Software to Support the Development of Road Pavement Energy Harvesting Devices

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Abstract. This paper deals with the development of a software to support the development of road pavement energy harvesting devices, allowing to define the device parameters and simulate the entire process from the vehicle-device interaction to the electric energy generation and consumption. This allows to quantify the forces induced and energy released from vehicles to the device in different vehicle motion scenarios, the energy harvested by the device surface, the energy transferred by the mechanical system and the energy generated and consumed by the electrical system. It enables the user to quantify the energetic efficiency of the process. A practical study is presented in order to show the effectiveness of the software, as well as its potential applications.

Keywords: Simulation software · Road pavement energy harvesting · System modelling · Energetic analysis

1 Introduction

Energy Harvesting is described as a concept by which energy is captured, converted, stored, and utilized using various sources, employing interfaces, storage devices, and other units [1, 2]. Put simply, energy harvesting is the conversion of ambient energy present in the environment into other useful means of energy; for example, electrical energy [3].

Road surfaces are continuously exposed to vehicle loads, making it possible to extract energy from which, using specific technologies, can be transformed into electrical energy [4, 5]. Vehicles consume energy to work their engines and release energy in different ways, by different components. Part of the energy released by vehicles goes into the road pavement. Approximately 15% to 21% of the energy is transferred to the vehicle's wheels [6, 7].

As vehicles abound in all cities in developed countries, it means that a considerable amount of energy is transferred to road pavements without being used. Road pavements can make use of that unused energy through specific technologies that can harvest and convert vehicles mechanical energy into electrical energy. These are called road pavement energy harvesting (RPEH) devices.

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Duarte and Ferreira [5] present a state of the art from the technologies used to convert vehicles mechanical energy into electrical energy, to be implemented on road pavements, being these from both groups, micro and macro energy harvesting.

In these technologies, typical systems have the following components: a surface that receives energy from vehicle tires and delivers energy to a transmission system; a system that transmits energy from the surface to an electrical generation unit (usually a mechanical or hydraulic system); and an electrical unit that converts the mechanical energy into electrical energy, delivering it to an electrical application.

In the last years a considerable amount of systems have been developed and tested to convert vehicles mechanical energy into electrical energy on road pavements [5], being most of them validated in laboratory environment, but none of them have reached a validation on relevant environment, as a public road with regular traffic actuating the system for a considerable amount of time.

Also, for most part of the existing technologies there have not being published any system modelling and computational simulations, that would allow to analyze its energy harvesting, transmission and conversion efficiency, which would allow to determine its global efficiency and conclude about its viability.

From a scientific perspective, PREH devices are not being developed with the appropriate technical support, since there is any software that quantifies the vehicle loads delivered to the system, in function of the vehicle characteristics, its motion situation and, at the same time, the RPEH device' properties, as its mechanical and electrical characteristics. All these parameters have a great impact in terms of the vehicle-device interaction and affect the way vehicle delivers forces to the equipment. Consequently, it also affects the amount of energy that enters in the RPEH device and its working efficiency.

Some commercially available software tools, as ADAMS® [8] and AUTOSIM® [9], allows simulating motions of multi-body mechanical systems, such as vehicles, being used both by the automotive industry and research laboratories [10–13] to perform studies regarding the vehicle components optimization (tires, suspension, chassis, etc.), road design, road safety, among other applications. However, this software does not allow users to introduce energy harvest devices on the road pavement with movable surfaces, which have their own motion equations, and affect the vehicle motion equations. Due to this fact, none of the presented software is suited for studying the vehicle-device interaction from an energetic perspective, from the energy released by the vehicle and the energy absorbed by the RPEH device.

In the present research work, it is intended to develop a software that allows to study both the vehicle-device interaction with an energetic perspective, as well as the RPEH device performance, both mechanical and electrical, in order to quantify the amount of energy released by the vehicle to the device and the energy harvested, transmitted and converted by the RPEH device. The software should enable the user to simulate this interaction according to the selected conditions and obtain both numerical and graphic results. The results will be useful to understand the vehicle-device interaction and to support the development of RPEH devices, providing precision quantification of the energy that can be harvested, and the most favorable conditions in which to harvest it, as well as the device' efficiency in function of its mechanical and electrical characteristics.

