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Evaluation of the impact of pavement degradation on driving comfort and safety using a dynamic simulation model

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Abstract

The dynamic effects exerted by the vehicles on the road pavement have been thoroughly investigated over years. The main reason for this investigation is the major influence on the propagation and worsening of the pavement damages exerted by the dynamic loads rather than the static ones. To date, the modelling theories of systems have evolved, along with the computational capability of the modern calculators. To this effect, three-dimensional simulations of the tire-surface interaction are commonly used. These simulations take into account the dynamics of the load and the consequent deformation of the pavement.

However, previous studies aimed at analyzing the above interaction for the optimisation strategies of the maintenance activities within the context of effective road asset management. On the contrary, this work focuses on the safety-related issues linked with the dynamic effects suffered by the vehicle, when passing on different road defects. The goal of this study is to analyse numerically the kinematic and the dynamic effects of the pavement degradations (and in particular rutting) on the driving safety.

The simulation of the main characteristics and the evolution of the pavement damages over the time (e.g., the simulation of the tire-pavement contacts and the dynamic response on the vehicles) is a useful method for the development of safe and comprehensive rehabilitation programs. These are of paramount importance to limit the accident rates. The effects on the driving safety was analysed using a simulation model for the vehicles behaviour in the case of damaged pavements. Different road geometries and vehicle types were considered to evaluate the rutting effects on safety, as a function of the evolution stage of this type of pavement damage. In more detail, the performance characteristics of the vehicles, the dynamic and kinematic parameters (e.g., the vehicle trajectory and the vertical acceleration), were collected for pavement conditions with progressively high levels of rutting.

The study proposes a theoretical model of qualitative relationships between differing stages and location of rutting, and the consequent effects on driving safety for different types of vehicles (passenger cars and powered two wheelers). It is worth to emphasize the relevance of this research for maintenance prioritization purposes at the road network level. Priority is based on the level of risk associated with the pavement degradations and with different types of vehicle.

Keywords

Vehicle behaviour, kinematic and dynamic effects, pavement damages, maintenance system.

1. Introduction

It is well-known that the main causes of road accidents are broadly related to human factors, vehicles' performance, roads and environmental conditions.

To improve the accidents prevention, several measures could be undertaken in terms of drivers' education, development of safer vehicles and improvement of infrastructure maintenance policies [1]. With regard to the latter, it has to be pointed out that the rate of road accidents caused by pavement defects is relevant in many countries worldwide. The severity of this issue may vary based on the considered country. In this regard, we can mention the use of maintenance programs and the relative financial investments, or the significant rate of Powered Two Wheelers (PTW). These are some of the most vulnerable users due to their dynamical behaviour [2-4].

In 2014, about 26.000 people were killed in road accidents throughout the European Union (EU). Motorcycle and moped fatalities (all together defined as PTW) accounted for 17% of the whole fatalities (16% in 2005) [4].

In the last decades, researchers' efforts have been focused on the development of supporting solutions for road safety managers. The primary focus of these interventions is to lower the risk of accidents by reducing the probability and the gravity of crashes [1, 5]. In terms of accidental probability, the development of effective

methods for the identification of the different pavement damages and the evaluation of their relevant effects on the vehicles dynamics and kinematics, are mandatory for the identification of the most effective maintenance measure.

In view of the above, highway designers and road engineers are increasingly using both dynamic effects exerted by or on dynamic loads [6, 7, 8] and simulation codes to analyse how roadway design choices or pavement conditions may affect the vehicles dynamics, hence, the driving safety [9]. As a result, simulation software manufacturers have recently invested significant resources to raise the reliability of the models. The evaluation of the vehicles' dynamic behaviour could be analysed by vehicle dynamics models. These have an enhanced capability of reproducing the vehicle dynamics including pitch, yaw and roll, as well as in generating realistic vehicle trajectories. In general terms, it is known that the forces and the moments generated between the tire and the ground rule the vehicle motion; hence, the validity of such virtual tests depends on the quality of both the tire model and the modelling of the ground surface.

The topic was tackled by Sayers et al. [10] in 2002. The Authors investigated how mathematical models of vehicles could be used to infer about their dynamic behaviour. Traditionally, computer simulation analyses have been limited to commercial-addressed experts' specific questions about the vehicles performance. However, less experienced engineers can also run mathematical models when the simulation technology is combined with a modern graphical interface and a proper database including the vehicle properties. Sayers described features in the user interface that supported quick learning on the part of the user.

