EXAMPLES OF AUTHORIAL MODELS FOR THE SIMULATION OF MOTOR VEHICLE MOTION AND DYNAMICS

1. Introduction

In motor vehicle research, analyses carried out with the use of simulation models are an element of great importance. Some of them are related to the motion and dynamic properties of a vehicle. The tools of this type have become more and more commonly used in engineer’s environment for the recent three decades. Previously reserved for universities and research institutes, such tools have now become helpful for specialists directly searching for practical solutions.

The author presents here examples of the simulation models of motor vehicle motion and dynamics that he built during 39 years of his work at the Warsaw University of Technology and during his guest-researcher stays at VTI (The Swedish National Road and Transport Research Institute) in Linköping, within numerous research, purpose-oriented, and development projects. He has paid special attention to highlighting the practical applications of the models developed. Mostly, the models are characterized by unique solutions; in many cases, they have been presented with specifying their co-authors or the persons for whom the models were developed with an intention of using them for joint applications.

The author would like to emphasize the great importance of the people and institutions he collaborated with when developing the models presented (see the attached list of publications). It is symptomatic that the number of people and institutions involved in practical application of the tools developed as aids to support the examination of motor vehicles and other engineering works steadily grew with time.


It would be difficult to imagine that the work on the issues presented here could be successfully done without knowledge of the publications issued by such organizations and publishers operating in Poland (as WNT, WKŁ, PWN, ZNIPPW, PNPW-Transport, AMot, ATr) and abroad (as VSD, SAE Paper, SAE SP, SAE Transactions, IJoFVD, IJoFSV, Swets & Zeitlinger Publishers, John Wiley&Sons Inc.). The benefits gained

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from the participation in seminars and conferences held in Poland (BwPS Warszawa, BwPS Kielce, BSwTS Kazimierz Dolny, AUTOPROGRES, KONMOT Kraków, KHiB Łódź, IES Kraków) and abroad (SAE, IAVSD, DSC) cannot be ignored, either.

Very much inspiration was also drawn from collaboration with colleagues working on similar issues, who in many cases were also co-authors of publications or implementations (P. Zagrodzki, G. Marcinkowski, M. Guzek, I. Stegienka, W. Mackiewicz, P. Zdanowicz, W. Pieniążek, J. Pokorski, T. L. Stańczyk, D. Żardecki, L. Prochowski, W. Luty, J. Jackowski, G. Ślaski, J. Unarski, W. Wach, A. Gajek, A. Reński, J. Wicher, D. Więckowski, S. Nordmark, O. Nordström).

2. Models for the research on low-velocity vehicle motion

Such models are used for the assessment of vehicle agility. The simplest of them are based on the principles of plane motion (Figs. 1 and 2). When building them, the author (together with co-authors of the models) used the known patterns, e.g. those presented in [1, 6], describing the vehicle motion, in most cases with ignoring the tyre sideslip angles, i.e. built with using the Ackermann model [1]. In [33] (Fig. 1), the agility of two-axle and three-axle city buses operated in Warsaw was assessed. Based on analyses carried out, the values of turning radii and swept path widths were determined. These calculations provided grounds for evaluating the method of dimensioning various transport infrastructure elements. Dimensional incompatibility between street intersections in towns and city buses was shown to be quite frequent. This incompatibility may pose a hazard to the road traffic safety. In [35] (Fig. 2), calculations were carried out for model data corresponding to specifications of the Mercedes Benz Actros 4148 AK truck. The most favourable and unfavourable configurations of the steered and non-steered wheels were indicated.

The vehicle agility was also assessed with the use of models where tyre sideslip was taken into account as well. Fig. 3 shows a model of motion of a two-axle motor vehicle with 10 degrees of freedom (DoF): coordinates \( x_{O1}, y_{O1}, z_{O1} \) of point \( O_1 \) (centre of vehicle mass) in inertial coordinate system \( Oxyz \), vehicle body yaw (heading) angle \( \psi_1 \), pitch angle \( \varphi_1 \), and roll angle \( \Theta_1 \), and steering angles \( \varphi_5, \varphi_6, \varphi_7, \varphi_8 \) [22]. An authorial simulation program named ZL_FL_3D determines them with rough methods but with high accuracy of calculations. A model of the steering system has been presented in Fig. 4, with solutions typical for motor trucks being used as an example. In this model, the geometric and spring characteristics of the system are taken into account.