2 Software

2.1 Introduction

Previously to the development of the software, an extensive study was performed of vehicle dynamics and vehicle road interaction based on the main references in this area [14–19]. Based on these references, the main formulations regarding the vehicle models, motion equations, tire force determinations and contact patch pressure distribution, among others things, were defined. Finally, a software tool was developed to simulate the vehicle-road interaction, named RoadVISS [20].

The most common RPEH devices were studied [5]. They are based on mechanical or hydraulic systems that transfers the mechanical energy received by the equipment' surface to an electrical generator, which converts it into electrical energy and delivers it to an electrical application. Analyzing the existent systems allowed us to perform a global systems modelling, with equations of motion to characterize each system and kinematic and forces analysis to support it.

Based on RoadVISS [20] and on this additional study, a software tool was developed in MATLAB® environment, in order to support the development of RPEH devices. The purpose of this software is to study the vehicle-device surface interaction in great detail, with the possibility of fully characterizing the vehicle under study, by defining its class, weight, axles, wheels, geometry, speed, acceleration, suspensions and tires, defining all the mechanical parameters (such as damping and stiffness for each suspension and tire), as well as fully characterizing the RPEH device, by defining its surface material, shape, geometry, displacement, mass, stiffness and damping properties, as well as its mechanical and electrical properties, in function of the selected system. The software allows to select the vehicle model (bicycle car or quarter car model) and also the vehicle-road interaction model (contact patch or single force).

Applying the vehicle dynamics, vehicle road interaction, as well as the mechanical, hydraulic and electrical system modelling equations, the software calculates all the displacements, both for the vehicle and the RPEH device components, the applied and received forces, and the energy transferred by each system component, presenting the results both graphically and numerically.

2.2 Software Inputs

To select the inputs, a Graphical User Interface (GUI) platform was developed (Fig. 1).

This GUI has 10 distinct panels, with eight for parameter selection, one for the preview of the selected features, regarding the vehicle, the pavement, the RPEH device (mechanical and electrical parts) and the electric load, and other for the selection of simulation features.

The first panel allows the user to select the vehicle and motion properties. In terms of the vehicle, it allows the vehicle class, weight, number of axles, wheels per axle, percentage of sprung and unsprung mass, drag and lift coefficients, and inertia moment of the vehicle to be selected. It also allows users to define the vehicle geometry in terms of distances from each axle to the center of gravity, as well as the height of the center

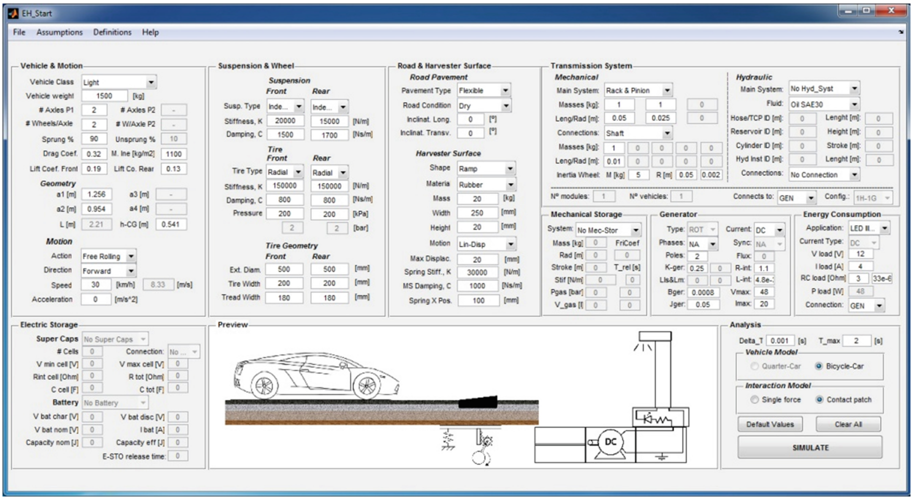

Fig. 1. Graphical user interface to select the inputs of the software.

of gravity. In terms of vehicle motion, it allows to the selection of the action, the motion direction, the vehicle speed and acceleration.

The second panel allows the user to select the suspension and wheel properties. In terms of suspension, it allows users to select the suspension type and to define the suspension stiffness and damping values, for both the front and rear suspension. In terms of tire, it allows the user to select the tire type and to define the tire stiffness, damping and pressure, for both the front and rear tire. The tire geometry in terms of external diameter, tire width and tread width can also be defined, for both front and rear tires.

