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ANALYSIS OF THE PROCESS OF DOUBLE-DECK BUS ROLLOVER AT THE AVOIDANCE OF AN OBSTACLE HAVING SUDDENLY SPRUNG UP

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Abstract

A critical traffic situation has been explored where a double-deck bus may roll over. The factors that may cause critical situations during a bus drive have been analysed. Based on this, they may be categorised as being related to vehicle construction, vehicle operation, and road infrastructure. A situation has been chosen for the analysis where the bus without passengers avoids an obstacle having suddenly sprung up in front of the bus at a distance within which the bus cannot be stopped. A similar problem occurring in the case of a passenger car drive was analysed in study [6]; it was indicated there that the manoeuvre of avoiding an obstacle is definitely more favourable in comparison with the braking process.

A model of the bus motion dynamics with 12 degrees of freedom was adopted. The vehicle trajectory was given in the form of a predefined input generated by a driver model. The course of the rollover process depends to a significant extent on the interaction between the tyres and the road surface. A semi-empirical non-linear TMeasy tyre model was chosen. The calculations were carried out with the use of a computing program specially built for this purpose, where a double-deck bus model and a driver model were applied to investigate the traffic situation as described above.

The calculation results obtained have shown that the process of rollover of a bus without passengers emerges at the final stage of the obstacle avoidance manoeuvre at a speed exceeding 108 km/h. This has been confirmed by the course of changes in the pressure of wheels on the road. Based on the simulation calculations carried out, an attempt was made to determine, from the observed courses of changes in physical quantities, the values that might warn the driver about a situation of imminent danger of rollover of the double-deck bus and thus might affect driver's actions.

Keywords: *transport, buses, road safety, buses roll over*

1. Introduction

The dynamically developing road transport leads to a high number of road accidents. Among them, the accidents with bus rollover make a special group because of the severity and extent of the injuries that occur to bus passengers because a passenger's body hits many times on bus interior elements during such an accident.

The factors that may cause critical situations during a bus drive may be grouped as follows:

- constructional factors, especially high location of the centre of vehicle mass, low suspension rate (excessive flexibility of suspension springs), and incorrectly selected characteristics of the suspension system and road wheels taken as a whole,
- operational factors such as, above all, excessive drive speed, too rapid performance of the obstacle avoidance manoeuvres, rapid gust of side wind, tyre blowout, suspension system failure, side-slip of rear axle wheels, etc.,
- road infrastructure factors, e.g. poor visibility at single or multiple road bends, cross slope of the road, steep road descents, elevated roundabouts, ruts, etc.

In most cases, the rollover directly results from:

- Excessive lateral forces caused by inertia or side wind,
- Excessive side tilt of the bus body during complex manoeuvres on the road.

This work was undertaken to explore the dynamic processes that determine the course of the double-deck bus rollover process. A situation has been chosen for the analysis where the bus without passengers must avoid an obstacle having suddenly sprung up in front of the bus at a distance within which the bus cannot be stopped. The behaviour of a bus fully loaded with passengers will be analysed separately.

The course of the bus rollover process may be analysed on the grounds of model tests and experimental trials. The model tests carried out within this scope are based on calculations and computer simulations. The purpose of this analysis was to show the factors that are decisive for the development of a critical situation, and in particular:

- to determine the critical drive speed value,
- to obtain information on the factors that may warn the driver about the imminent danger of rollover even before the critical bus body tilt is reached,
- to improve the vehicle construction in respect of the protection of bus occupants.

No results of such tests have been presented in the literature available. The minibus tests described in [7] indicate serious dangers related to the possibility of bus rollover during a lane-change manoeuvre.

2. Description of the model of a bus and road infrastructure

The reference systems adopted when building a model of the bus motion dynamics have been shown in Fig. 2.1.

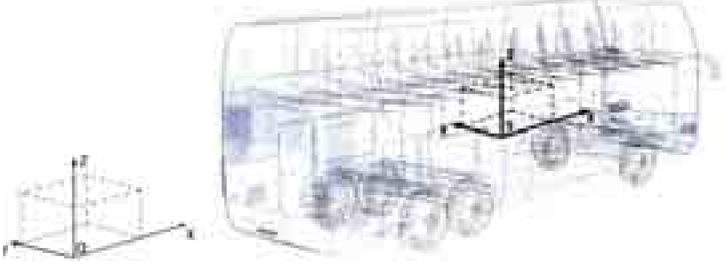

Fig. 2.1. Reference systems adopted: O – global system; S – local system

The bus body was treated as a rigid body with six degrees of freedom; the independent movements of the springing of each wheel (along the axes parallel to the vertical axis of the bus body) were taken into account separately.

