# THE VIRTUAL PROTOTYPE OF AN OFF-ROAD VEHICLE

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## ABSTRACT

In paper, the virtual prototype of the rolling – guiding – suspension system of an off-road vehicle is presented. The prototype has been made with the MBS software ADAMS, and takes into consideration the geometric restrictions as well as the nonlinear characteristics of the elastic and damping elements. The experiment designed is one frequently carried by the automotive manufacturers, namely dynamic with shock test, which consists in the sudden release of the car to fall on the ground from a given height. On the virtual prototype, a lot of measurements have been made having in view to optimize the dynamic behavior of the suspension system and to enhance the vehicle safety.

## INTRODUCTION

The revolutionary evolutions in the field of motor vehicles imposed the development and utilization of high technologies both for manufacturing and design. Among these, the simulation techniques allow the engineers to conceive and equip virtual prototypes, which permit a large-scale evaluation of the system behavior. The working precision is high, so that the car behavior may be predicted in very early stages.
The increasingly growing demand for more comfortable cars nowadays imposes a new way for dynamic analysis of the guiding - suspension systems, with elaboration of models that are closer to the real mechanisms on the car. Involving the compliant constraints, the elastic and damping elements, and the body oscillations, the degree of freedom of the system is increasing and it’s practically impossible to analyze such models with classical methods and programs. Under these circumstances, it is necessary to use mechanical systems simulation software MBS (Multi-Body Systems). The multi-body system analysis and simulation software automatically formulates and solves the dynamic equations of motion. The major difference of mechanical system dynamics from the conventional structural system dynamics is the presence of a high degree of geometric non-linearity associated with large rotational kinematics. Governing equations for conventional structural system dynamics are linear differential equations, while those equations for mechanical system dynamics are nonlinear differential equations that are coupled with nonlinear algebraic equations of cinematic constraints.
These type of packages were lanced in commercial versions even in the 70’s but in the last decade a new type of studies were defined through their use: Virtual Prototyping. This consists mainly in conceiving a detailed model and using it in a virtual experiment, in a similar way with the real case.

## THE VIRTUAL PROTOTYPING PLATFORM

Virtual Prototyping is a software-based engineering process, which enables modeling the suspension system, simulating its motion under real operating conditions and, finally, optimizing the suspension through iterative studies.
Virtual Prototyping brings several advantages: reduce the time and cost of new product development; reduce the product cycles; reduce the number of expansive physical prototypes and experiment with more design alternatives; automotive engineers can quickly exploring multiple design variations, testing and refining until optimizing suspension behavior, long before building the first physical prototype.
Virtual prototyping platform includes CAD (ex. EUCLID, CATIA, PROENGINEER), MBS (ex. ADAMS, DYMES, SDS) and FEM (ex. NASTRAN, NISA, COSMOS) software, the general scheme being shown in figure 1. A main factor of the virtual prototyping solution is the integration that defines the connections between the programs from virtual prototyping platform. The virtual prototyping should provide the ability to work within CAD environment, having in view to model mechanical systems and perform simple motion studies; the ability to easily transfer geometry between CAD system and virtual prototypes; the ability to transfer loads from virtual prototyping to FEA, and to bring component flexibility from FEA back into virtual prototyping; the ability to transfer plant models to controls design packages and transfer control laws back to virtual prototyping.
The main component of the virtual prototyping platform is the mechanical systems analysis and simulation software (MBS). The steps to create a virtual model with MBS software mirror the same steps to build a physical prototype:

- build - modeling parts, constrain the parts, create forces acting on the parts;
- test - measure characteristics, perform simulation, review animation, review numeric results as plots;
- validate - import, superimpose test data on plots;