The third panel allows the road and RPEH device properties to be selected. In terms of road pavement, the user can select the pavement type, the road condition, the longitudinal and transversal inclination of the pavement. For the harvester surface, users can select the shape, the motion type, the material, the width and height, its maximum displacement, its mass, and also its stiffness and damping can be defined.

Panels four to eight allow to fully characterize the RPEH device: its mechanical or hydraulic characteristics (system selection and its parameters), in panel four; its mechanical storage characteristics, in panel five; its electrical generator characteristics, in panel six; the electric load, in panel seven; and the electrical storage characteristics, in panel eight.

The ninth panel presents a summary of the selection, showing an image of the selected vehicle, pavement type, surface shape, RPEH device type (mechanical and electrical parts) and the electrical energy application. With this information, the user can confirm selection visually.

The tenth panel allows the user to define the simulation time and each iteration interval, as well as the vehicle model to be simulated and interaction model, in terms of the inclusion of the tire *contact patch*. In this panel, the user can clean all the fields to select new values, and can press the “Simulate” button to start the simulation.

2.3 Formulations

When the simulation starts, the software defines all the “static” variables, i.e., those that do not depend on the vehicle or RPEH system dynamics, such as the front and rear unsprung masses, the sprung mass, drag and lift forces, forces per axle, both vertical and longitudinal, the contact patch geometry for each wheel, or the initial kinetic energy of the vehicle.

Four vehicle and interaction models were developed using the SIMULINK® tool:

(1) Quarter-car model, single force interaction model;
(2) Bicycle-car model, single force interaction model;
(3) Quarter-car model, contact patch interaction model;
(4) Bicycle-car model, contact patch interaction model.

The selected vehicle and interaction model is then connected to the correspondent energy harvesting mechanical or hydraulic system model. Six models were developed using SIMULINK® and Simscape® tools:

(1) Rack and pinion mechanical system, without mechanical energy storage;
(2) Rack and pinion mechanical system, with flywheel mechanical energy storage;
(3) Level mechanical system, without mechanical energy storage;
(4) Level mechanical system, with flywheel mechanical energy storage;
(5) Hydraulic system, without mechanical energy storage;
(6) Hydraulic system, with pressure energy storage.

The selected mechanical or hydraulic model is then connected to the correspondent electrical system model. Six models were developed using the SIMULINK® and Simscape® tools:

(1) DC electrical generator, DC load, without electrical energy storage;
(2) DC electrical generator, DC load, with electrical energy storage;
(3) AC SP electrical generator, DC load, without electrical energy storage;
(4) AC SP electrical generator, DC load, with electrical energy storage;
(5) AC TP electrical generator, DC load, without electrical energy storage;
(6) AC TP electrical generator, DC load, with electrical energy storage.

Depending on the user’ selection, the software connects the vehicle and interaction selected models with the mechanical or hydraulic system model and with the electrical system model, defines each system parameters with the data defined in the *Input GUI*, and runs the simulation, in order to perform the dynamic analysis.

2.4 Software Outputs

To present the software outputs graphically, a GUI platform was developed in MATLAB® environment (Fig. 2).

This GUI has nine distinct panels, with seven for outputs graphical presentation, one for outputs numerical presentation and other for the selection of the plots to print.

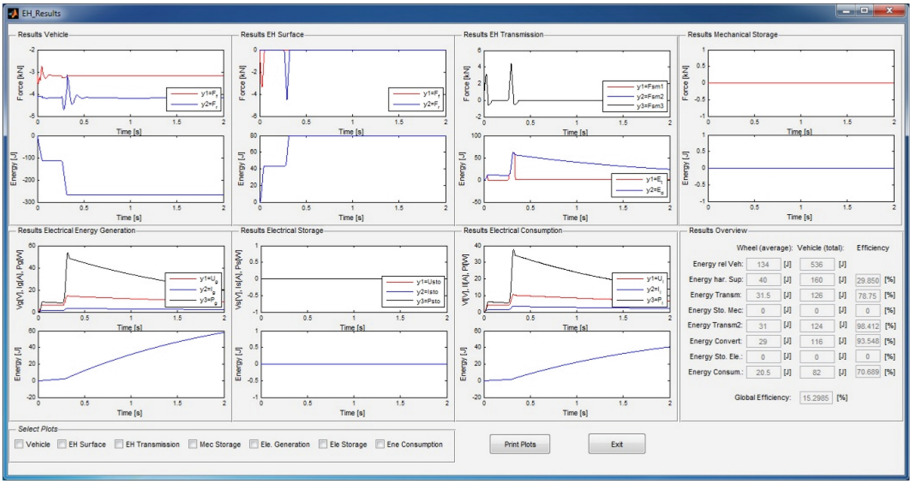

Fig. 2. Graphical user interface to present the outputs of the software.

