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Research Article

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Gender-based risk analysis of vehicle control loss due to localized water puddles: An analytical approach

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Highlights

- Local water puddles in pavements cause risk on steering
- Female and male drivers' risk velocity differs
- 70 km/h velocity and higher cause the same risk for female and male drivers.

Abstract

Adverse weather conditions significantly increase the risk of traffic accidents, yet most studies focus on uniform conditions across all tires. This study investigates the impact of asymmetric drag forces when only one tire encounters a local water puddle, causing potential vehicle control loss. Using analytical methods, we calculate drag forces and their transmission to the steering wheel, accounting for variations in water film thickness, vehicle speed, and driver gender. The results indicate that female drivers face higher risks of control loss, with critical speeds decreasing as water film thickness increases. The study highlights that localized water puddles, especially at low speeds and water depths exceeding 3 cm, pose significant risks. These findings can inform road safety guidelines and vehicle design standards to mitigate accident risks in adverse weather conditions.

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1. Introduction

According to the World Health Organization's [1] data for 2016, the traffic accidents caused about 1.35×10^6 deaths worldwide. Traffic accidents affect all groups of road users like pedestrians, drivers and passengers. Especially, for peoples, between the ages 15 to 29, the main death cause globally is traffic accidents. Based on the National Highway Traffic Safety Administration's [2] data between 2014 and 2018, 32.4×10^6 crashes occurred and 25.2×10^6 persons are estimated to be involved in injuries while 411.2×10^3 persons died because of fatal crashes. 29.4% of the total crashes have occurred during adverse weather. About 6.8×10^6 (26.9% of total injuries) people are injured by accidents occurred during adverse weather while about 122.5×10^3 (29.8% of total deaths) people died. Hao and Daniel [3], analysed the inclement weather affecting highway-rail grade crossings in the United States between the years 2002 and 2011 and found that 30.7% of the total crashes occurred during adverse weather. Umar and Bashir [4] investigated the truck traffic injuries and found that driver's involvements as statistically significant. Also, Mutlu and Alver [5] in their study put forth that young drivers aged between 18 and 29 are more likely to break red light, using mobile phone during drive and they don't see this behavior as risky.

When the five-year-long period for the United States is examined, almost one-third of the accidents occur during adverse weather. Pitaksringkarn et al. [6] studied the correlation between skid resistance and wet pavement related accidents in Thailand. They found that there is an inverse proportion between them. Lee et al. [7] investigated the city of Seoul for nine years between 2007 and 2015 and found that accident severity is correlated with rain and water film thickness on the pavement. Mondal et al. [8], point that rainy weather and wet pavement conditions are one of the significant weather-related parameters which increase the probability of occurrence of an accident. Saplioglu et al. [9] investigated the skid resistance at accident occurred urban intersections. They found a relation between the texture depth and the accident occurrence probability which is also an inverse proportion. When the texture depth decreases, the probability of accident occurrence

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increases. Kassu and Anderson [10] analysed the effect of wet pavement surface condition to non-severe crashes on two and four-lane highways. They found that the effective parameters which influence the crash are the segment length, traffic volume and speed limit. Liu et al. [11], evaluated the braking performance on wet pavement using integrated tire and vehicle approach. They build a 3D tire, water and pavement model on ABAQUS and simulate the hydroplaning effect. They simulate the water film thickness between 0.5-10 mm and used a 170/70R15 tire size. Besides these, there are many aquaplaning/hydroplaning studies [12-15].

Moreover, there are many studies about; vehicle control loss is the role of environmental factors, such as water accumulation on roadways [16], the integration of advanced technologies in vehicle systems has been explored in the context of improving safety [17], in the realm of artificial intelligence and decision-making frameworks [18]. Furthermore, the research by Yoo et al. [19] on risk-conditioned reinforcement learning provides a foundation for developing adaptive systems that can respond to varying risk measures in real-time. The impact of urbanization on traffic safety and vehicle control is also a pertinent topic [20].