The equations of motion of the bus body solid have the form as follows:

$$\begin{cases} m\ddot{x} = \sum_{i=1}^{n} F_{xi}, \\ m\ddot{y} = \sum_{i=1}^{n} F_{yi}, \\ m\ddot{z} = \sum_{i=1}^{n} F_{zi}, \\ I_{x'}\dot{\omega}_{x'} + I_{z'}\omega_{y'}\omega_{z'} - I_{y'}\omega_{y'}\omega_{z'} = \sum_{j=1}^{k} M_{x'j}, \\ I_{y'}\dot{\omega}_{y'} + I_{z'}\omega_{x'}\omega_{z'} - I_{x'}\omega_{x'}\omega_{z'} = \sum_{j=1}^{k} M_{y'j}, \\ I_{z'}\dot{\omega}_{z'} + I_{y'}\omega_{x'}\omega_{y'} - I_{x'}\omega_{x'}\omega_{y'} = \sum_{j=1}^{k} M_{z'j}, \end{cases} \tag{1}$$

where:

the symbol “prime” (′) has the meaning that the physical quantity involved has been referred to thenlocal coordinate system {Sxyz},

m – vehicle mass,

F_{xi}, F_{yi}, F_{zi}, $M_{x'i}$, ... – external forces and moments acting on the bus body,

$\vec{r}$ – vector from the origin of coordinates to the centre of vehicle mass with coordinates (x, y, z) expressed in the inertial coordinate system {Oxyz},

I_i – moments of inertia of the bus body relative to the centre of mass, expressed in the local coordinate system {Sxyz}, i.e. $I_{x'}$, $I_{y'}$, $I_{z'}$,

$\omega_{x'}$, $\omega_{y'}$, $\omega_{z'}$ – projections of the vector of angular speed of the bus body in the local coordinate system {Sxyz}.

The following generalised external forces act on the vehicle:

- resultant aerodynamic force,
- road surface reaction forces applied to bus wheels (vertical, lateral, and longitudinal) and moments of these forces relative to the local coordinate system {Sxyz}.

To make simulation calculations of the critical situation explored, the program PC Crash 9.0 was chosen, the suitability of which for the analysing of such critical situations has been well substantiated in [8]. In the model adopted, the impacts of component forces of gravity and air resistance were taken into account, including the defined components of the longitudinal and lateral aerodynamic force at the points of application of these forces to the bus body. The vehicle trajectory was given in the form of a predefined input generated by a driver model.

The values of the road surface reaction forces applied to all the bus wheels were determined at every step of the calculation process, in accordance with the current state of motion and with taking into account the local wheel-to-road adhesion conditions.

The course of the rollover process depends on the interaction between the tyres and the road surface. Therefore, an important step is the defining of a tyre model. For the purposes of this analysis, a semi-empirical non-linear TMeasy tyre model was chosen, which makes it possible to approximate the actual forces and moments generated by the tyre based on experimentally determined slip characteristics of the pneumatic tyre.

Great difficulties were encountered when the values of the parameters and characteristics describing the properties of double-deck buses were collected. Following an analysis of the available descriptions of the existing constructions [4, 5] and a significant number of trial computations, the numerical values as shown in Tab. 2.1 were adopted for the actual calculations.

Tab. 2.1. Basic parameters of the bus model adopted

Description	Unit	Value
Unladen mass	Kg	17 275
Overall length	M	14.0
Overall height	M	4.2
Overall width	M	2.5
Height of the centre of mass	M	1.45
Moment of inertia relative to the Sx axis	kgm^2	34 500
Natural frequency of vertical vibrations of the bus body	Hz	1.4
Natural frequency of transverse angular vibrations	Hz	1.1

A PID driver model, i.e. a driver model with a proportional–integral–derivative controller, was adopted, which was to follow the predefined bus trajectory. Simultaneously, some limitations were applied to the driver model as specified below:

- The predefined constant bus speed should be maintained,
- The steering wheel rotation speed should not exceed 500 deg/s,
- The turning angles of the steering wheel and the steered axle wheels should not exceed 500 deg and 25 deg, respectively.

3. The computing program and the calculation process

The calculations were carried out with the use of a computing program specially built for this purpose, where a double-deck bus model and a driver model were applied to investigate the following traffic situation:

- An obstacle has suddenly sprung up on the bus lane in front of the bus,
- At the instant of the obstacle being noticed by the driver, the distance between the bus and the obstacle is shorter than the minimum achievable bus stopping distance,
- The bus may enter the adjacent lane for a short while only.