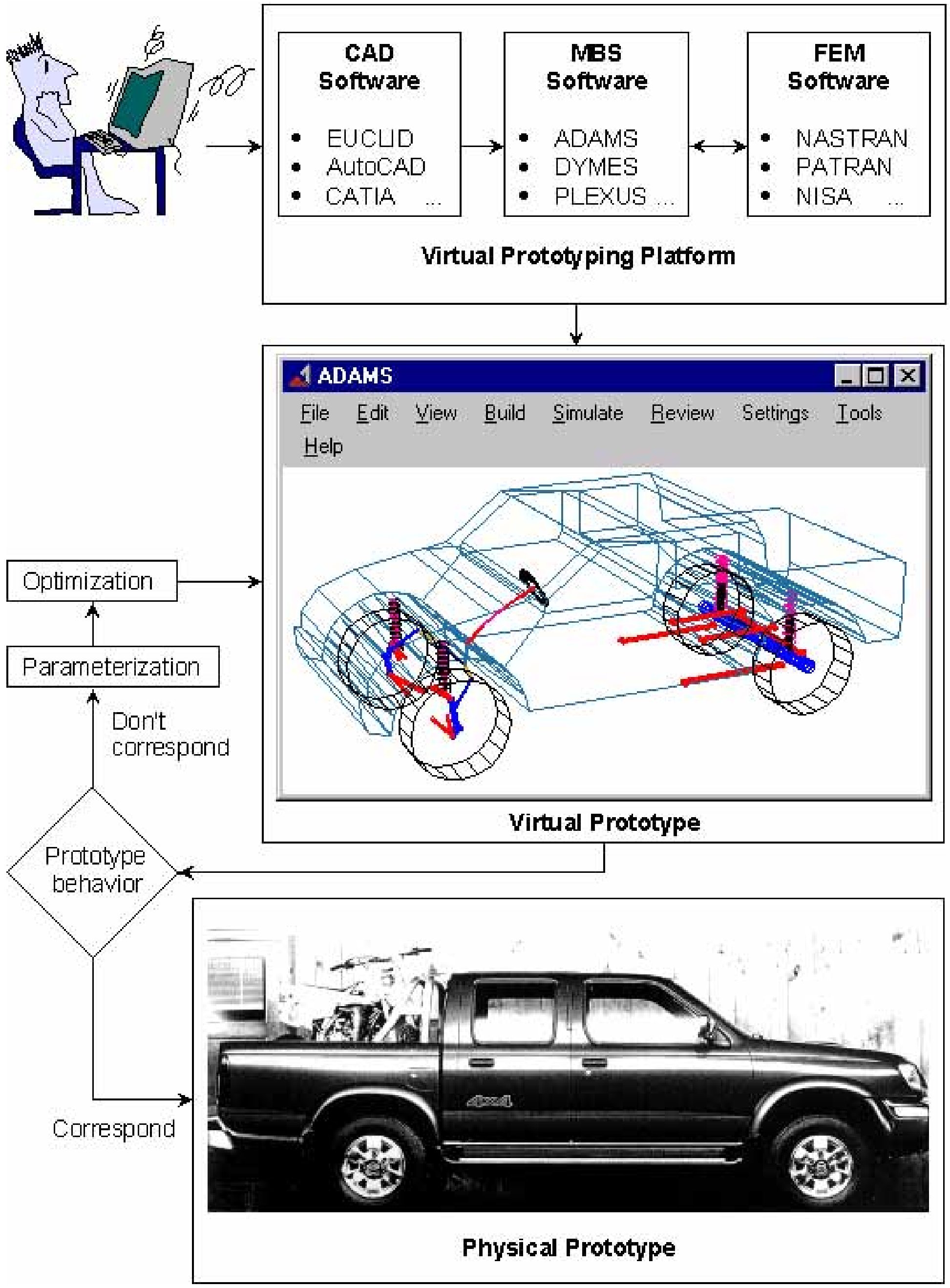



**Figure 1. Virtual Prototyping Platform.**

- refine - add friction, define flexible bodies, implement force functions, define controls;
- parameterize - add parametrics, define design variables;
- optimize - perform manual studies, perform design sensitivity studies, perform design of experiments, perform optimization studies.

Therefore, the three goals most often stated by virtual prototyping users are to cut time and cost, increase quality and increase efficiency.

## THE DESCRIPTION OF THE PROTOTYPE

The paper presents a virtual prototype of an off-road vehicle, which was made with the MBS software ADAMS. The prototype takes into account the guiding linkages of the unsprung masses (front and rear axles), the elastic and damping elements of the suspension system (springs, dampers, bushings, rubber bumpers limiting the run, anti-roll bars, tires). The suspension corresponds to the Romanian off-road vehicle ARO:

independent suspension of the front wheels and dependent suspension of the rear wheels (i.e. solid axle suspension).