Within works reported in [39, 40], a model of a two-axle motor truck was tested to find out how strong effect on the turning radius value is produced by asymmetric operation of the braking system and power transmission system. Prior to this, the simulation model was verified experimentally. The test results obtained confirmed the preliminary hypothesis as regards the expectation that the agility of a two-axle vehicle can be thus improved.

In study [10], the agility of a passenger car moving “forwards” was compared with that of the same car moving “backwards”. This was done with the use of a vehicle model presented in Fig. 3 and a steering system model similar to the one shown in Fig. 4, but with a parallel structure typical for passenger cars and delivery vehicles (see also Fig. 18). The vehicle manoeuvres simulated during the tests included vehicle drive along a path with a constant curvature radius (steady-state curvilinear motion) on a road surface affording good adhesion, vehicle drive with a “saw-tooth” input applied to the steering wheel, and vehicle pulling-in to a parking place parallel to a roadway edge. The vehicle speed was limited to 40 km/h. The results obtained have shown significant
differences in the vehicle behaviour when it moved “forwards” and “backwards”. Some of them are known to every experienced driver and this fact may rather be considered just confirmation of the usefulness of the simulation method adopted.

The models presented in Figs. 3 and 4 were used at simulation testing of motor vehicles Fiat CC, Daewoo FSO***, Star 1142, and MAN-Star.

3. Models for the research on vehicle dynamics in frequency domain

The vehicle testing in frequency domain provides information different from that obtainable from the testing of vehicle motion in space or in time domain. In this case, the matter of particular interest is the susceptibility of mechanical systems (with motor vehicles being counted among them), to phenomena related to oscillations. The models used for this purpose may be linear or non-linear. The former, in spite of simplified description of vehicle properties, make it possible to carry out analyses of more general nature, including the application of one-dimensional or multidimensional (transmittance matrix) notation based on operational transmittance (transfer function) of selected quantities. Theoretical fundamentals for such an approach to dynamics of mechanical
systems, especially including vehicles, may be found in publications [1, 6, 43, 44, 45]. In most cases, “quarter-car” models are used, including strongly non-linear models as well (e.g. [11]).

Figs. 5 and 6 show two linear models used for examining selected vehicle features in frequency domain. The model presented in Fig. 5 with the accompanying simulation program named SIDYSL [11] were employed by the author for comparative examinations, in frequency domain, of models used at many universities and research centres and representing the radial characteristics of a pneumatic tyre, referred to as PCTM (point contact tyre model) and FFTM (fixed footprint tyre model). At the examinations, the road surface was assumed to have random irregularities. The examinations confirmed the opinion, expressed also by other authors in their publications, about the superiority of the latter model. In turn, the model presented in Fig. 6 with the accompanying simulation program named ZLCT1 [12] were used to assess the impact of flexible fastening of the tow hook (elements $k_c$ and $c_c$) on the dynamics of a motor vehicle with a trailer in constant-velocity rectilinear motion. Such a design solution was the subject of a more extensive research carried out at VTI (The Swedish National Road and Transport Research Institute) in Linköping. The calculations carried out by the author revealed that the vertical dynamic loads of the hook would be considerably reduced, by 10% to almost 40% depending on the road class and vehicle speed, thanks to the application of the flexible fastening of the tow hook. This would lead to a reduction in the probability of separation of the trailer being towed from the towing vehicle. Such cases took place in Sweden when tow hooks of traditional design were used.

![Fig. 5. Model of a system used for comparative examinations of the PCTM and FFTM pneumatic tyre models in frequency domain [11]: road surface with random irregularities; 4 DoF: $z_M$, $\alpha$, $w_p$, $w_T$; vehicle velocity $V = \text{constant}$; vehicle modelled: Fiat 125p](image-url)
Fig. 6. Model of constant-velocity ($V = \text{const}$) rectilinear motion of a two-axle motor vehicle with a one-axle trailer: road surface with random irregularities; 4 DoF: $z_F, z_R, z_T, z_{BW}$; vehicle modelled: Mercedes 508 D (delivery vehicle) [12]

4. General-type models for the research on vehicle motion and dynamics in time domain and in space

These models were built by the author for research purposes and as tools used at works carried out to support design engineers or specialists working on motor vehicle safety issues.

A model of rectilinear motion of a two-axle motor vehicle on an uneven road surface has been presented in Fig. 7. The model shown in Fig. 7a, incorporated in the simulation program ZLS2D, is the basic version [7, 11], used at author’s work on his doctoral dissertation and at other studies. The model shown in Fig. 7b, associated with the simulation program ZLS2D(MK), constitutes a version expanded by adding a representation of the possible movements of the cargo transported on the load bed [8].