The seven panels that presents the results graphically are related to each system component output: vehicle results in panel 1, both for front wheel and rear wheel forces and energy released; RPEH device surface in panel 2, both for received force and energy transferred; RPEH mechanical or hydraulic system results in panel 3, both for transmitted force and energy; RPEH mechanical storage system results in panel 4, both for transmitted force and stored energy; RPEH electrical generator results in panel 5, both for voltage, current, power and energy generated; RPEH electrical storage system results in panel 6, both for voltage, current, power and energy stored; and RPEH electrical load results in panel 7, both for voltage, current, power and energy consumed. These results are related to each vehicle side, representing half vehicle.

Panel 8 presents the results numerically, for each component of the system, for each vehicle wheel actuation and for the entire vehicle, presenting also the efficiency of the respective component, as well as the global efficiency of the system, from the mechanical energy released by the vehicle and the electrical energy consumed by the electrical load.

Panel 9 offers users the possibility to print the plots, allowing them to select the desired plots to be printed and pressing the “Print Plots” button. Finally, it contains an “Exit” button to close the results GUI and return to the initial GUI.

3 Case Study

Considering all the variables of the software, one can easily conclude that it allows a user to perform thousands of different simulations. A case study considering a light vehicle moving on RPEH device with a rack and pinion mechanical system, connected to a DC electrical generator and a DC load, without mechanical or electrical energy storage is presented. Two different surface profiles are considered (*Ramp* and *Crest*), for different mechanical system characteristics. The variable values for the vehicle are presented in Table 1.

Table 1. Fixed values for the simulation variables of the vehicle.

	Variable name	Value	Unit
Vehicle & motion	Vehicle class	Light	
	Vehicle weight	1,500	kg
	No. axles I Axles/wheel	2 I 2	
	Sprung - unsprung mass%	90%–10%	
	Drag coefficient	0.32	
	Inertia moment	1,100	$kg.m^2$
	Lift coefficients (F I R)	0.19 I 0.13	
	Motion I Direction	Free rolling I Forward	
	Speed I Acceleration	30 I 0	km/h I m/s^2
Suspension & wheel	Suspension type (F I R)	Independent I Independent	
	Suspension stiffness (FI R)	20,000 I 15,000	N/m
	Suspension damping (FI R)	1,500 I 1,700	Ns/m
	Tire type (F I R)	Radial I Radial	
	Tire stiffness (F I R)	150,000 I 150,000	N/m
	Tire damping (F I R)	800 I 800	Ns/m
	Tire pressure (F I R)	200 I 200	kPa
	Tire exterior diameter (F I R)	500 I 500	mm
	Tire width (F I R)	200 I 200	mm
	Tire tread width (F I R)	180 I 180	mm

Table 2. Fixed values for the simulation variables of the road surface and PREH device.

	Variable name	Value	Unit
Road & harvester surface	Pavement type I R. condition	Flexible I Dry	
	Inclination long. I transversal	0 I 0	°
	Motion I Material	Linear disp. I Rubber	
	Harvester width I Height	250 I 20	mm
	Harvester mass	20	kg
	Harvester stiffness	30,000	N/m
	Harvester damping	1,000	Ns/m
RPEH mechanical & electrical characteristics	Transmission System	Mechanical: Rack & Pinion	
	Rack mass I length	1 I 0.05	[kg] I [m]
	Pinion mass I length	1 I 0.025	[kg] I [m]
	Shaft mass I length	1 I 0.015	[kg] I [m]
	Inertia wheel mass I radius	5 I 0.05	[kg] I [m]
	Electric generator type	ROT I DC	
	Electric generator R I L I K	1.1 I 0.0048 I 0.25	[Ω] I [H] I -
	Electric generator B I J	0.0008 I 0.05	
	Electric load V I R I P	12 I 3 I 48	[V] I [Ω] I [W]

The variable values for the road and RPEH device properties are presented in Table 2. The results achieved by the simulations are presented in Tables 3 and 4, for the energy outputs and each component efficiency, respectively. Note that the value of the total energy released by the vehicle, considering a bicycle car model, is achieved by multiplying the calculated half vehicle released energy by two, which is the number of vehicle sides.

