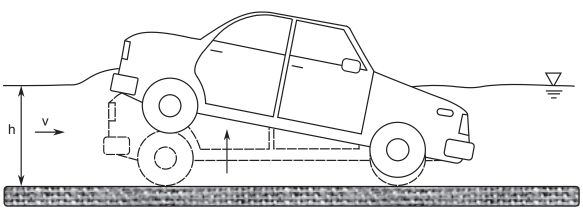


**Fig. 1.** Floating instability adopted from [1].

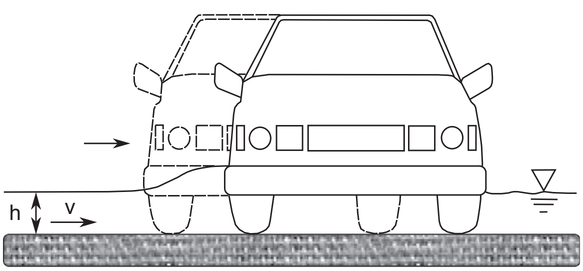


**Fig. 2.** Sliding (frictional) instability adopted from [1].

$$F_D = \frac{1}{2}\rho C_D A v^2 \tag{2}$$

where $F_D$ is the drag force, $\rho$ the density of the fluid, $A$ the cross sectional area, $C_D$ the drag coefficient and $v$ the flow velocity. According to Keller and Mitsch [2], the drag coefficient is a function of the flow depth and can be set to 1.1 once the water level is below the chassis and to 1.15 while the water level is above it. The friction force acts between the tyres and the road surface and is given by:

$$F_R = \mu F_N = \mu(F_G - F_B) \tag{3}$$

where $F_R$ is the friction force, $F_N$ the normal force, $F_G$ the weight force, $F_B$ the buoyancy force and $\mu$ the friction factor. Based on previous experimental investigations, Bonham and Hattersley set the friction factor to $\mu = 0.3$, which is almost certainly adequate for most surfaces [3]. Considering the resultant horizontal forces on the submerged vehicle body, incipient motion occurs as soon as the threshold:

$$F_D = F_R \tag{4}$$

is exceeded. Substitution of $F_D$ and $F_R$ by Eqs. (2) and (3) leads to the following equation of the incipient velocity for partially submerged vehicles in floodwater:

$$v = \sqrt{2\frac{(F_G - F_B)\mu}{\rho C_D A}} \tag{5}$$

This equation is published in different studies including Keller and Mitsch [2], where the axle load distribution of front and rear axis are taken into consideration, and Shu et al. [4], where additional experimentally determined parameters related to vehicle shape, tyre type and roughness of the road surface are considered.

### 1.3. Experimental investigations

There have been limited publications of experimental studies on vehicle stability, see Table 1. These studies differ in various aspects, e.g. in vehicle type, vehicle orientation, friction coefficient and submergence (partial and full).

Bonham and Hattersley [3] conduct tests on a partially submerged Ford Falcon model with a length scale ratio of $L_r = 25$ in order to establish criteria for the safe design of submersible causeways for use on country roads. 46 different combinations with typical flow depths ranging from $h_n = 0.11–0.57$ m and typical velocities between $v_n = 0.48$ m/s and 3.09 m/s are investigated in an experimental flume, where the vehicle is aligned perpendicular to the flow. This direction is defined as a flow angle of $\alpha = 90°$ within this study.

Gordon and Stone [5] carry out stability investigations on a partially submerged Morris Mini model with a length scale ratio of $L_r = 16$. The model faces upstream ($\alpha = 0°$) during the tests while vertical and horizontal reactions are measured by a modified standard beam balance. Stability curves for a car having front and rear wheels locked are obtained as a function of water depth and velocity.

Xia et al. [6] derive an equation of incipient velocity for fully submerged vehicles based on the mechanical theory of sliding

**Table 1**
Experimental studies on vehicle stability; n.d.: not defined.

| Name | Year | $L_r$ | $\mu$ | $\alpha$ | submergence |
|---|---|---|---|---|---|
| Bonham and Hattersley | 1967 | 25 | 0.3 | 90° | partial |
| Gordon and Stone | 1973 | 16 | 0.3 ÷ 1.0 | 0° | partial |
| Xia et al. | 2010 | 18, 43 | n.d. | 180° | full |
| Shu et al. | 2011 | 18 | 0.39, 0.5, 0.68 | 0°, 180° | partial |
| Teo et al. | 2012 | 18, 43 | n.d. | various | full |
| Xia et al. | 2014 | 14, 24 | 0.25, 0.75 | 0°, 90°, 180° | partial |