When these studies are examined, the effect of low skid resistance and wet pavement are all well studied. However, all these studies focus on the situation where both tires drive on the same circumstances and pavement-tire contact. But it is not always true that all the tires encounter the same conditions while driving, and therefore a resistance force difference occurs. When there are pavement deteriorations like rutting, corrugations or shoving occurs, only one of the front wheels may drive into water puddle while the other one drive-through dry or drained through macro-texture/slope of the pavement. When such a case has occurred, there would be a tremendous difference between the resistance faced by the front wheels. In such a situation, the difference in the resistance of the wheels would affect the vehicle in a way where the vehicle changes its direction. Here, the driver should react on time with a corresponding force on the wheel to keep the vehicle in its way. Since the vehicle's velocity decreases overtime during an ordinary drive in the fluid, the resistance force is maximum when the vehicle contacts the fluid puddle. Therefore, the calculated forces are subject to the contact time in this study.

Localized water puddles can cause asymmetric drag forces, which may lead to loss of vehicle control. This study addresses this gap by investigating the effects of these forces on vehicle steering dynamics. The analysis will focus on how driver gender, speed, and water film thickness influence the risk of vehicle control loss. By analyzing these parameters, we aim to highlight the importance of localized water hazards and their impact on different driver demographics.

There are few studies about such a case which could lead to over- or under-steering the vehicle and losing control. A sample could be given with the technical paper of Hight et al. [21]. Ivan et al. [22], investigated accidents in Connecticut and listed four major factors for fatal and injury crashes. Drivers losing control is the second and third major factor for fatal and an injury resulted in crashes, respectively. Penmetsa et al. [23] found that over-steering results most likely with fatality or injury to the driver. They also suggest researching the factors associated with over-steering to reduce the frequency and severity of the crashes. This study aims to highlight that asymmetric wheel resistance because of fluid on the pavement could also lose control of steering.

The primary goals of the study could be listed as; (i) analyzing the resistance forces for different water film thicknesses on the pavement, (ii) associate the resistance forces with the driver gender, and at last (iii) getting the speed limits for the vehicle which leads to likely control loss (defined as critical speed), and probably accident occurrence (defined as accident speed).

In this study, the gap in the literature is aimed to be filled by using an analytical approach. Therefore, a 205/55R17 sized tire (Figure 1) is used as the object tire. The resistance force on the tires' contact area has been calculated. Next, the force needed to control the steering wheel because of the resistance force has been got and compared with drivers control force based on gender, age and speed. As a result, the critical speed of the vehicles based on water film thickness is got. First, the drag force applying on the tire is explained as the next section. After, the force transmitted to the steering wheel is calculated.

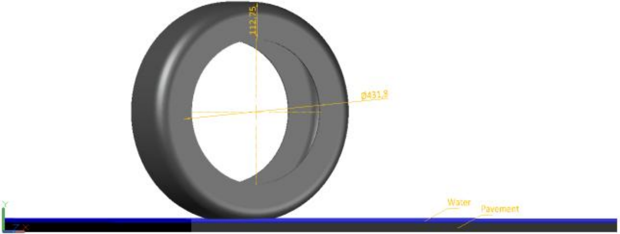

Figure 1. 205/55R17 size tire on a water layer

2. Methodology

This study models the effect of asymmetric resistance forces caused by localized water puddles. A 205/55R17 tire was used as the test case, and the drag force has been calculated. Drag force is a force which acts opposite to the motion of the object moving through the liquid or gas. This force could be between fluid and solid surface as well as fluid and fluid surfaces. The force is the dynamic pressure applied on a surface with a coefficient of the shape of the object moving through the fluid. The formula of the drag force because of the fluid (liquid or gas) is given in Equation (1).

$$F_d=\frac{1}{2}\rho V^2 C_D A \quad (1)$$

where, F_d is the drag force (N), ρ is the density of the corresponding fluid (kg/m^3), V is the velocity of the object (m/s), C_D is the complex coefficient for the shape of the object, and A is the cross-sectional area of the object faced with the fluid (m^2). The cross-sectional area is calculated using the water film thickness on the pavement.