**The modeling of the parts**

The dynamic model of the car's suspension is characterized as a constrained, multi-body, spatial mechanical system, in which rigid bodies (parts) are connected through compliant joints and force elements. Constraints define how bodies are attached and how they are allowed to move relative to each other.
The front wheels are guided with spatial quadrilateral mechanisms (i.e. double-wishbone suspension), which perform the guidance through driving three points per wheel. The lower and upper control arms are connected to the car body through compliant joints (i.e. bushings), which allow 6 elastic restricted degrees of freedom. A spherical joint constrains the wheel carriers to the upper and lower arms, and also the wheel carriers to the tie rods. The two suspension linkages (left and right) are symmetrically disposed relative to the longitudinal plane of the vehicle.
The steering system contains a parallel-link mechanism (i.e. four-bar steering mechanism) consisting of a pitman arm, center link and idler arm. A worm and wheel gear transmits motion from the input shaft to the pitman arm that rotates to impart motion to the center link and idler arm. The translation of the center link pulls and pushes the tie rods to steer the wheels.
For the rear axle, a dependent suspension with guiding mechanism by five links is used. This achieves the axle guidance through driving five axle points. The upper and lower longitudinal arms, and the transversal arm (i.e. Panhard arm) are connected to the car body, and to the solid axle, through bushing elements.
To modeling the dampers as parts, not only as internal force elements, strut parts are used. These are connected to the car body and to the control arms, axle respectively, with bushings.
The car is modeled and analyzed in a global coordinate system (GCS), which it is an inertial system. The ground, which is automatically created when the model is build, acts as the global coordinate system that defines the global origin and axes about which the model is created. For any mobile body (car body, links, axle, wheels carrier), a local coordinate system (LCS) is assigned, which moves with the body and its original position defaults to that of the GCS.
To modeling rigid bodies, ADAMS contains a set of predefined solid geometry. These are 3-dimensional objects that have mass and inertia properties. The mass of the body, the center of mass position and the inertia properties are automatically calculated in relation to the part's geometry and material type, which can be established from a database.

**The modeling of the elastic and damping elements**

The elastic and damping elements of the suspension system represents forces acting between two parts (car body – axle/wheel carrier, car body – guiding links) over a distance and along a particular direction.
For the front suspension, the translational spring-damper elements are disposed between car body and upper control arms. In the case of the rear suspension, the elastic and damping elements are disposed between car body and axle. The suspension spring is modeled as a double active (tension – compression) elastic element of translational nature. The inputs for modeling are the global coordinates of points in which the springs are connected to the adjacent bodies, the undeformed spring length and the force vs. deflection characteristic.
The front and rear suspensions contain bound-stop and rebound-stop that acts between the upper and lower strut parts. The internal forces of elastic bumpers have transitory character. These elastic elements are modeled as translational springs with unilateral rigidity, that are active only when spring is in tension or in compression, by using one-sided impact forces.
The front/rear anti-roll bar, which represents a bar fitted transversely to the suspension, is disposed between car body and lower arms. Drop links transmit the suspension motion to the bar ends. A revolute joint connects the two bar halves of the anti-roll bar system. Bushing elements attach the bar halves to the car body. The drop links are connected to the bar ends and to the suspension with spherical joints.
The connections of the front and rear guiding links to the car body, as well as the connections of the rear links to the axle, are made through bushing elements. These are compliant (flexible) joints with six degrees of freedom. These flexible connections do not cinematically constraint the relative motion between adjacent parts.

**The degree of freedom of the virtual prototype**

The above-described model contains 41 mobile parts, as follows:
- Car body (one part);
- Front suspension system: rims (two parts), wheel carriers (two parts), lower and upper control arms (four parts), drop-links (two parts), anti-roll halves (two parts), lower and upper struts (four parts), tie rods (two parts);
- Rear suspension system: rims (two parts), solid axle (one part), longitudinal and transversal guiding links (five parts), drop-links (two parts), anti-roll halves (two parts), lower and upper struts (four parts);
- Steering system: center link (one part), pitman and idler arms (two parts), steering column (one part), intermediate shaft (one part), input shaft (one part).

The geometric constraints (i.e. joints) from the virtual prototype are:
• Bracket joints: wheel carriers/axle - rims (four joints);
• Revolute joints: left - right antiroll bar halves (two joints), pitman/idler arms - car body (two joints), steering column - car body (one joint), input shaft - car body (one joint);
• Worm and wheel gear;
• Cylindrical joints: upper - lower struts (four joints);
• Hooke joints: steering column - intermediate shaft (one joint), intermediate shaft - input shaft (one joint);
• Spherical joints: wheel carriers - lower/upper control arms (four joints), wheel carriers - tie rods (two joints), tie rods - center link (two joints), center link - pitman /idler arms (two joints), drop links - antiroll bar halves (four joints), drop links - lower control arms /guiding links (four joints).

The total number of degrees of freedom (DOF), which represents the number of undetermined motions, is equal to the difference between the number of allowed part motions and the number of active constraints (Gruebler count), DOF=6·n-r, as follows:
DOF=6·41 - (4·6 + 6·5 + 1·4 + 4·4 + 2·4 + 18·3)=110.
Consequently, the virtual prototype of the vehicle has 110 independent generalized coordinates.