Table 3. Simulation results (energy).

Surface profile	r_p [mm]	m_{iw} [kg]	E_v [J]	E_{Ha} [J]	E_{Tr} [J]	E_{De} [J]	E_{Ge} [J]	E_{Lo} [J]
Ramp	15	5	263.0	83.0	19.0	19.0	17.0	13.8
		10	263.0	83.0	19.0	19.0	16.0	12.9
	20	5	265.0	82.0	37.0	37.0	33.0	27.0
		10	265.0	82.0	37.0	36.0	31.0	25.1
	25	5	266.0	81.0	59.0	59.0	53.0	43.5
		10	266.0	81.0	59.0	58.0	51.0	41.6
Crest	15	5	184.0	87.0	22.0	22.0	19.9	16.1
		10	184.0	88.0	22.0	22.0	19.0	15.4
	20	5	182.0	84.0	41.0	41.0	37.0	29.9
		10	183.0	85.0	41.0	41.0	35.0	28.2
	25	5	182.0	82.0	65.0	64.0	59.0	47.9
		10	182.0	83.0	65.0	64.0	57.0	46.2

Table 4. Simulation results (efficiencies).

Surface profile	r_p [mm]	m_{iw} [kg]	η_{Ha} [%]	η_{Tr} [%]	η_{De} [%]	η_{Ge} [%]	η_{Co} [%]	η_{RPEH} [%]	η_{TOT} [%]
Ramp	15	5	31.6	22.9	99.7	89.7	80.9	16.6	5.2
		10	31.6	22.9	99.7	84.4	80.3	15.5	4.9
	20	5	30.9	45.1	99.9	89.3	81.8	32.9	10.2
		10	30.9	45.1	97.3	86.1	81.0	30.6	9.5
	25	5	30.5	72.8	99.9	89.9	82.1	53.7	16.4
		10	30.5	72.8	98.3	87.9	81.6	51.4	15.6
Crest	15	5	47.3	25.3	99.8	90.7	80.9	18.5	8.8
		10	47.8	25.0	99.8	86.6	81.1	17.5	8.4
	20	5	46.2	48.8	99.9	90.4	80.8	35.6	16.4
		10	46.4	48.2	99.9	85.5	80.4	33.1	15.4
	25	5	45.1	79.3	98.5	92.2	81.2	58.4	26.3
		10	45.6	78.3	98.5	89.1	81.0	55.6	25.4

From the results presented in Table 3 it is possible to compare the differences between the energy released by the vehicle (E_v), harvested by the RPEH surface (E_{Ha}), transmitted (E_{Tr}) and delivered (E_{De}) by the mechanical system, generated (E_{Ge}) by the electrical generator and consumed (E_{Lo}) by the electrical load, in function of the different system parameters - surface profile, pinion radius (r_p) and inertia wheel mass (m_{iw}). Table 4 presents the efficiency of each system component: harvester surface (η_{Ha}), transmission system (η_{Tr}), mechanical energy deliver system (η_{De}), electrical generator (η_{Ge}) and electrical load (η_{Co}), as well as the RPEH device efficiency (η_{RPEH}), from the energy harvested by the surface to the electrical energy consumed, and the total efficiency (η_{TOT}) from the energy released by the vehicle to the electrical energy consumed by the electrical load.

It is possible to quantify the impact of each variable change on the system results and to optimize each component characteristics, evaluating its impact on the global system. From the results analysis it can be concluded that the efficiency of the system is greatly affected by the pinion radius, reaching higher efficiencies for higher pinion radius values. Also, the *Crest* surface profile is more efficient than the *Ramp* surface profile. It can also be concluded that the *Rack and Pinion* mechanical system can have interesting efficiencies, with some scenarios reaching more than 50% efficiency. This value can, however, be improved, with appropriate studies, using this software.