Fig. 7. Model of rectilinear motion of a two-axle motor vehicle on a rough road surface: a) basic version [7,11]; 7 DoF: $x_M, z_M, \alpha, \zeta_P, \zeta_T, \phi_P, \phi_T$; vehicles modelled: Fiat 125p, Zastava 110, Berliet PR110; 
b) version expanded by adding a representation of the cargo transported on the load bed [8]; 8 DoF: $x_M, z_M, \alpha, \zeta_P, \zeta_T, \phi_P, \phi_T, \xi_Q$; vehicle modelled: FSO 1500 pick-up
A three-dimensional 14-DoF model of a two-axle motor vehicle has been presented in Fig. 8. Fig. 8a shows its basic version, which is used in a simulation program named SYMRU14 [13, 30, 31]. A developed version of this model, covering a wider range of model properties, can be seen in Fig. 8b; it is used with the simulation program ZL3DSYM [14, 15, 19]. These models were employed to assess the effects of asymmetric operation of vehicle brakes [31] (at this work, a model representing the controlling properties of the driver, drawn from the US literature – see [18], was used as well), to assess the impact of random irregularities in the road surface on the course of a single lane-change manoeuvre [13], and to assess driver’s activities when the vehicle moved on an even (smooth) and uneven (rough) road surface [15]. A next version of this model, developed again and related to the simulation program ZL3D_SYM [18], has been presented in Fig. 9. It was used to assess the impact of suspension roll stiffness and distribution of this stiffness between the front and rear suspension system on the transverse stability of the vehicle, which was a prototype design of a DAEWOO delivery vehicle [5]. The primary objective of the design changes was to reduce vehicle’s propensity to rollover.

Fig. 8. Three-dimensional model of a two-axle motor vehicle;
14 DoF: $x_{O1}$, $y_{O1}$, $z_{O1}$, $\psi_1$, $\vartheta_1$, $\zeta_{1O2}$, $\zeta_{1O3}$, $\zeta_{1O4}$, $\alpha_5$, $\beta_6$, $\beta_7$, $\beta_8$ (or $\varphi_5$, $\varphi_6$, $\varphi_7$, $\varphi_8$); vehicle modelled: FSO Polonez 125PN:
  a) basic version [13, 30, 31]; b) modified version [14, 15, 19]
A three-dimensional 14-DoF model of a two-axle motor truck has been presented in Fig. 10. It is related to a simulation program ZL_STAR [18, 34]. This model was used to assess the propensity of a motor truck to rollover [17, 18, 34]. At the work described in [21], it was used to analyse the impact of damping in vehicle suspension system, especially the dry friction, on the values of the dynamic normal reactions at the tyre-road contact area during motion on an uneven road surface with random irregularities.

The models shown in Figs. 9 and 10 were also used at works being done to assess the impact of simplifications in the construction of automotive “black boxes”, referred to as event data recorders (EDR) or accident data recorders (ADR), on road accident reconstruction results, especially with respect to the assessment of pre-accident situations [2, 3]. The models representing the operation of automotive EDR and ADR units were made by M. Guzek.
This group of models includes the one the use of which for the vehicle agility assessment purposes has been described in a previous section and which has been shown in Fig. 3. The model was used [9] for simulation calculations, carried out to compare the characteristics of steerability (ease of steering) of a specific motor vehicle when moving “forwards” and “backwards”. The vehicle velocity was limited to 40 km/h because it would be difficult to achieve higher velocities when “reversing” in real conditions and it would not be possible then to consider the results obtained in relation to actual manoeuvring. The steerability characteristics were more favourable when the vehicle moved forwards: the vehicle remained understeering over the whole range of lateral accelerations under consideration; the understeering is considered better than the varying characteristics observed at “reversing”, when the vehicle may be understeering or oversteering depending on the value of its lateral acceleration and, in result of this, the vehicle behaviour becomes unpredictable and requires higher psychomotor capabilities of the driver.