## THE SIMULATION OF THE PROTOTYPE

The virtual prototype has been tested and simulated in dynamic with shock regime, which consists in the sudden release of the car to fall on the ground from a given height (fig. 2). For the left and right wheels, different level of falling have been considered ($h_r$=200 mm - right wheels, $h_l$=100 mm - left wheels), having in view to evaluate the roll motion of the vehicle.

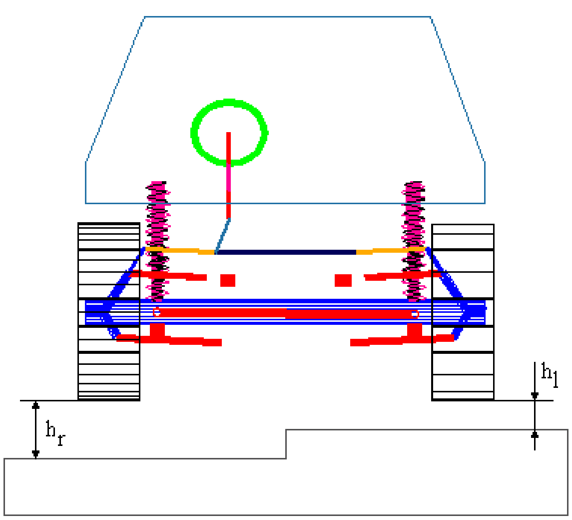



**Figure 2. Dynamic with shock test.**

Taking into consideration the non-stationary character of the connection between tires and ground, the tires was modeled as one-sided impact forces (similarly with the shock bumpers limiting the run). On the other hand, due to the test that has been simulated, the rims are rigid connected to the wheels carrier, and axle respectively, through bracket joints.
The prototype of the off-road vehicle is presented in figure 3. The details of the front and rear suspensions systems are shown in figure 4 and 5.
The simulation was achieved for a time interval long enough to catch all relevant motions during the experiment (t=3 sec). In figure 6, the main frames of the graphical simulation are presented, for the vehicle movement during the virtual benchmark.

## THE OPTIMIZATION OF THE PROTOTYPE

The optimization of the model has been made with the following steps:
- parameterizing the model
- defining the design variables,
- defining the objective function for optimization,
- performing design study and design of experiments,
- optimizing the model on the basis of the main design variables.

Parameterizing the model simplifies changes to model because it helps to automatically size, relocate and orient bodies. In this way, relationships into the model can be build, so that when a modeling object is changed, ADAMS updates any other objects that depend on it. The virtual prototype has been parameterized while creating rigid bodies using design variables, which represent values of the body geometry (for example, the length of a guiding link).
Design variables allow creating independent parameters and tie modeling objects to them. In addition, by using design variables, the parametric analyses have been performed: design study, design of experiments and optimization.
Design optimization represents the capability to define design objectives, constraints and variables, and then have the software iterate automatically to the optimally - performing configuration.
Design of experiments (DOE) is a complementary technique to design optimization. DOE is a methodology for running a statistically significant battery of tests on a design to determine its sensitivity or robustness to design or manufacturing variations.
Design study describes the ability to select a design variable, sweep that variable through a range of values and then simulate the motion behavior of the various designs in order to understand the sensitivity of the overall system to these design variations. Before running the design study, the range (list) of values for each design variable has been specified.