4 Conclusions

The main goal of the present research work consisted of the development of a software tool to support the development of RPEH devices, allowing users to study all the process from the vehicle-device interaction until the electrical energy consumed by an electrical load, as well as quantifying all the forces, displacements and energy being transferred by each component of the system. The software was developed in MATLAB® environment, including a GUI where the user can select and define all the variables associated to the simulation, and another GUI where the results are presented. The software has an extensive database of considered variables, allowing a huge amount of different combinations of values to be simulated, leading to the possibility of performing a great number of studies. The outputs of the system are focused on the forces and energy released by the vehicle, received and transmitted by the RPEH surface, mechanical or hydraulic system, to the electrical generator, and the electrical energy generated, stored and consumed. From the performed simulations, it was possible to conclude that the software corresponds to the goals of the project. It allows users to obtain the necessary outputs and easily permits the comparison of scenarios, regarding energy lost by a vehicle and transferred by each component of the system, until its final consumption on an electrical load, as well as quantify each process efficiency. The existing software tools, mainly ADAMS® and AUTOSIM®, already allow users to select all the vehicle characteristics and motion conditions, but the main differences of the developed software are evident: it allows us to model a RPEH device and obtain energetic outputs, select the device characteristics and dimensions, and get its performance outputs in a way that none of the other software tools do. The developed software has as its main application the support for the development of road pavement energy harvesting devices. This initial version, not yet publicly available, is optimized for light vehicles. Further developments are being done to optimize it to heavy vehicles, with and without trailers. There are also considered two mechanical systems, while further developments are being done to include additional systems.

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References

1. Khaligh, A., Onar, O.: Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. CRC Press Inc., Boca Raton (2010)
2. Priya, S., Inman, D.J. (eds.): Energy Harvesting Technologies, vol. 21. Springer, Heidelberg (2009)
3. Kazmierski, T., Beeby, S. (eds.): Energy Harvesting Systems - Principles, Modeling and Applications. Springer, Heidelberg (2009)
4. Andriopoulou, S.: A review on energy harvesting from roads. MSc Thesis, KTH (2012)
5. Duarte, F., Ferreira, A.: Energy harvesting on road pavements: state of the art. Proc. Inst. Civil Eng. Energy **169**(2), 1–12 (2016)
6. IEA: Technology Roadmap: Fuel economy of road vehicles. International Energy Agency, Paris, France (2012)
7. Hendrowati, W., Guntur, H., Sutantra, I.: Design, modelling and analysis of implementing a multilayer piezoelectric vibration energy harvesting mechanism in the vehicle suspension. Engineering **4**(11), 728–738 (2012)
8. MSC.Software: http://www.mscsoftware.com/product/adams. Accessed 30 Oct 2016
9. Mechanical Simulation Corporation: https://www.carsim.com. Accessed 30 Oct 2016
10. Sharp, R., Evangelou, S., Limebeer, D.: Multibody aspects of motorcycle modelling with special reference to Autosim. In: Ambrosio, J.A.C. (ed.) Advances in Computational Multibody Systems, pp. 45–68. Springer, Heidelberg (2005)
11. Kinjawadekar, T., Dixit, N., Heydinger, G., Guenther D., Salaani, M.: Vehicle dynamics modeling and validation of the 2003 ford expedition with esc using carsim, No. 2009-01-0452, SAE Technical Paper (2009)
12. Wei-qun, R., Yun-qing, Z., Guo-dong, J.: A new application of multi-body system dynamics in vehicle-road interaction simulation. Wuhan Univ. J. Nat. Sci. **8**(2), 379–382 (2003)
13. Rao, S.: Development of a heavy truck vehicle dynamics model using TruckSim and model based design of ABS and ESC controllers in Simulink. Doctoral dissertation, The Ohio State University (2013)
14. Gillespie, T.: Fundamentals of Vehicle Dynamics. Society of Automotive Engineers, vol. 114 (1992)
15. Wong, J.: Theory of Ground Vehicles, 3rd edn. Wiley-Interscience, Hoboken (2001)
16. Pacejka, H.: Tire and vehicle dynamics. Elsevier, New York (2005)
17. Jazar, R.: Vehicle Dynamics: Theory and Application. Springer, New York (2008)
18. Popp, K., Schiehlen, W.: Ground Vehicle Dynamics. Springer, Heidelberg (2010)

19. Rajamani, R.: Vehicle Dynamics and Control. Springer, Heidelberg (2011)
20. Duarte, F., Ferreira, A., Fael, P.: Software for simulation of vehicle-road interaction. In: Rocha, A., Correia, A.M., Adeli, H., Reis, L.P., Teixeira, M.M. (eds.) New Advances in Information Systems and Technologies. AISC, vol. 444, pp. 681–690. Springer, Cham (2016). doi:10.1007/978-3-319-31232-3_64