As seen from Equation (1), the force depends on the velocity, area, density and coefficient. In our study, the most important part is the density because the rest of the parameters affect both tires as the same. However, there is a tremendous difference between the water ($1000\,kg/m^3$) and air ($1.225\,kg/m^3$). Because water's density is almost 815 times higher than the density of air, a huge drag force difference occurs between the tires which are transmitted to the steering wheel. When the driver cannot react on time with enough force for exactly the needed duration, it is possible to lose control of the vehicle. Velocity is the speed of the vehicle. The area is the cross-sectional area of the tire placed in the water paddle. The coefficient is the most complex parameter of the equation. The coefficient is determined experimentally. In this study, the coefficient is taken as 0.33 which is used by Keogh et al. [24]. Here, it should be noted that the coefficient is determined based on the shape of the wheel and does not affected from the environment.

Once the drag force is calculated, the force needed to control the steering wheel will be calculated. To do it first, the force on the wheel should be determined. For a steady-state vehicle, the force would be the mass multiplied with the friction coefficient, also the friction force. But in this paper, drag force will be taken into consideration since the vehicle is not in a steady-state and because friction force affects both tires the same, it is neglected. We focus only on forces affecting one tire. Once the force on the wheel is got, the torque on the wheel should be calculated (Equation 2).

$$\tau_{drag}=F_d \times r_{scrub} \quad (2)$$

where, τ_{drag} is the torque because of drag force (Nm) and r_{scrub} is the scrub radius (m). Scrub radius can be explained by the distance between the kingpin axis's theoretical extension to the road and the centre of the contact area of the wheel to the road. Scrub radius is taken as 0.1 m in this study. Next, the force on the tie rod should be calculated (Equation 3).

$$F_{tierod}=\frac{\tau_{hf}}{d} \quad (3)$$

where, F_{tierod} is the force on the tie rod (N), τ_{hf} is the torque for horizontal force from the tie rod (Nm) and d is the perpendicular distance between the kingpin axis to the end of the outer tie rod. The distance is taken as 0.0945 m in this study. The calculated torque because of drag force would be equal to the torque because of horizontal force from the tie rod. So, the force on the rack would be the difference between the force on tie rod from the two tires where one drives through water puddle and the other on the regular surface, through the air in this paper. Once the force on the tie rod is calculated, the force needed to control the steering wheel can be finally determined (Equation 4).

$$F_{driver}=\frac{F_{rack} \times r_{pinion}}{r_{SW}} \quad (4)$$

where, F_{driver} is the force applied by the driver to the steering wheel to control (N), F_{rack} is the total force on rack calculated as the difference on tie rod from two tires as mentioned above (N), r_{pinion} is the radius of the pinion (m) and r_{SW} is the radius of the steering wheel (m). Pinion radius is taken as 0.028 m while the steering wheel radius is 0.2 m.

3. Results and Discussion

As explained above, calculating the force needed to control the steering wheel depends on the radius of the steering wheel, pinion and scrub, total force on the rack, and force on the wheel. Since all parameters are the same but the force on the wheel, force on the wheel will be simulated and the needed force to control the steering wheel will be determined. Calculated forces on the steering wheel will be analysed to determine whether the forces are applicable. Eksioglu and Kizilaslan [25] analysed the applied forces on the steering wheel by 13 participants where 8 of them are males aged between 22 – 43, while 5 are females aged between 24 – 30. Eksioglu and Kizilaslan [25] take measurements of forces to control the vehicle while the drivers drive through a test area with speeds of 72 and 105 km.h-1 where the pavement type includes smooth and rough areas. As a result, they found that only the gender of the drivers is statistically significant. The maximum grip force values are 223.7 N and 135.1 N for males and females, respectively. An average grip force value while driving is reported as 66.3 N and 42.7 N for males and females, respectively. Based on the study of Eksioglu and Kizilaslan [25], when the force needed to control the steering wheel exceeds the maximum grip forces reported, the vehicle is most likely to get out of the way resulting with an accident. When the force needed is between the average and maximum grip force values, then the vehicle is at critical speed and the outcome would be up to the driver's mental and physical condition. Here, the idea behind using the grip forces of the drivers is that the difference of the resistance on the wheels would try to turn the steering wheel and the drivers should keep it stationary.