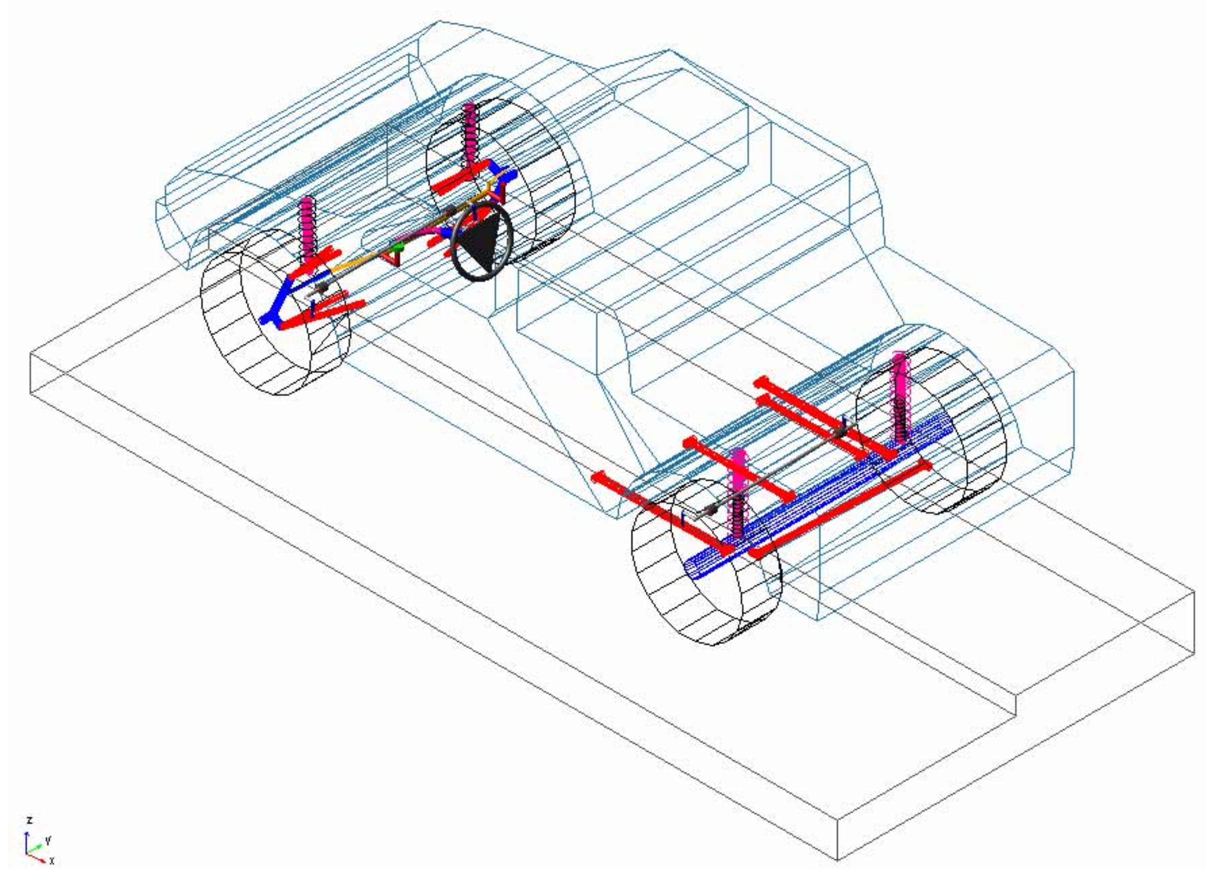


**Figure 3. Virtual prototype of the vehicle.**

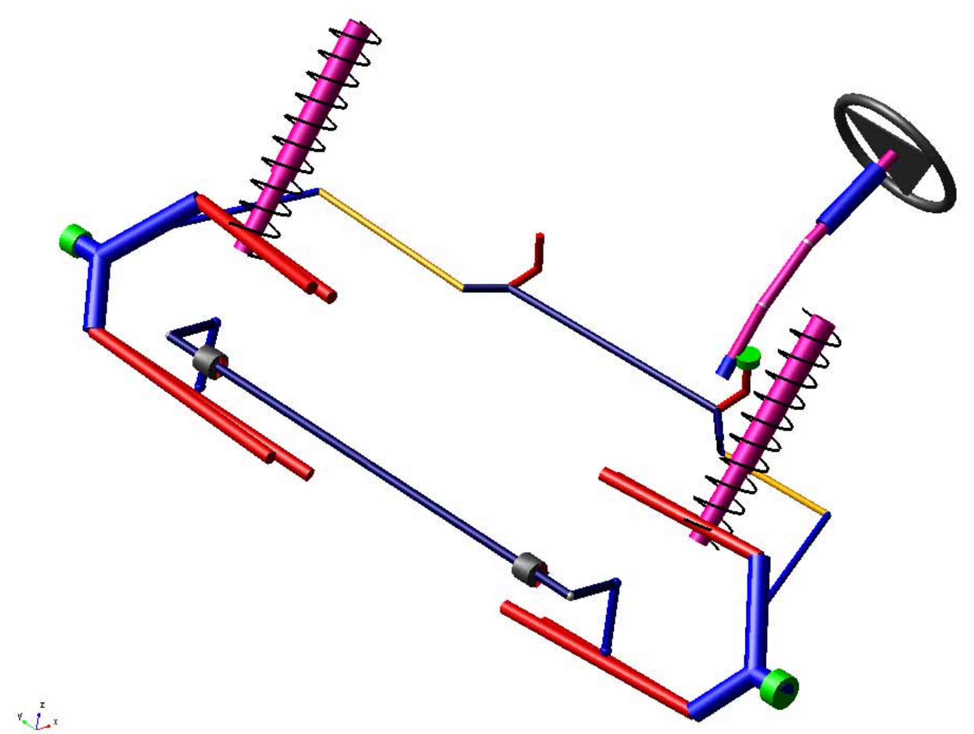


**Figure 4. Front suspension system.