Later on, Gillespie [11] provided an overview of the simulation software applications. The Author also showed how these software were used in automotive engineering courses to analyse acceleration, braking, aerodynamics and cornering performances. In this work it was reported that the CarSim® vehicle dynamics simulation software was introduced at the University of Michigan as a tool for improving the learning experience in laboratory courses.

Yu and Johnson [12] reported successful validations of the model with regard to the steering input and the conditions of lateral acceleration. Furthermore, Carsim was used by Xu et al [13] for brake system testing in a virtual environment. The primary motivation for this was related to the relatively high cost and limited coverage of test conditions for real-life experimental investigations. The software allowed to record the performance of a benchmark vehicle in a wide range of differing test conditions. As a result, simulations proved time- and cost-effective performances. Indeed, several applications supported by mathematical models can be already found in the literature [14-16].

With regard to the motorcycles case, more scientific contributions [17, 18] have focused on the effects exerted by the pavement conditions on the dynamics of PTWs. To this purpose, a further high-reliability simulation software, namely Bikesim®, was used with promising outcomes. This study reports on the preliminary activities performed within a wider research path [19], and deals with the evaluation of the effects exerted by the presence of pavement rutting, on the vehicles' dynamics. The pavement rutting is generally described as a longitudinal deformation along the wheel paths. It is characterized by two main attributes, i.e., depth and width, and it is usually caused by several possible causes such as the inadequate compaction in surfacing or base, the plastic deformation of bituminous materials (accelerated by the combination of traffic load and high temperature) and the structural failure of the subgrade. In particular, a driving scenario characterized by increasing rutting conditions was virtually tested by means of Carsim® and Bikesim® softwares [20], to evaluate the dynamic impact suffered by cars and PTW, respectively. As a result, useful suggestions for planning maintenance interventions, based on the evaluation of the risk connected to different configurations in terms of damage evolution and different impacts on different types of vehicles, are retrieved.

The paper is outlined as follows. In Section 2, the different variables for the simulation scenarios are given, and the analysis criteria are described. In Section 3, the outcomes from the simulations are reported with respect to the considered geometries and vehicles. An interpretation of the results and comparison between different configurations is proposed in Section 4. Finally, conclusions and future perspectives of the research are given in Section 5.

2. Methodology

The simulation codes used in this study provide accurate reproduction of the dynamic performance of cars and motorcycles in different pavement surface conditions. According to a specific research program, simulation layouts including several pavement degradations, such as polishing, potholes, etc., were previously tested [17-19]. In this work, the authors tackled the topic of the dynamic effects on the vehicles motion of rutting in bituminous pavements (i.e., one of the most frequent damages).

The experimental design aims at defining the variables that mostly affect the dynamic behaviour of both cars and PTW when travelling along differing road elements affected by rutting. The investigated variables were both geometrical and functional. In particular, i) the geometric features of the road elements where damages are located, ii) the geometric characteristics of rutting and iii) the speed of the vehicles were here investigated.

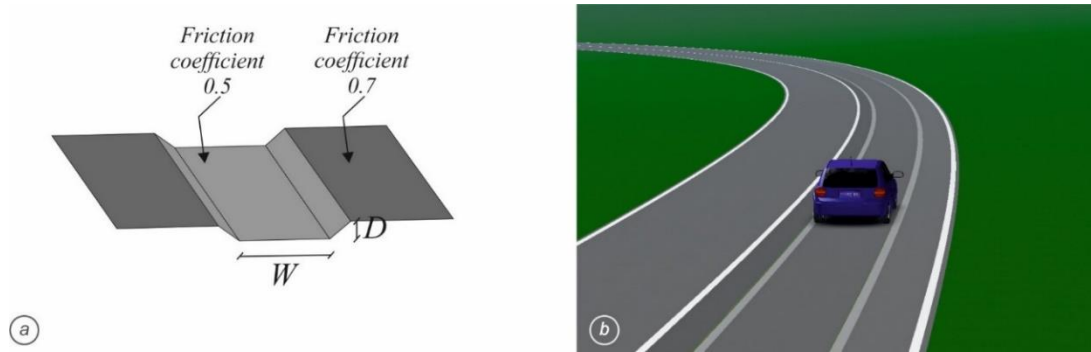


Figure 1: Rutting characteristics and localization.