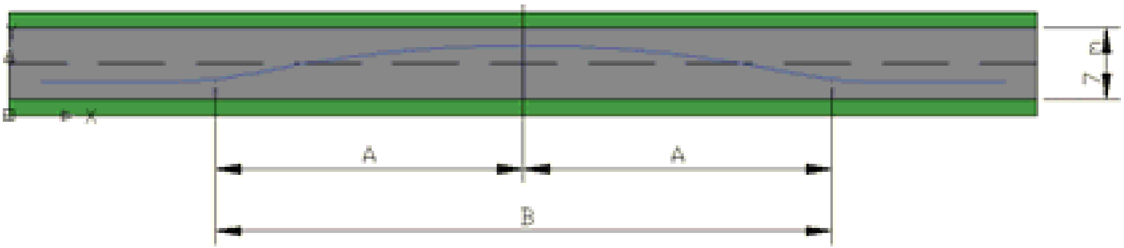

Fig. 3.1. An example of the bus trajectory

An assumption was made at the calculations that the manoeuvre under consideration was carried out on a flat horizontal road section with no cross slope, 7 m wide, and with hardened road shoulders (Fig. 3.1). The important dimensions were A = 30 m, B = 60 m, with the bus stopping distance from a speed of 70 km/h being not shorter than 42 m. Thus, the manoeuvre of avoiding the obstacle is the only way to prevent an accident in the situation as explored. The process of braking in such a situation would cause a reduction in the maximum available values of the side tangent reaction forces that may develop on the wheels, which means that the possibility of the manoeuvre to be performed by the driver would be reduced as well. This is consistent with the dependencies given in [1, 2] and concerning the adhesion forces available:

$$\sqrt{X_K^2 + Y_K^2} = W, \qquad W \le \mu Z_K \ , \tag{2}$$

where X_K and Y_K are tangent reaction forces and Z_K is a normal reaction force, present at the contact between the wheel and the road surface; the directions of these forces are consistent with the symbols given in Fig. 2.1. The index "*K*" indicates a specific bus wheel and μ is the coefficient of adhesion of bus tyres to the road surface.

At the calculations, particular attention was paid to the course of changes in the physical quantities that describe the bus rollover process.

4. General description of the bus rollover process

Before the actual calculations were started, many preliminary simulations were carried out to analyse the course of the physical processes that may occur in the traffic situation as explored. The selected sequence of photos presented in Fig. 4.1 shows the process of driver's reaction to a sudden entry of a passenger car from the road shoulder onto the carriageway. A rapid change from straight-line to curvilinear motion of the bus can be seen. The bus rollover process is preceded by significant sideslip of the rear axle wheels and increasing tilt of the bus body. The slip traces are marked as shadowed stripes on the road surface.

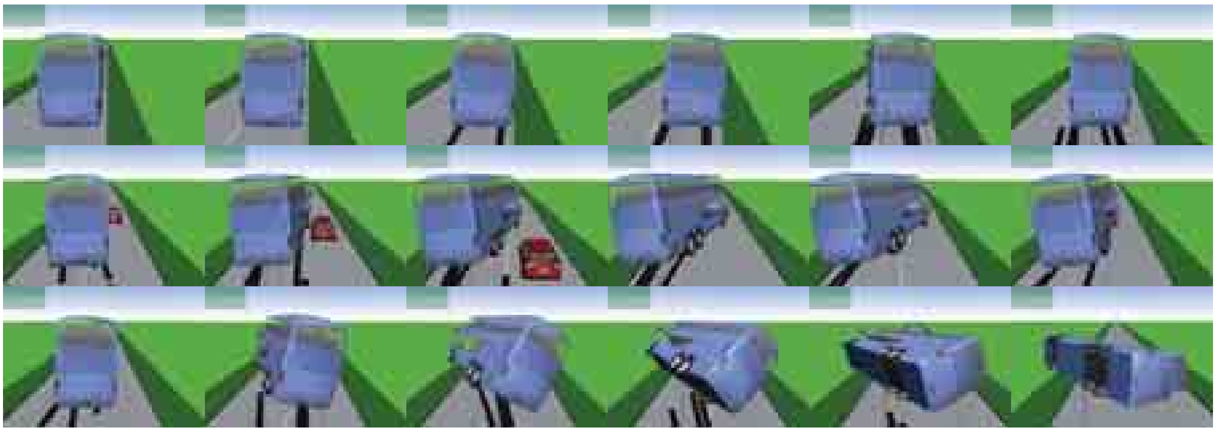

Fig. 4.1. An example of the results (a sequence of pictures) of a simulation of the bus rollover process at the avoidance of an obstacle having suddenly sprung up; bus without passengers, driven with a speed of 110 km/h

5. Results of simulation calculations

The curves representing changes in the most important physical quantities that describe the bus behaviour during the avoidance of an obstacle have been shown below. The following parameters have been chosen:

- Trajectory of the centre of mass,
- Bus body tilt angle,
- Lateral acceleration of the centre of mass,
- Bus wheel pressure on the road,
- Slip angle of the rear axle wheels.