**

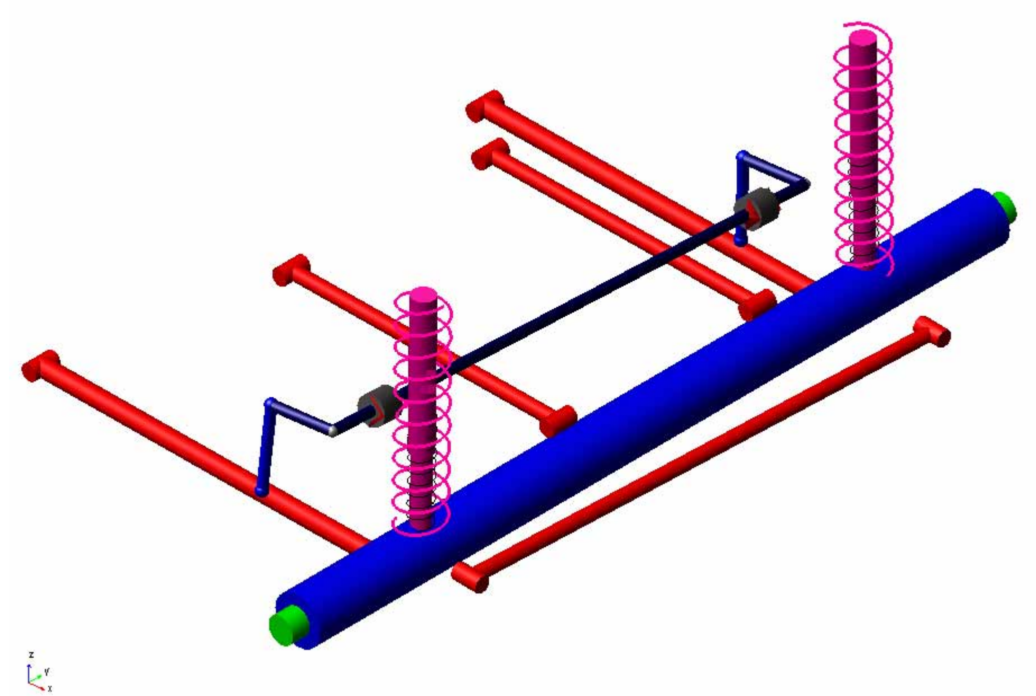


**Figure 5. Rear suspension system.**

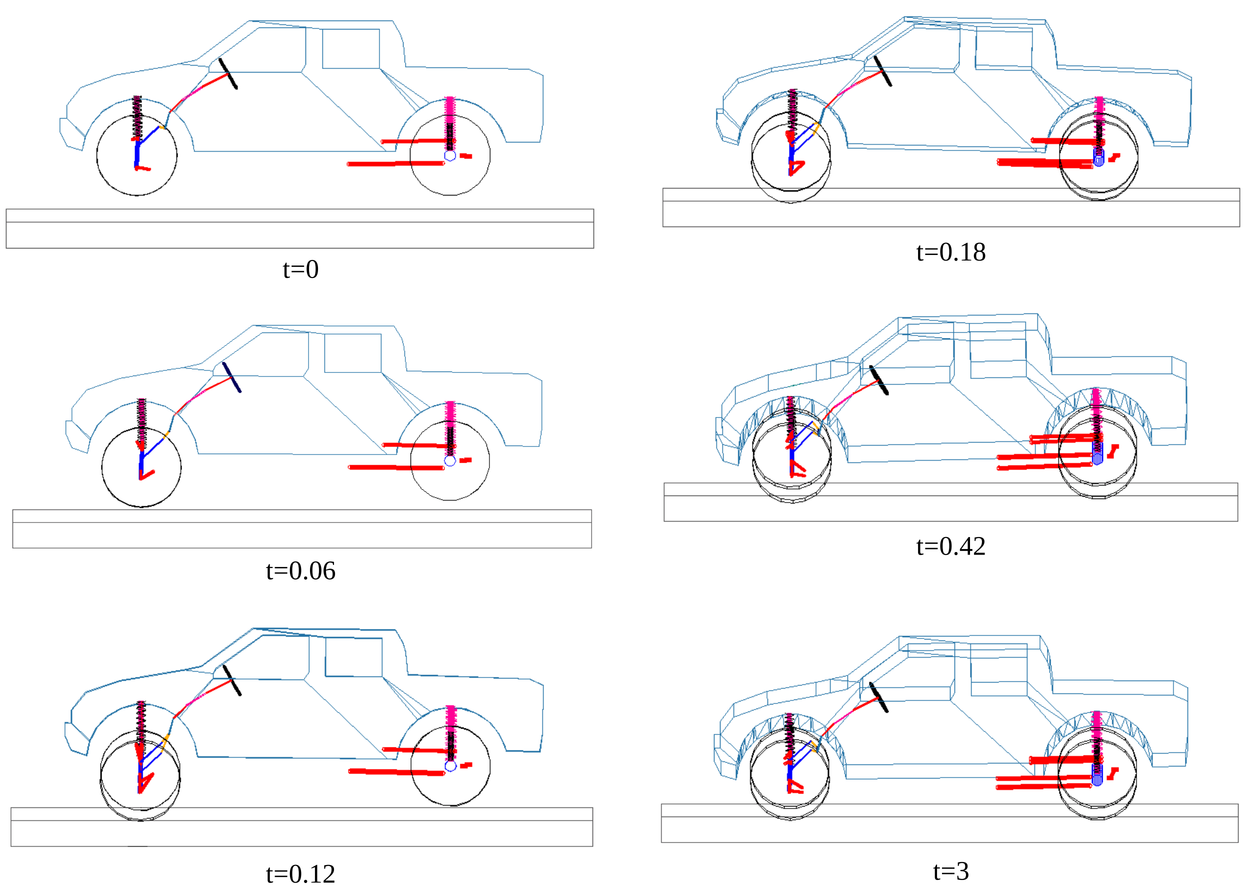
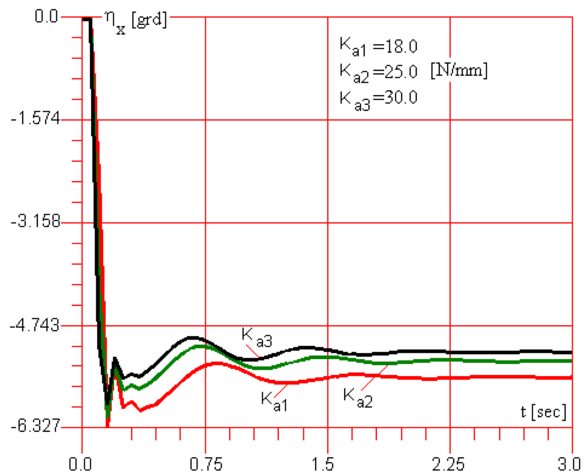