Fig. 11 shows a three-dimensional 14-DoF model of a Light Tactical Vehicle (LTV) Dzik, a patrol and intervention motor vehicle, which was manufactured at AMZ-Kutno Sp. z o.o. The model is associated with a simulation program named ZL_Dzik [24]. Publication [41] includes results of calculations carried out to assess the impact of the position of the centre of mass of this vehicle on its behaviour in curvilinear motion. The assessment was based on results of an analysis of uniform vehicle motion along a circle (steady-state curvilinear motion) and on determining the maximum velocity at which the steering wheel may be rapidly turned by 90 ° without vehicle rollover. The model used for this purpose was previously verified experimentally, with carrying out the typical tests recommended by ISO. Furthermore, results of simulation tests carried out to assess the impact of immunity of the LTV Dzik to tyre sideslip and of the stiffness of its anti-roll bar on the vehicle behaviour in curvilinear motion have been presented in [42].

Fig. 11. Three-dimensional model of a two-axle motor vehicle;
14 DoF: x_{O1}, y_{O1}, z_{O1}, \psi_1, \varphi_1, \vartheta_1, \zeta_{1O4}, \vartheta_4, \zeta_{1O9}, \vartheta_9, \varphi_5, \varphi_6, \varphi_7, \varphi_8;
vehicle modelled: LTV Dzik [24]
Fig. 12 shows a three-dimensional 22-DoF model of a four-axle vehicle KTO-Rosomak, associated with a simulation program ZL_KTO1 [26]. Publications [4, 27, 28, 29] include results of experimental verification of the model and the simulation program, providing grounds for using this tool at vehicle stability tests, inclusive of tests carried out under tyre blow-out conditions.

The simulation test results having been published were obtained from tests performed with simulating the conditions in which experimental tests are difficult or impossible for being carried out. They confirmed good properties of the object under test, even at high velocities of vehicle motion. The tests revealed a visible impact of the failure of a vehicle tyre (or tyres) on vehicle characteristics in rectilinear and curvilinear motion. The testers also managed to identify specific situations where the object under test showed a tendency to lose its stability.

One of the three-dimensional models of motion of a two-axle motor vehicle, with a complex model of the steering system, has been presented in Fig. 13. The models of this family have 14 degrees of freedom. They are related to programs ZL_DZ*** [36, 37, 38]. They were built in order to incorporate two formal descriptions of the phenomena of friction (tar(...)) and freeplay (luz(...)), formulated by D. Żardecki, into a program for the simulation of motion and dynamics of a motor vehicle. In [36], the authors presented results of testing the susceptibility of the lateral dynamics of a two-axle vehicle (at tests: parking manoeuvre to standard ECE 79; combination of two tests, i.e. transient test to ISO 7401 and steady-state circular driving test to ISO 4138; test with steady sinusoidal input applied to the steering wheel to ISO 7401) to changes in the freeplay and friction in the steering system. In [37], the authors presented results of a typical open-loop test (combination of three tests, i.e. transient test to ISO 7401, steady-state circular driving test to ISO 4138, and “let-go-of-the-steering-wheel” test) for vehicles provided with 2WS and 4WS systems, for different levels of dry friction and freeplay in the steering system. It was ascertained that both of these phenomena have a significant impact on the motion and dynamics of a motor car. In [38], the authors presented the influence of various formalisms in the description of dry friction on the course of vehicle tests (combinations of the said open-loop manoeuvring tests recommended by ISO). It was found that in spite of using three different descriptions of dry friction, recommended in various publications, the mutually corresponding results of the simulation tests carried out were very similar to each other.

![Fig. 12. Three-dimensional model of a four-axle special vehicle; 22 DoF: xoC, yoC, zoC, yC, φC, θC, ζCOi, φi, i=1,...,8; vehicle modelled: KTO-Rosomak [26]](image-url)
Fig. 13. One of the three-dimensional models of a two-axle motor vehicle, with a complex model of the steering system. The models of this family have 14 degrees of freedom: $x_C$, $y_C$, $z_C$, $\psi$, $\vartheta$, $\varphi_1$, $\varphi_2$, $\varphi_3$, $\varphi_4$, $\alpha_k$, $\alpha_p$, $\alpha_2$, $\alpha_3$.

Vehicle modelled: Fiat Seicento [36, 37, 38]

5. Models for the simulation of vehicle motion and dynamics in time domain and in space, dedicated to driving simulators

A separate group may be formed from models intended for being used in driving simulators. Apart from high accuracy of mapping real vehicle properties in various conditions of motion, these models should make it possible to carry out “real-time” calculations and this, for the usually adopted time sharing for simulator computers (regardless of series or parallel configuration of the software operation system), leads to a requirement that the computer system should operate with a speed higher by more than an order of magnitude (calculations for one second of motion and dynamics of a motor vehicle should be carried out within less than 0.1 second). The growth in computation speed is fostered by ongoing improvements in computer performance and appropriate construction of algorithms of the vehicle motion and dynamics simulation programs.