With regard to the geometric conditions, two different cases were accounted for. The presence of a longitudinal rutting in a straight road element was first evaluated. Afterwards, the curve case was considered. To ensure an intersection between the vehicle trajectories and the rutting paths, vehicles were committed to “virtual overtaking maneuvers” when travelling in straight road sections. In the curve element cases, instead, the trajectory of the vehicles always met the longitudinal ruts. This was due to the lateral offset caused by the lateral forces and the adherence conditions (Figures 2a and 2b). According to the driver model, at this first stage of the research the drivers were requested to drive within the target path originally defined. This must be respected also in the case of the occurrence of several forces related to the pavement degradations. The above condition was taken to have the same reaction of car and motorcycle drivers to counteract negative effects in terms of trajectory. Different reactions of the drivers will be investigated in future research.

To contain the number of the variables, a single value of radius ($R=400$ m) was considered, for reproducing rural road curve elements. The vehicle speed (S) ranged between 70 and 150 km/h regardless of the geometrical conditions. This was set to investigate the dynamic effects resulting in rural road conditions.

According to the international distress classification standards [21-25], the severity of the rutting was defined with regard to two main attributes, i.e., depth and width. The rut depth (D) and the width (W) were set to range between 2 cm and 6 cm and between 20 cm and 40 cm, respectively (see Figure 1a).

In order to reproduce rutting effectively, a different tire/ground friction coefficient was used inside the ruts, to simulate an internal polishing or the presence of water. In more detail, a general value of tire/ground friction was set as 0.7 for a “regular” pavement friction level, whereas a lower value of 0.5 was used inside the ruts (see Figure 1a), in accordance to the suggestions of the software manuals [20].

The vehicles for the simulations were chosen to reproduce a C-class passenger car (Figure 1b) and a standard model of a PTW, respectively (Figure 2). However, the software databases include several models of passenger cars and motor vehicles and will be used to evaluate different dynamic responses in the future. All of the aforementioned parameters were used as input data for the simulation software. After running the mathematical models, the results were returned as video and numerical outputs. The former allow the users to macroscopically understand the dynamic responses of both cars and motorcycles, in order to have an immediate visualization of the incurred issues. On the other hand, the numerical output allow for a further data processing to investigate possible correlations between the variables.

With regard to the video output, the following four macroscopic behaviours were recorded:

- No particular dynamic effects caused by rutting
- Skid effects
- Severe skid effects, followed up by a roadway departure or fall down
- Rails effects: vehicle trajectory is fully constrained by rutting



Figure 2: Localization of rutting damage and simulated maneuver in both Straight and Curve elements.

With regard to the numerical output, several driving parameters were recorded. Among these, we can mention the three components of the acceleration applied to the mass-centre of the motorcycle (longitudinal, transversal and vertical), the three components of the rear tire force, the three components of the front tire force, the destabilizing moment on the front tire and the lateral position (trajectory) of the vehicles against the damages.

In this paper, an evaluation of the large number of the video results was performed in order to preliminarily define the dynamic responses of the vehicles in differing simulation scenarios, and to evaluate and to compare the differences in cars and motor vehicles trajectories under the same conditions of pavement damage. To this purpose, a qualitative approach was followed. More than one thousand simulations (3 widths * 5 depths * 17 speeds * 2 geometrical elements * 2 vehicles types) were performed and analysed. The processed numerical database is expected to be used for the development of predictive models, in forthcoming studies.

3. Analysis and Results

According to the above methodology, the vehicle dynamic response was recorded, with varying travel speed and rutting conditions. Table 1 summarizes the considered simulation scenarios.

The results from the tests are hereafter presented by means of graphical tables illustrating vehicles' behaviour with respect to speed and rutting conditions. Three or four main effects on the vehicles are recorded and identified using a chromatic scale, for each considered vehicle-geometry configuration. Tables 2 and 3 illustrate the results recorded in straight road condition tests, whereas Tables 4 and 5 refer to the curve element simulations.