**Figure 6. Graphic simulation frames.**

Design study report includes the design sensitivity, which helps to determine the design variables that can be used for optimization study (i.e. variables that have the greatest effect on the vehicle behavior).
The model has been parameterized using the points that define the topological scheme of the virtual prototype. The global coordinates of the points have been transformed in design variables that control the locations of the design points. On the other hand, the elastic/damping characteristics of the elements (springs, dampers etc.) have been considered as variables in optimization process. During the design study, ADAMS runs a series of simulations with different values for each design variables and gives feedback on the effects of the changes.

## RESULTS AND CONCLUSIONS

A lot of measures (i.e. positions, velocities, accelerations, and forces) define the dynamic behavior of the vehicle. In paper, the minimization of the roll motion, respectively the pitch motion of body has been considered, successively, as goal of the optimization.

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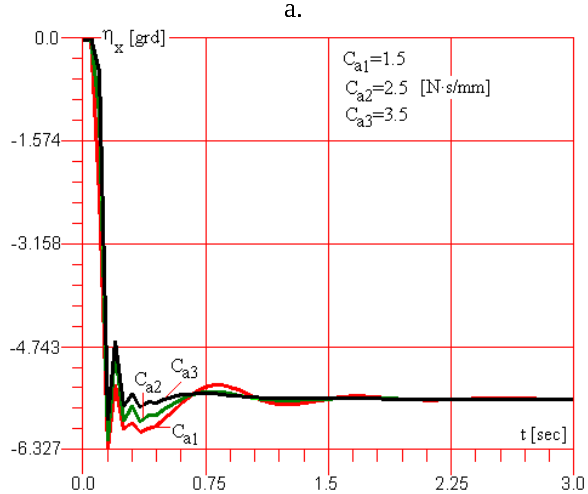


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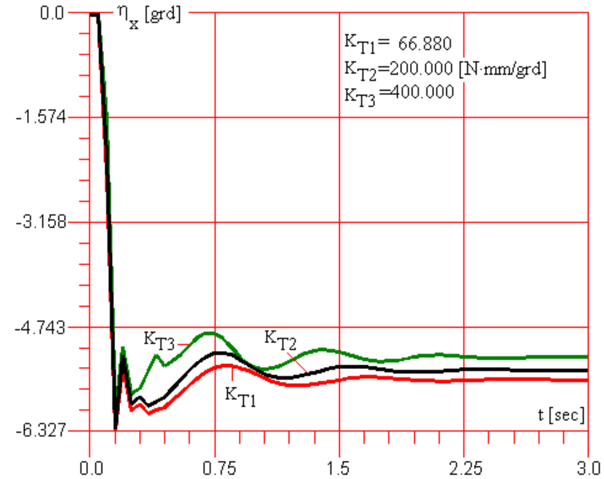