Using Equations (1-4) the needed force to control the steering wheel is calculated for a speed ranged between

30 – 150 km.h-1 and water film thickness ranged between 0.001 – 0.3 m. Calculated force values are visualized and given in Figure 2.

As seen in Figure 2, the needed force to control the steering wheel increases polynomial. While the needed force is very low to control during low speeds, even high-water film thickness, with the increase of the velocity value the needed control force increases quickly. In Table 1, the critical speeds (CS) and probably accident speeds (AS) are given for male and female drivers. The terms CS and AS are when force incurred at the steering wheel exceeds the average grip strength and when force incurred at the steering wheel exceeds maximum grip strength, respectively.

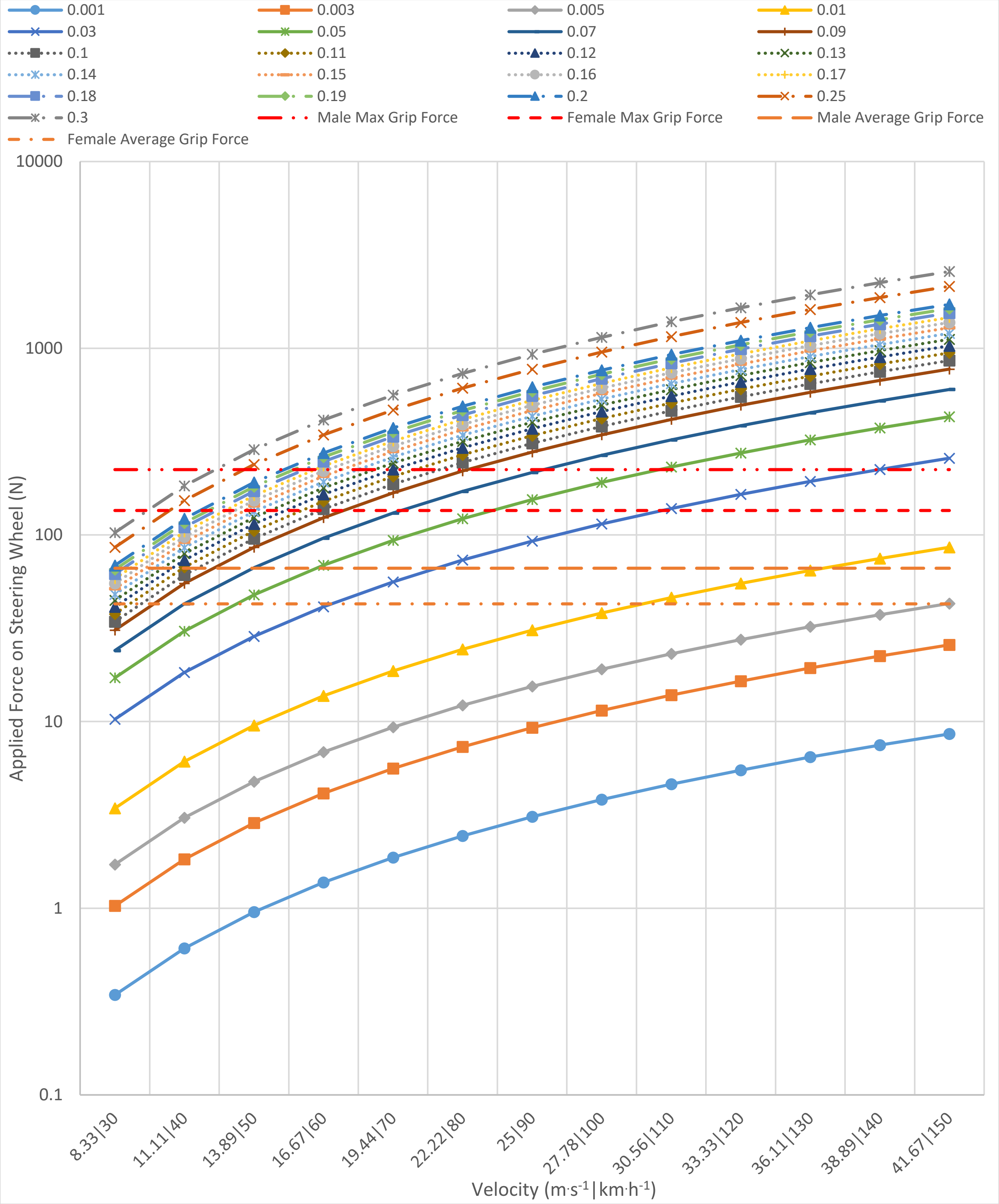

Figure 2: The calculated force needed on the steering wheel to control based on velocity and water film thickness.

Table 1: The lower limit of critical (CS) and probably involving into accident speed (AS) matrix obtained from Figure 2

Water film thickness, m	The limit velocity of vehicle for different conditions, km.h-1			
	♀-CS	♂-CS	♀-AS	♂-AS
0.30	>30	>30	34	45
0.25	>30	>30	37	48
0.20	>30	>30	42	54
0.19	>30	30	43	55
0.18	>30	31	44	56
0.17	>30	32	45	58
0.16	>30	33	47	61
0.15	>30	34	48	63
0.14	>30	35	50	65
0.13	>30	36	52	68
0.12	30	38	54	70
0.11	32	40	57	73
0.10	33	42	60	77
0.09	35	44	63	81
0.07	40	50	71	92
0.05	52	59	84	108
0.03	61	71	109	140
0.01	106	132	>150	>150
0.005	150	>150	>150	>150
0.003	>150	>150	>150	>150
0.001	>150	>150	>150	>150

As seen in Table 1, up to 5 mm height water film thickness could be able to be tolerated because the needed force is very low. For a high-speed road section, 1 cm height water film thickness causes serious safety issues for female drivers. For urban areas where the speed limit is 70 km.h-1 or higher, 3 cm high water film thickness is dangerous for male and female drivers. For low-speed roads, there is a tremendous difference for male and female drivers between the critical and probably involving into accident water film thicknesses. When the drivers drive less or are equal to 30 km.h-1, they only need to pay attention and the force they face is lower than their maximum grip force. When Table 1 is investigated, 12 cm height water film thickness is critical because it is possible that this height would occur on the pavement because of rutting heavy traffic, especially in the developing countries, and the speed values for probably involving into accident speeds are very easily accessible and posted design speeds for urban areas.