The calculation results presented have been obtained for increasing speeds with which the bus travelled a specific road section. In the bus model, the driver tried to keep the bus (in the follow-up mode) on the predefined trajectory as shown in Fig. 3.1 and represented by the red curves in Fig. 5.1-5.5. The calculation results shown represent the behaviour of a bus without passengers where the selected suspension system and tyre characteristics were treated as being standard (nominal).

Fig. 5.1 provides the basic information on the course of the obstacle avoidance process, i.e. on the trajectory of the centre of mass of the bus plotted as a function of the distance travelled. In spite of the impact of significant lateral forces (centrifugal forces of inertia), this trajectory was close to that applied as the predefined input up to a bus drive speed of 104 km/h. This means that the driver could practically follow the predefined trajectory and thus to avoid the obstacle within a speed range of up to 104 km/h. Further increase in the drive speed resulted in significant departure from the predefined trajectory in spite of driver's counteraction.

The course of changes in the sideward tilt angle of the bus body (Fig. 5.2) showed that the process of rollover of a bus without passengers emerged at the final stage of the obstacle avoidance manoeuvre at a speed of 110 km/h. This was confirmed by the course of changes in the pressure of wheels on the road, presented in Fig. 5.4. The changes in the wheel pressure on the road have been shown for the bus side on which the wheels lift off at the bus rollover stage.

A separate presentation of the calculation results has been made in Fig. 5.5, where the results of calculation of the slip angle of the rear axle wheels, averaged for the tandem real axle of the bus, have been shown.

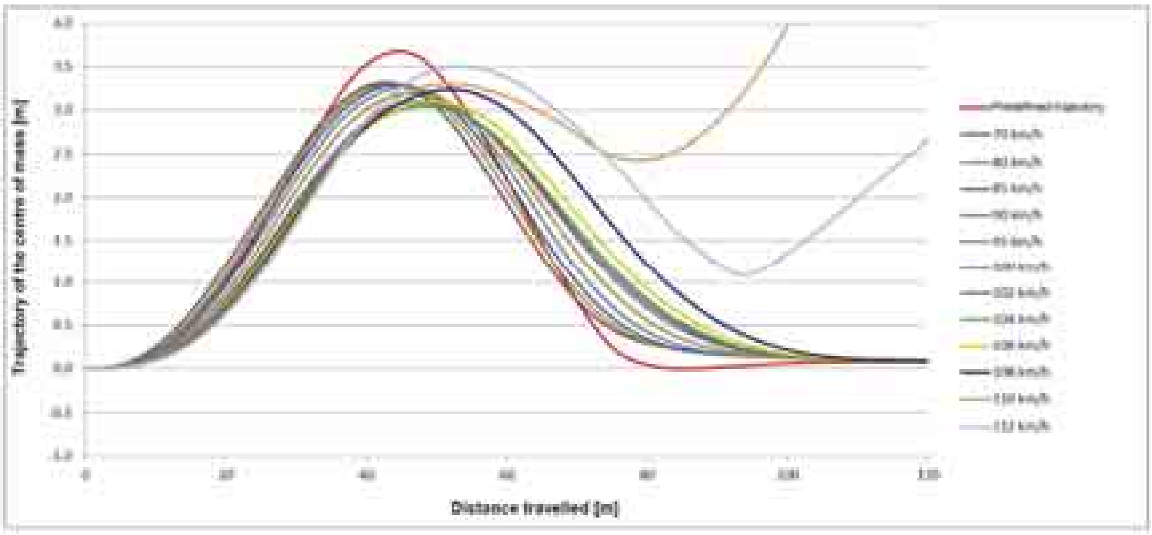

Fig. 5.1. Comparison of the calculation results for bus drive speeds ranging from 70 to 112 km/h; trajectory of the centre of mass of the bus