3.1 Straight road element

The dynamic response of the vehicles in the case of a straight road element affected by rutting was evaluated by forcing the vehicle to a double deviation from its straight trajectory. In view of this, an overpassing maneuver was simulated. Accordingly, the model allowed to grant always the intersection between the vehicle trajectory and the longitudinal rut (Fig. 2a).

In order to evaluate the same test conditions, the deviation angle between the vehicle trajectory and the rut was set to be the constant, regardless of the travel speed. The trajectory of the vehicle during the overpassing maneuver was defined according to the Italian standards for the construction of roads [26].

3.1.1 Carsim simulation code

Table 2 illustrates the dynamic response of the cars travelling along a straight road element, by simulations run in CarSim software. The whole set of macroscopic dynamic behaviours presented in Section 2 was encountered once the outputs had been analysed. They were marked with different shades of grey, ranging from white to dark grey, and standing for "no effect" and "rails effect", respectively.

Table 1: Simulation scenarios

		Straight road element	Curve element	Carsim simulation code Bikesim simulation code
Rutting characteristics	Width [cm]	20/30/40	20/30/40	
	Depth [cm]	from 2 to 6	from 2 to 6	
	Friction Coefficient	0,5	0,5	
Geometrical characteristics	Vehicle Manoeuvre	Overpassing manoeuvre	Target path -1,75 m	
	Curvature [1/R]	0	0,0025	
	Transversal gradient [%]	2.5	from 2.5 to 7	
	Friction Coefficient	0,7	0,7	
Speed [Km/h]		from 70 to 150	from 70 to 150	

Table 2: Passenger Car Behaviour in Straight Road Element

W [cm]	D [cm]	S [km/h]																
		70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150
W20	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W30	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W40	D2																	
	D3																	
	D4																	
	D5																	
	D6																	

No effect

Skid effect

Severe skid effect

Rails effect

As it is listed in Table 2, the dynamic behaviour of the vehicle shows no dependence on the speed of the vehicle itself. Conversely, the rutting geometric features (i.e., width and depth) significantly influence the dynamics of the vehicle. In particular, as the value of rutting width is kept constant, the vehicle tends to loose stability as the depth of the rut increases. On the contrary, unstable dynamic behaviours were recorded for shallower rutting depth if we consider wider ruts. This was verified up to the case of 40 cm wide ruts, where unstable behaviours were observed even in the lower considered depth range (2-3 cm).

If both the depth and the width increase, the vehicle route (trajectory) is increasingly affected by rutting, up to occurrence of rails effect. In the case of width of 40 cm, for instance, this occurrence is verified from 5 cm of depth onward.

3.1.2 Bikesim simulation code

The motorcycles behaviour in straight elements were analysed by running the same simulations in the Bikesim software. In this case, only three categories of dynamic effects were observed, ranging from “no effects” to “sever skid effects”. Despite of few exceptions, Table 3 shows that travel speed seems not to affect heavily the interaction among the rutting and the vehicle dynamics. On the contrary, rutting conditions strongly affect the motorcycle stability, even for low depth and width values. An exception to this behaviour was observed at the depth of 2 cm.

Table 3: Motorcycle Behaviour in Straight Road Element

W [cm]	D [cm]	S [km/h]																
		70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150
W20	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W30	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W40	D2																	
	D3																	
	D4																	
	D5																	
	D6																	

No effect

Skid effect

Severe skid effect

3.2 Curve element

In this case, the intersection between the vehicles trajectory and the longitudinal rutting was ensured by the lateral offset from the set trajectory. This is exerted on the vehicle by the lateral forces and the adherence conditions (Fig. 2b).

3.2.1 Carsim simulation code


As Table 4 demonstrates, in this case the vehicle behaviour is more affected by the travel speed rather than the rutting features. Indeed, the vehicles motion becomes more unstable as the speed increases. The analysed simulations pointed out that, in the whole set of considered speeds, the skid conditions are always observed. More specifically, simple skid effects are observed to turn into rails phenomena (regardless of the rutting conditions) at a speed of 85-110 Km/h. If the velocity keeps increasing, the vehicles behaviour skips to severe skid conditions, hence leading to a roadway way out of the vehicle.