Fig. 14 shows a 2-DoF “bicycle model” of a four-wheel vehicle [46]. The accompanying program ZL-IP was used for the simulation of curvilinear motion of a motor vehicle on a drum-type test rig. Therefore, this model may be said to be a precursor of a motor vehicle driving simulator, implemented in a joint effort by the teams of the Institute of Vehicles and the Faculty of Transport of the Warsaw University of Technology.

Fig. 14. “Bicycle model” of a four-wheel vehicle; 2 DoF: $y_{O1}$, $\psi_1$ (V = const);
vehicle modelled: Fiat 125p [46]
Fig. 15 shows a 7-DoF model of a two-axle vehicle for “real-time” simulation of motion and dynamics of a motor vehicle [20, 23]. This model is associated with a simulation program ZL_RTS3; it has been successfully used since 1998 in the first Polish driving simulator named “autoPW”, built at the Faculty of Transport of the Warsaw University of Technology in cooperation with colleagues from the Institute of Vehicles of the same University, Institute of Automobiles and Internal Combustion Engines of the Cracow University of Technology, and Grapolectronic (Krzysztof Grąziewicz).

Fig. 15. Model of a two-axle vehicle for “real-time” simulation of motion and dynamics of a motor vehicle [20, 23], used in the “autoPW” driving simulator; 7 DoF: $x_{O1}$, $y_{O1}$, $\psi_1$, $\phi_5$, $\phi_6$, $\phi_7$, $\phi_8$; vehicles modelled: Fiat CC, Chrysler Neon, Daewoo FSO***, Ford Transit, Star 1142, and MAN-Star

Since 2008, a team of specialists from the Department of Vehicle Maintenance and Operation of the Faculty of Transport of the Warsaw University of Technology, assisted (within the scope of experimental testing of tyres and vehicles) by partners from Institute of Automobiles and Internal Combustion Engines of the Cracow University of Technology, Vehicle Tests Laboratory (BLP) and Simulation Tests Laboratory (BLY) of PIMOT (Automotive Industry Institute), and Division of Construction and Safety of Motor Vehicles of the Institute of Motor Vehicles and Transportation of the Military University of Technology, has been collaborating with ETC-PZL Aerospace Industries Sp. z o.o. in the field of the construction of dynamic simulators of motor vehicle driving. The simulators covered by the scope of this cooperation include devices meeting the minimum requirements for the “top-of-the-range simulators” and are intended for being used in the process of training and examining of drivers for the purposes of initial qualification of drivers, according to provisions of EU Directive 2003/59/EC. A 12-DoF model of a three-axle bus or motor truck for “real-time” simulation of motion and dynamics of the vehicle, used in the SYM-SAM driving simulator developed by ETC-PZL Aerospace Industries Sp. z o.o., has been presented in Fig. 16. Fig. 17, in turn,
shows a 29-DoF model of a tractor-and-bus-semi trailer unit for “real-time” simulation of motion and dynamics of the vehicle, used in the same driving simulator.

Fig. 16. Model of a tree-axle bus or motor truck for “real-time” simulation of motion and dynamics of a motor vehicle, used in the SYM-SAM driving simulator developed by ETC-PZL Aerospace Industries Sp. z o.o.;
12 DoF: \(x_{O1}, y_{O1}, z_{O1}, \psi_1, \phi_1, \theta_1, \phi_5, \phi_7, \phi_8, \phi_{51}, \phi_{61}\);
vehicles modelled: MAN- Star 1142, Mercedes Atego, Autosan Lider A1012T

Fig. 17. Model of a tractor-bus-semi trailer unit for “real-time” simulation of motion and dynamics of the vehicle, used in the SYM-SAM driving simulator developed by ETC-PZL Aerospace Industries Sp. z o.o.; 29 DoF: \(x_{O1}, y_{O1}, z_{O1}, \psi_1, \phi_1, \theta_1, \zeta_{C1}, \zeta_{C2}, \zeta_{C3}, \zeta_{C4}, \phi_1, \phi_2, \phi_3, \phi_4, \psi_N, \phi_N, \theta_N, \zeta_{N1}, \zeta_{N2}, \zeta_{N3}, \zeta_{N4}, \zeta_{N5}, \zeta_{N6}, \theta_7, \phi_8, \phi_9, \phi_{10}, \phi_{11}, \phi_{12}\);
vehicle modelled: Mercedes Actros 1841
Within one of the projects carried out, a model and a simulation program for driving simulators for special vehicles were built for ETC-PZL Aerospace Industries Sp. z o.o. Such simulators are used by the Police Academy in Szczytno and by the Republic of Poland’s Government Protection Bureau. Figs. 18 and 19 show 14-DoF models of a passenger vehicle and a light-duty vehicle for both the carriage of goods and passengers, respectively [25]. The related simulation programs have been named ZL_SPC1 and ZL_SPC2, respectively.