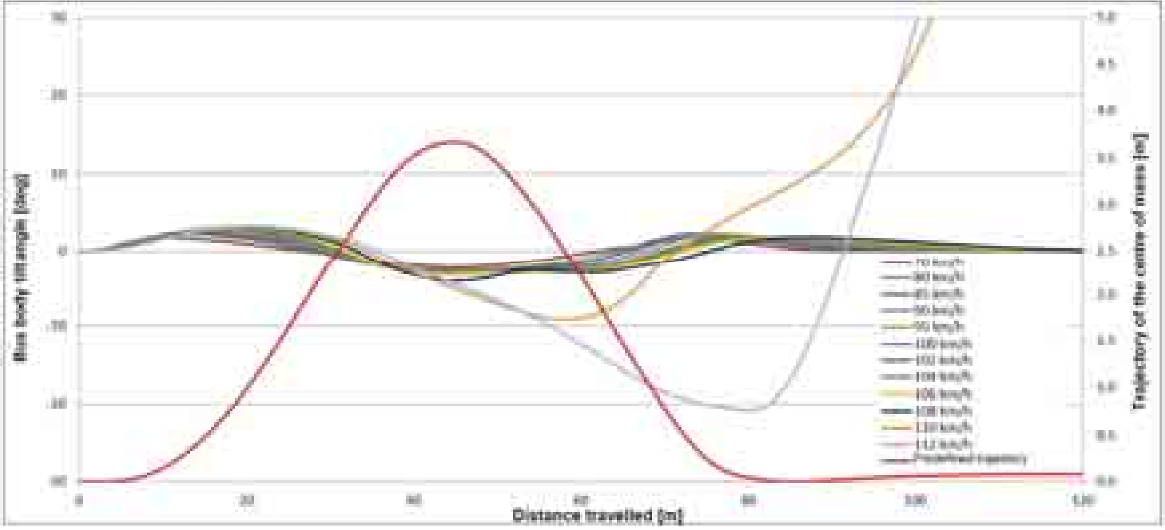

Fig. 5.2. Comparison of the calculation results for bus drive speeds ranging from 70 to 112 km/h; sideward tilt angle of the bus body vs. distance travelled

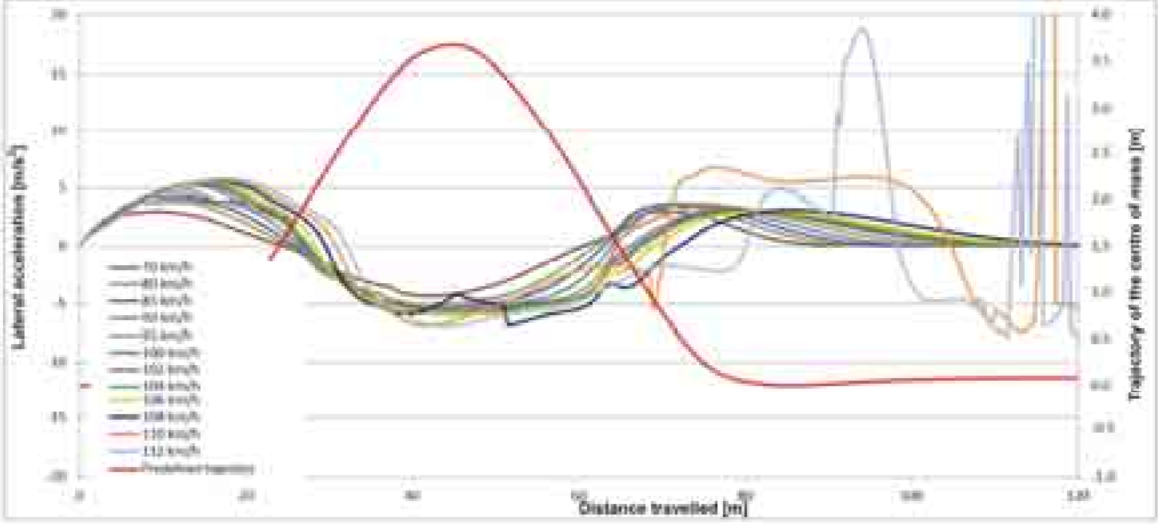

Fig. 5.3. Comparison of the calculation results for bus drive speeds ranging from 70 to 112 km/h; lateral acceleration of the centre of mass vs. distance travelled

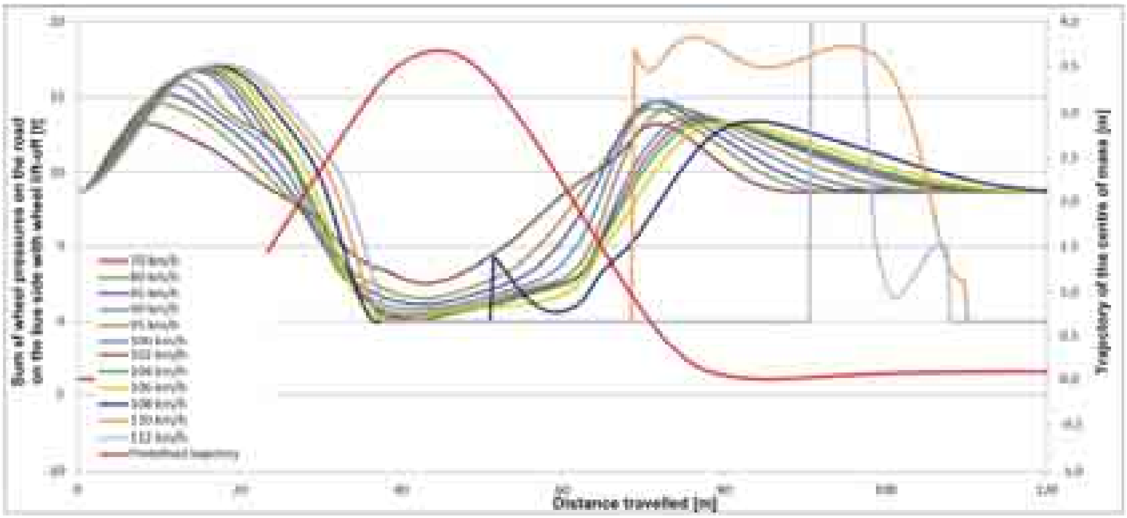

Fig. 5.4. Comparison of the calculation results for bus drive speeds ranging from 70 to 112 km/h; wheel pressure on the road on the bus side with wheel lift-off vs. distance travelled