4. Conclusion

In this study, the gap in the literature as the lack of speeds and water film thicknesses leading to an accident for male and female drivers when only encounter on one wheel. An analytical approach is used to model the case for different speeds and water film thicknesses. A 205/55R17 sized tire is considered, but the texture is neglected. Based on the results of the study, the following conclusions could be drawn.

Male and female drivers have a significant difference in the grip of the steering wheel. This leads female drivers to probably involving into an accident at lower water film thicknesses for lower speeds than male drivers. The ratio for probably involving into accident thicknesses is about 1.8 times higher for males when Table 1 is examined and decreases with the increase of the speed. From up to 140 km.h-1, 3 cm height water film thickness is dangerous for both male and female drivers. The ratio for the critical area is lower than the ratio of probably involving into accident thicknesses. Here is the ratio 1.6 for the speed of 30 km.h-1 while almost the same for higher speeds.

Drivers would face up with higher force on the steering wheel than their average force applied at speeds 70 km.h-1 and higher while driving through 3 cm depth water puddles. If the driver is not fatigue or give correct reactions on the correct time, the vehicle would pass experiencing no adverse situation. But, since 3 cm is very low, the drivers should be warned when there is water puddles locally distributed on the pavement.

This study puts forth, though not a normative paper, the importance of the relationship between gender of drivers, water puddle depths and speeds of vehicles. This result may lead the way for further studies about the water film thickness and one-wheel contact. Type of vehicles, the effect of the mass of the vehicles, tire type, size and texture could be investigated for future works. Also, the mechanical characteristics of steering for autonomous vehicles could be investigated.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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