Fig. 18. Model of a passenger car for “real-time” simulation of motion and dynamics of a motor vehicle, used in the driving simulator developed by ETC-PZL Aerospace Industries Sp. z o.o. [25]; 14 DoF: $x_{OC}$, $y_{OC}$, $z_{OC}$, $\psi_C$, $\varphi_C$, $\theta_C$, $\zeta_{Co1}$, $\zeta_{Co2}$, $\zeta_{Co3}$, $\zeta_{Co4}$, $\varphi_1$, $\varphi_2$, $\varphi_3$, $\varphi_4$; vehicle modelled: KIA cee’d SW

Fig. 19. Model of a light-duty vehicle for both the carriage of goods and passengers for “real-time” simulation of motion and dynamics of a motor vehicle, used in the driving simulator developed by ETC-PZL Aerospace Industries Sp. z o.o. [25]; 14 DoF: $x_{OC}$, $y_{OC}$, $\psi_C$, $\varphi_C$, $\theta_C$, $\zeta_{Co1}$, $\zeta_{Co2}$, $\zeta_{Co3}$, $\zeta_{Co4}$, $\varphi_1$, $\varphi_2$, $\varphi_3$, $\varphi_4$; vehicle modelled: Fiat Ducato
6. Conclusion

Examples of authorial models of motor vehicle motion and dynamics, used at the “off-line” and “real-time” simulation, have been presented. Almost all of them successfully passed experimental verification, which has been more comprehensively described in monographs [4, 18, 23, 26, 28, 29] and other publications [3, 16, 19, 32]. Some of the results of the successful verification of the simulation models, especially those of commercial importance, have the nature of industrial secret.

The models were developed during the recent period of 39 years. They are still used at author’s own work, at research works carried out by his younger co-workers, or at research, purpose-oriented, development, and commercial projects.

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Abstract
The author has presented examples of the simulation models of motor vehicle motion and dynamics that he built during 39 years of his work at the Warsaw University of Technology and during his guest-researcher stays at VTI (The Swedish National Road and Transport Research Institute) in Linköping, within numerous research and development projects. The models are characterized by various degrees of complexity; they describe the vehicle motion and its dynamics on the road surface plane, in frequency domain as well as in time and in space. Some of them were intended for driving simulator applications. Mostly, the models are characterized by unique solutions; in many cases, the models have been presented with specifying their co-authors or the persons for whom the models were developed with an intention of using them for joint applications. Special attention has been paid to highlighting the practical applications of the models developed.

Keywords: model, simulation, motor vehicle motion, motor vehicle dynamics

PRZYKŁADOWE AUTORSKIE MODELE DO SYMULACJI RUCHU I DYNAMIKI SAMOCHODU

Streszczenie
Autor przedstawił przykładowe modele symulacyjne ruchu i dynamiki samochodu, które zbudował w okresie 39 lat swej pracy na Politechnice Warszawskiej, w trakcie pobytów w Szwedzkim Narodowym Instytucie Badań Dróg i Transportu w Linköping (VTI – The Swedish National Road and Transport Research Institute) oraz w trakcie realizacji projektów badawczych, celowych i rozwojowych. Są to modele o różnym stopniu złożoności, opisujące ruch pojazdu i jego dynamikę na płaszczyźnie drogi, w dziedzinie częstotliwości oraz w czasie i w przestrzeni. Część z nich była dedykowana zastosowaniom w symulatorach jazdy samochodem. Większość z nich ma autorski charakter. Część ma wskazanych współautorów lub osoby, na rzecz których powstała z myślą o wspólnej aplikacji. Autor szczególną uwagę zwraca na wskazanie praktycznych zastosowań zbudowanych modeli.

Słowa kluczowe: model, symulacja, ruch samochodu, dynamika samochodu