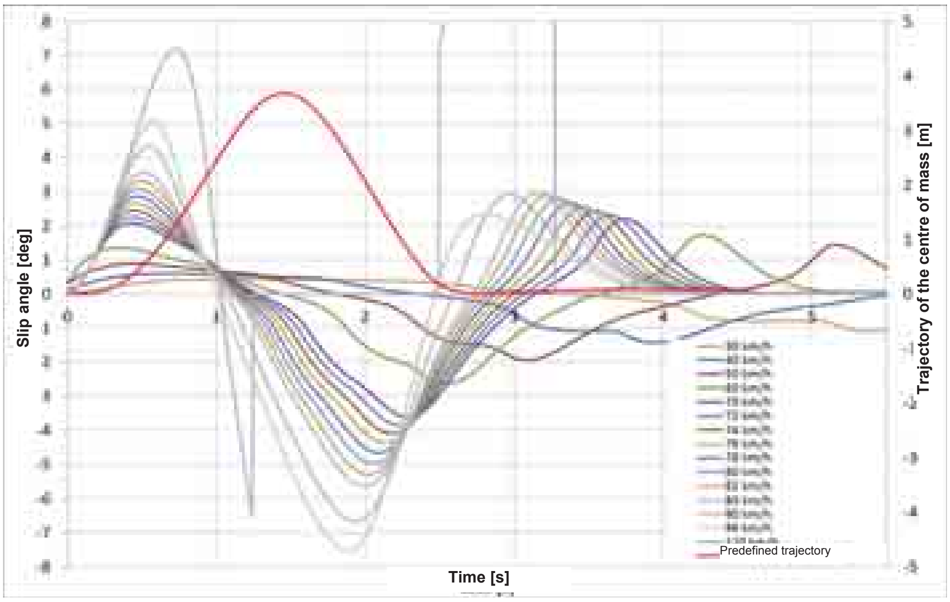

Fig. 5.5. Slip angle of the equivalent rear axle wheels vs. time

6. Summary of the most important values determined in result of the calculations

Based on the simulation calculations carried out, an attempt was made to define certain characteristic features of the observed courses of changes in physical quantities that might make it possible to detect the start of a bus rollover process while the process still can be staved off. In result of an analysis, the following quantities were selected:

- Extreme value of departure of the actual trajectory of the centre of mass from that predefined, at the final stage of bus return to the carriageway lane occupied originally (determined at a distance of 70-80 m from the beginning of the obstacle avoidance manoeuvre, cf. Fig. 3.1);
- Extreme values of the lateral acceleration at the initial stage of the obstacle avoidance process (change from straight-line to curvilinear motion of the bus);
- Minimum pressure of wheels on the road on one bus side (determined at the halfway stage of the obstacle avoidance manoeuvre);
- Extreme values of the slip angle of the equivalent rear axle wheels (determined at the halfway stage of the obstacle avoidance manoeuvre, as the average value for the wheels of both rear axles).

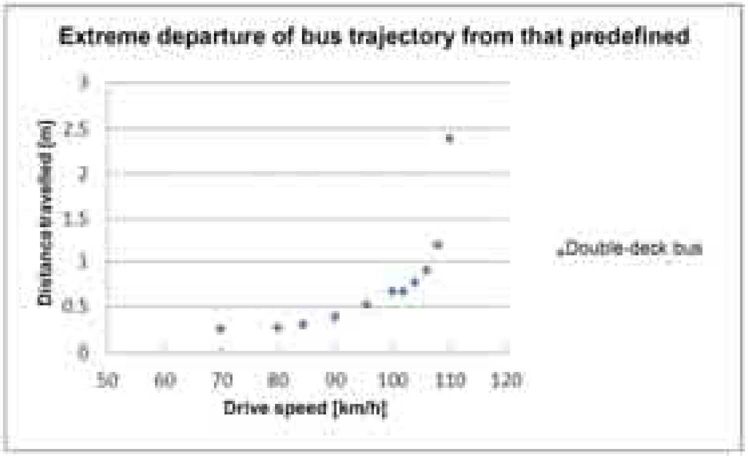

Fig. 6.1. Extreme departure of the actual trajectory of the centre of mass from that predefined