3.2.2 Bikesim simulation code

Results in Table 5 demonstrate the severe effects exerted by rutting on the motorcycle dynamics while traveling in a curve road section. In most cases, this type of pavement damage produces dangerous instabilities, generally leading to a fall down. Within a rutting depth lower than 5 cm, it is always recognizable a range of speed related to stability conditions. This means that in some particular cases the speed can help to increase the stability of a motorcycle interfering with the longitudinal rutting.

Table 4: Passenger Car Behaviour in Curve Element

W [cm]	D [cm]	S [km/h]																	
		70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	
W20	D2																		
	D3																		
	D4																		
	D5																		
	D6																		
W30	D2																		
	D3																		
	D4																		
	D5																		
	D6																		
W40	D2																		
	D3																		
	D4																		
	D5																		
	D6																		

 Skid effect

 Rails effect


 Severe skid effect

Table 5: Motorcycle Behaviour in Curve Element

W [cm]		D [cm]		S [km/h]																	
				70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	
W20	D2																				
	D3																				
	D4																				
	D5																				
	D6																				
W30	D2																				
	D3																				
	D4																				
	D5																				
	D6																				
W40	D2																				
	D3																				
	D4																				
	D5																				
	D6																				

No effect

Skid effect

Severe skid effect

4. Discussion

In this Section, the aforementioned simulation outcomes are commented more thoroughly. In Section 3, the dependence of the dynamic behaviour of both cars and motorcycles in differing geometric configurations (Curve or Straight road elements) has been pointed out. Such a results is hereafter discussed with regards to: (i) vehicles typology and (ii) geometric element analysis.

4.1 Vehicles behaviour

As far as the passenger car is concerned, Carsim simulations have highlighted a high dependence of the vehicles dynamics on the severity of the rutting conditions rather than the travelling speed, for straight and curve geometric conditions, respectively (Tables 2-3). In more detail, for straight conditions, the rutting depth seems to be the variable that mostly affects the vehicle stability.

Moreover, cars have showed to be highly subject to rails effects. These are detected for different stages of dynamic and rutting conditions. Indeed, for straight elements, the rails effect were detected for the most critical scenarios, represented by the deepest ruts. On the contrary, rails effects are recorded as intermediate conditions for curve elements, recognized for a range of speeds approximatively located in the center of the considered set of speeds. This fact could be referred to the higher values of lateral force recorded in curve elements, allowing the vehicles to get out from the rut path.

Concerning the motorcycle case, simulations showed generally more severe effects of rutting on the stability of the PTW (Tables 4-5). This is particularly true for the curve case, where, in addition, the applied lateral force and the balance condition amplify the effect of the defects on the PTW's stability.

4.2 Geometric elements

At different rate of impact, the presence of rutting in a straight road element generates non-negligible effects on both cars and motorcycles. The severity of these effects was found to depend on the rutting depth, in the only former case (Table 2). With regard to the motorcycle case, severe effects were recorded all along the depth range, for values higher than 3 cm (Table 3). In such a framework, it is worthwhile noting that this behaviour could be strictly related to the geometry of the vehicle trajectory. In particular, simulations should be run for more trajectory-rutting deviation angles, in order to found reliable relationships.

With regard to the curve elements, Table 3 shows that for the cars simulations, the speed is the most impactful variable. It is also showed that, for the considered curve radius, critical dynamic conditions are reached for speeds higher than 85 Km/h. In these conditions, rails effects were recorded.

This can be related to the higher values of the lateral force applied, forcing the vehicles trajectory towards the rutting direction. For speed levels higher than 110 Km/h, the later force reaches values sufficient for the vehicle to overcome the rut, but also involving a roadway departure.

Concerning the motorcycle case, a diffused instability condition was observed for the whole set of tested configurations, with the exception of a speed range, ranging between 120 Km/h and 145 Km/h, and between 2 cm and 5 cm of depth (Table 5). Due to the uniqueness of the case, this was furtherly investigated in Section 4.3.

4.3 Further remarks

From a further analysis of the simulations, it was possible to divide the motorcycles falls down in two different classes, namely:

- Rutting fall
- Dynamic fall

Rutting fall refers to a fall occurring during the exit of the motorcycle from the rut path. This is strictly related to the deviation angle between the trajectory and the rutting, and to the lower speeds, within the analysed range. On the other hand, the dynamic fall refers to the dynamic instability caused by the too high speed at that particular geometric condition. Indeed, the weak equilibrium of the motorcycle caused by its leaning during the curve, generates the fall down as the PTW comes to interfere with the rutting. In this case, the fall down occurs at the first intersection of the motorcycle with the rutting.