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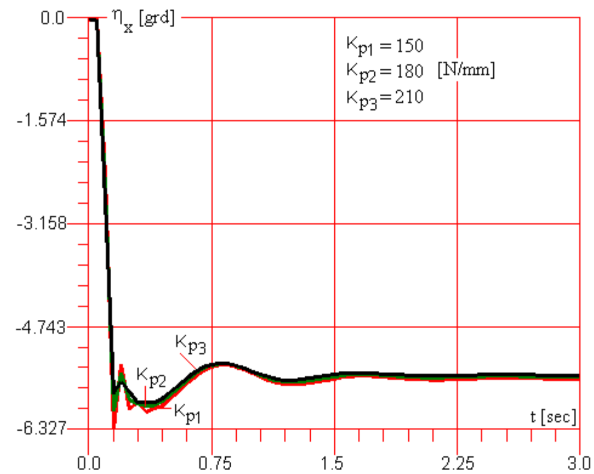


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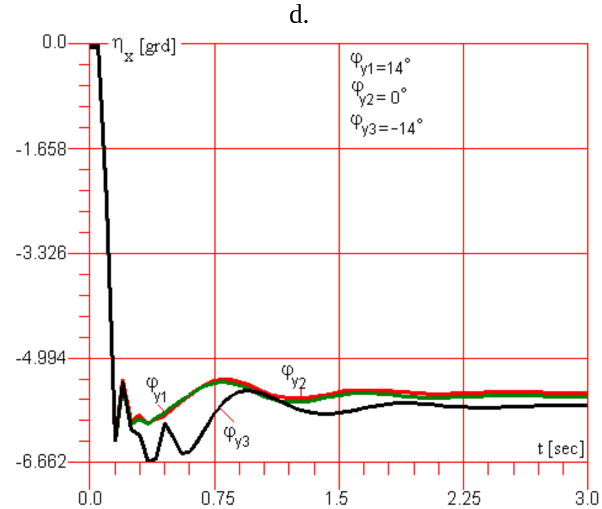


e.

**Figure 7. Results of design study for roll motion.**

The diagrams shown in Figure 7 present the influence of same design variables on the roll angle, as follows:
a. stiffness characteristic (force vs. deformation) of the rear springs,
b. damping characteristic (force vs. velocity),

c. torsional stiffness (torque vs. deformation) of the bushing elements,
d. vertical stiffness of the tires,
e. disposing of the springs in longitudinal plane.
For each design variable, the list of values is indicated on the plot. The authors have diagrams for a lot of design variables, which are not presented in paper due to the lack of space.
In figure 8 the vertical car body motion history is presented. The "virtual" behavior of the car body corresponds, as amplitude and frequency, with the experimental results that are presented in [13], therefore the virtual prototype of the off-road vehicle has been experimentally validated.

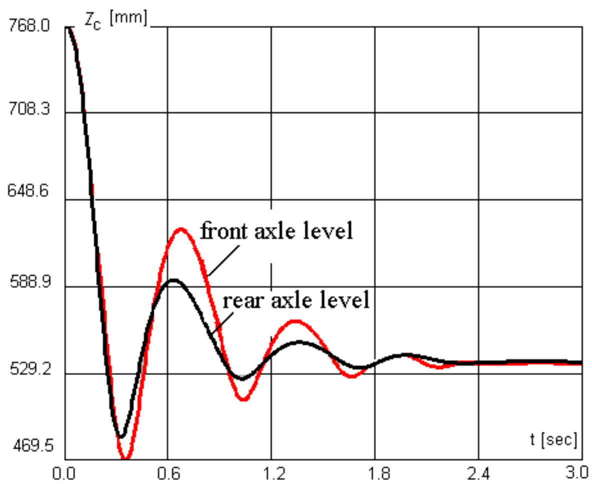


**Figure 8. Vertical motion of the car body.**

The application presented in paper is a typical example of virtual prototyping of the vehicle's suspension. One of the most important advantages of virtual prototyping in automotive industry consists in the possibility of make easy virtual measurements in any point and/or area of the system and for any parameter. This is not always possible in the real cases due to the lack of space for transducers placement, lack of appropriate transducers or high temperature. This helps engineers to make quick decisions on any design changes without going through expensive prototype building/testing. The achievement of the dynamic model of the vehicle may demonstrate the design possibilities already existing at "Transilvania" University, which are already used in some Romanian corporation (DACIA, ARO).

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