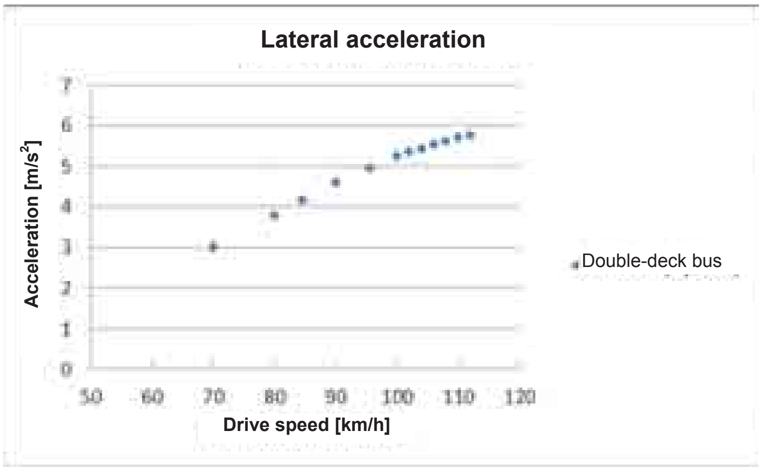

Fig. 6.2. Extreme values of the lateral acceleration measured at the centre of mass

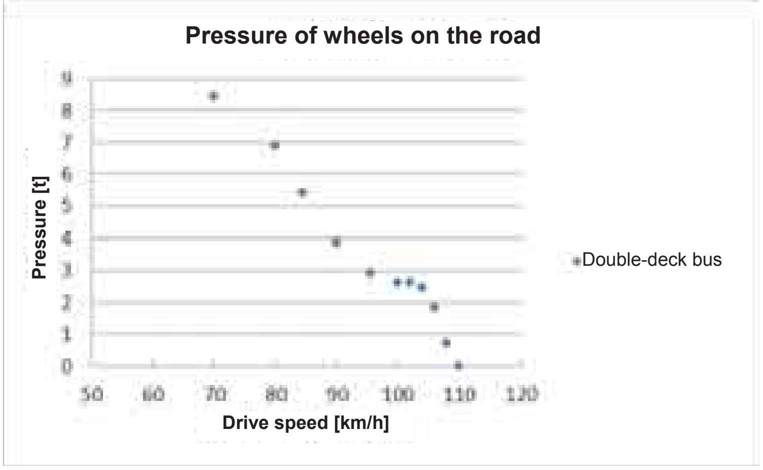

Fig. 6.3. Minimum values of the sum of the pressures of wheels on the road on one bus side

An analysis of changes in the quantities observed vs. the bus drive speed (see Figs. 6.1-6.4) has revealed the following:

- The extreme values of the slip angle of rear axle wheels and the lateral acceleration of the centre of mass increase almost proportionally to the bus drive speed.
- The extreme values of departure of the actual trajectory of the centre of mass from that predefined rapidly rise at a speed of 106-108 km/h while the bus was actually found to roll over at a speed of 110 km/h.

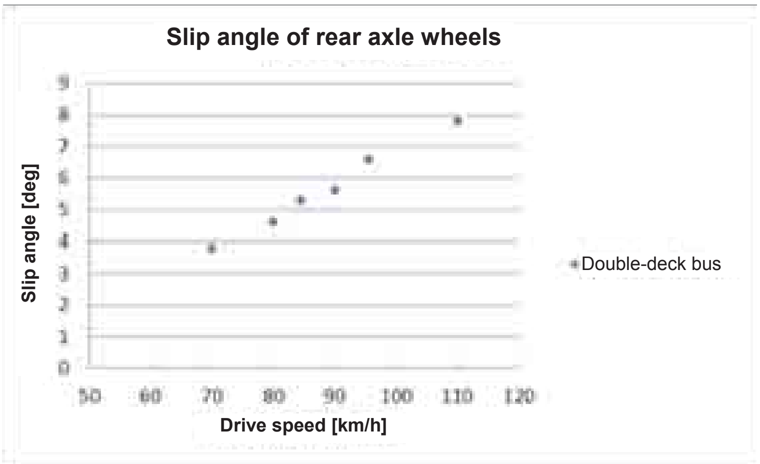

Fig. 6.4. Extreme values of the slip angle of the equivalent rear axle

The calculations carried out have shown the behaviour of the bus without passengers to be as follows in the traffic situation explored:

- The bus rollover takes place at a speed of about 110 km/h and is preceded by wheel lift-off on one bus side.
- The bus rollover is "signalled" by significant slip of rear axle wheels and the slip results in a rapid growth in the departure of bus trajectory from that predefined; both these factors become a clear warning for the driver of immediate danger.
- The time elapsing from the wheel lift-off to the reaching of the critical value of the bus tilt angle is 1.8 to 2.2 s; a part of this time may be used by the driver for a defensive reaction.