After detecting these two major behaviours within the simulation scenarios, Table 2 could be therefore updated to a new version (i.e., Table 6) that includes four conditions: stability, skid effects, rutting falls and dynamic falls.

It is worthwhile noting how, regardless of the rutting width conditions, it is always possible to detect a stability area between the areas linked with the two types of fall down. This area tends to extinguish as the rutting depth reaches a critical level (6 cm).

This particular feature can be interpreted by considering the dynamic condition undergone by the motorcycles between the two fall-down areas. In this context, on the one hand the rutting fall is compromised by the inertial force generated by the high speed (that allows the motorcycle to overcome the rutting borders). On the other hand, the applied lateral forces are not sufficient to make the cycle falling down.

In Figure 3 the aforementioned behavioural analysis was summarized into three plots describing the stability conditions of the motorcycles, within the considered range of speed and rutting depth. Each plot refers to an increasing rutting width level.

5. Conclusions and future perspectives

This paper reports a preliminary analysis of the dynamic effects caused by longitudinal rutting to the motion of cars and motorcycles in differing road elements.

The analysis was performed running the same virtual scenarios by means of two vehicle dynamic simulation softwares, namely, CarSim and BikeSim. These allowed to reproduce differing rutting conditions and operational speeds.

At the present stage of the research, a qualitative analysis of the macroscopic effects induced by the particular rutting/speed configurations was carried out and reported by means of grey-scale tables. As a result, promising considerations can be done with regard to the different dynamic behaviours observed at various tested conditions. It is worth to emphasize the relevance of this research for maintenance prioritization purposes at the road network level. Priority is based on the level of risk associated with the pavement degradations.

As a major upgrade of the research, a thorough numerical analysis of the dataset is planned to provide quantitative relationships between the test parameters and the relative dynamic effects. Furthermore, the gathered database should be enriched with different damages conditions as well as with a larger number of curve geometries, vehicle types and simulation conditions.

Table 6: Motorcycle Falling Conditions in Curve Element

W [cm]	D [cm]	S [km/h]																
		70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150
W20	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W30	D2																	
	D3																	
	D4																	
	D5																	
	D6																	
W40	D2																	
	D3																	
	D4																	
	D5																	
	D6																	

No effect

Skid effect

Rutting fall

Dynamic fall

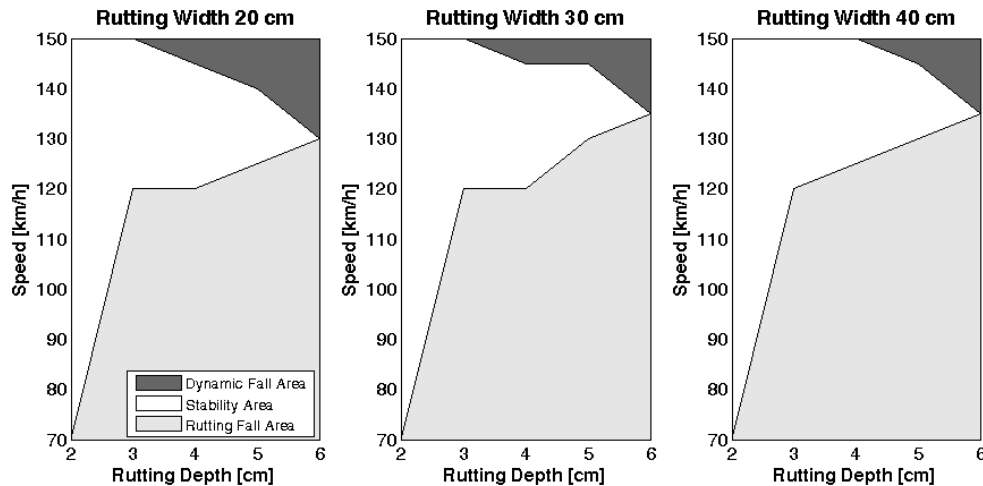


Figure 3: Safety diagrams in case of Motorcycle Falling Conditions in Curve Element.

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