The analysis of the bus behaviour also indicates a strong relationship between the bus tilt and the rollover-inducing force arising from variations in the steering wheel turning angle, necessary for the manoeuvre under consideration to be performed. The time history of this force is close to a sinusoidal vaveform and its frequency is about 0.8-1.2 Hz. The above has been illustrated in Fig. 6.5. This input frequency is close to the natural frequency of transverse angular vibrations of the bus body (cf. Tab. 2.1), which has an additional adverse impact on the obstacle avoidance process. This is one more factor indicating that the biggest danger arises at the final stage of the obstacle avoidance manoeuvre.

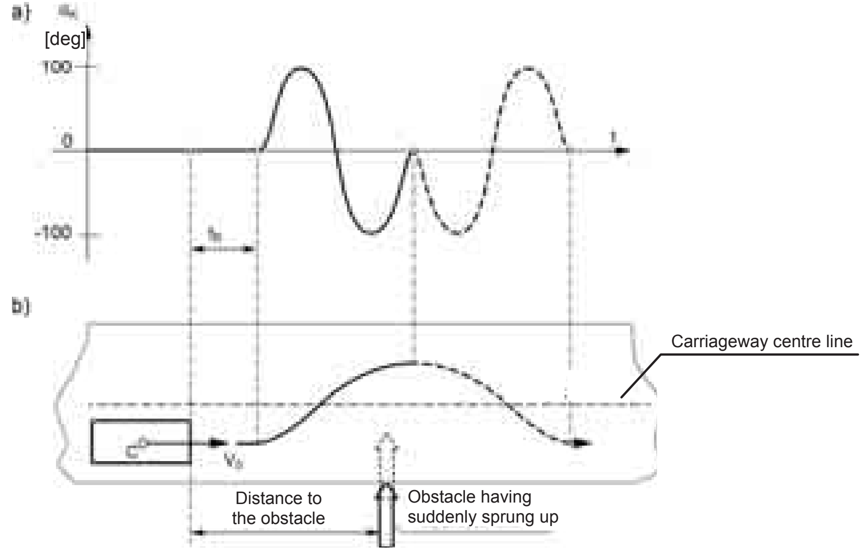

Fig. 6.5. Schematic diagram of the obstacle avoidance process: a) – time history of the steering wheel turning angle; b) – outline of the bus trajectory and relationship between the trajectory and the steering wheel turning angle; C – bus centre of mass; v0 – drive speed and direction; tR – driver reaction time and the corresponding distance travelled by the bus

7. Recapitulation

The analysis of the calculation results has provided important information abut the process of rollover of double-deck buses. For the bus model selected, the difficult manoeuvre of avoiding an obstacle having suddenly sprung up will end in rollover if the bus speed exceeds a threshold of about 110 km/h. In this case, therefore, this speed threshold is higher than the official bus speed limit. This shows that the model built and the model parameters selected well describe the operational bus characteristics that are important in the critical traffic situation as explored.

The analysis of changes in the physical quantities that describe the motion of the model of a bus without passengers has indicated how complex processes are decisive for the bus behaviour during rollover. The bus without passengers may carry out the difficult manoeuvre of avoiding an obstacle having suddenly sprung up even when the bus speed exceeds 100 km/h, i.e. practically within the whole range of permissible speeds. It should be taken into account that the same bus fully loaded with passengers would roll over at a speed much below this limit because the centre of mass of such a bus is situated higher than it is in the situation of the bus being driven without passengers. Even this very brief description of the traffic situation explored highlights the very serious dangers that may be encountered by double-deck buses in real traffic conditions.

References

[1] Prochowski, L., Unarski, J., Wach, W., Wicher, J., *Podstawy rekonstrukcji wypadków drogowych (Fundamentals of the reconstruction of road accidents),* WKiŁ, Warszawa 2008.

[2] Prochowski, L., *Pojazdy samochodowe, mechanika ruchu (Automotive vehicles, motion mechanics)*, WKiŁ, Warszawa 2008.

[3] Prochowski, L., Żuchowski, A., *Samochody ciężarowe i autobusy (Goods vehicles and buses)*, WKiŁ, Warszawa 2007.

[4] *ZF Axle Systems for City Buses and Coaches*, ZF publications, www.zf.com.

[5] *Double Deck Intercity Coach Td925*, www.abc-companies.com.

[6] Eckert, A., Hartmann, B., Rieth, D., Peter, E., *Emergency steer assist – advanced driver assistance*, FISITA, conference proceedings, 2010.

[7] Renfroe, D., Semones, P., Roberts, A., *Quantitative measure of transient oversteer of road vehicles*, ESV conference proceedings, Lyon 2007.

[8] Steffan, H., Moser, A., *How to use PC-CRASH to simulate rollover crashes*, SAE 2004-01-0341, USA 2004.