Mixed Lagrangian Eulerian Method for Tire/Road Interaction in Finite Element Vehicle Dynamic Simulation

Vincenzo Puleo, Raffaele Saponaro, Paolo Smeriglio

Fiat Research Centre

Efthimio Duni, Giovanni Toniato

Fiat Group Automobiles S.p.A.

Abstract: *In the early design phases of car development, when no prototypes are available, is essential to calculate loads transmitted to the vehicle running on fatigue reference roads for structural performances assessment. In current Fiat practice, to perform this analysis, a simplified and general finite element tire model, combined with a traditional full-vehicle model, is used; fundamental parts of this methodology are Fiat fatigue reference track digitalization, its implementation as a rigid body and some issues related to tire/road interaction.*

In this paper, a new mixed Lagrangian-Eulerian approach for tire/road interaction is presented: this new methodology is based on a different road modeling principle, where the road profile is described in time domain rather than space domain. The aim is to reduce the contact problem dimension and therefore calculation time. Comparison between current practice and new approach has been developed to verify the equivalence of results.

As a result, the new method shows a significant reduction of calculation time without any appreciable changing in simulation outputs and is numerically validated, ready to be implemented in vehicle assessment process.

Keywords: *Connectors, Dynamics, Experimental Verification, Fatigue, Mechanisms, Multi-Body Dynamics, Scripting, Suspension, Tires, Vibration.*

1. Introduction

In recent years, current market impose short time development cycles and cost reductions. In this process, virtual test plays a crucial role since it allows to minimize the number of prototypes built, leading to an increasing need for the creation of complicated models for high simulation accuracy. In current Fiat practice, a virtual environment to simulate dynamic maneuvers has been developed: this way is possible to calculate loads transmitted to the vehicle running on fatigue reference roads for structural performances assessment.

In this virtual environment, a traditional full-vehicle model runs on a fatigue reference track; the main aspect of the methodology is the application of a finite element tire model, instead of a simplified one, based on a limited numbers of degree of freedom, so tire-road contact interaction can be better evaluated and all loads evaluation are more reliable.

A critical point approached during methodology development is the best strategy adopted for combining simulations of quasi-static and dynamic phenomena: non-linear transient vehicle dynamic analysis require, in fact, to find static equilibrium before performing dynamic simulations; results of static equilibrium are then imported as initial condition for dynamic simulation. Quasi static analysis are performed trough an implicit finite element method, that allows to find the equilibrium with a good accuracy. Dynamic simulations, instead, are made with an explicit finite element method, since it allows to manage tire-road contact interaction in a more efficient way compared to an implicit method. Unfortunately, this advantage is negatively balanced by the analysis time required for durability evaluations, as simulation time goes from 60 to 120 seconds, that is order of magnitude compared to simulation time usually used in explicit calculations as crash events. The problem of solution accuracy due to large number of increments and the calculation time required have been analyzed as they represent the two main issues influencing the success of such approach.

Calculation time performance of dynamic simulations is dominated by contact problem solution as the solver has to manage the interaction between big surfaces ("pave" road) and tire external surfaces; this solution is not efficient because search contact algorithm is not local and involves part of road far away from tires. In order to improve time calculation performance, a new road modeling principle has been developed, where the road profile is described in time domain rather than space domain and the contact problem dimension is reduced, making faster the computation. This is possible making deformable the road mesh and constraining movement of its nodes using appropriate amplitudes of displacement; the road can be modeled as a closed roller and nodes and elements can be used repeatedly. Thanks to this new modeling principle, only the part of the road under the tires need to be modeled and, as a consequence, search contact algorithm has to manage a reduced problem.

2. Vehicle model

The model for dynamic simulations is assembled using a mixed approach: only parts of vehicle whose compliance is important in dynamic maneuvers (as tires, antiroll bar and twistbeam) are considered deformable using a finite element representation. The other parts of the vehicle are modeled using a method based on a multibody approach: rigid bodies joined by connector elements with appropriate stiffness and damping properties; all rigid bodies are characterized with a mass and a rotary inertia element. In figure 1 an example of a front suspension modeling is shown.

2.1 Finite element tire model

In dynamic simulation of a vehicle running on virtual fatigue reference track, a significant role is played by the tire model. Historically, tire has been modeled with either an analytical approach (complex spring-mass-damper system) or with an empirical one, integrated with a multibody technique for the overall system. All these approaches show limitations, as the problem of being in need of a continuous calibration based on experimental data of real components. With a finite element approach, it is possible to better evaluate tire/road interaction and it is possible to create a simplified and generic model that need a shorter phase of calibration.

Since dynamic simulations are made with an explicit code, it is important to consider that minimum time increment of the solver is governed by element size employed. Modelization

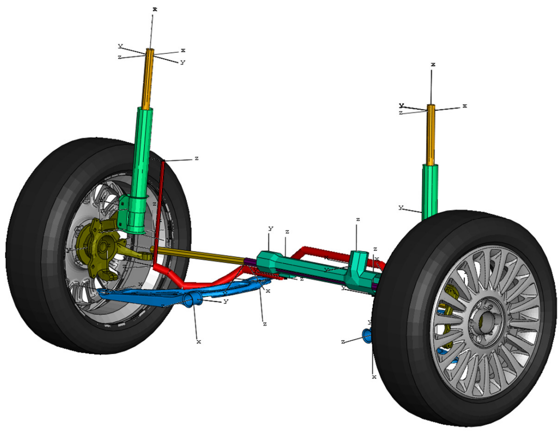

Figure 1. Example of suspension modeling

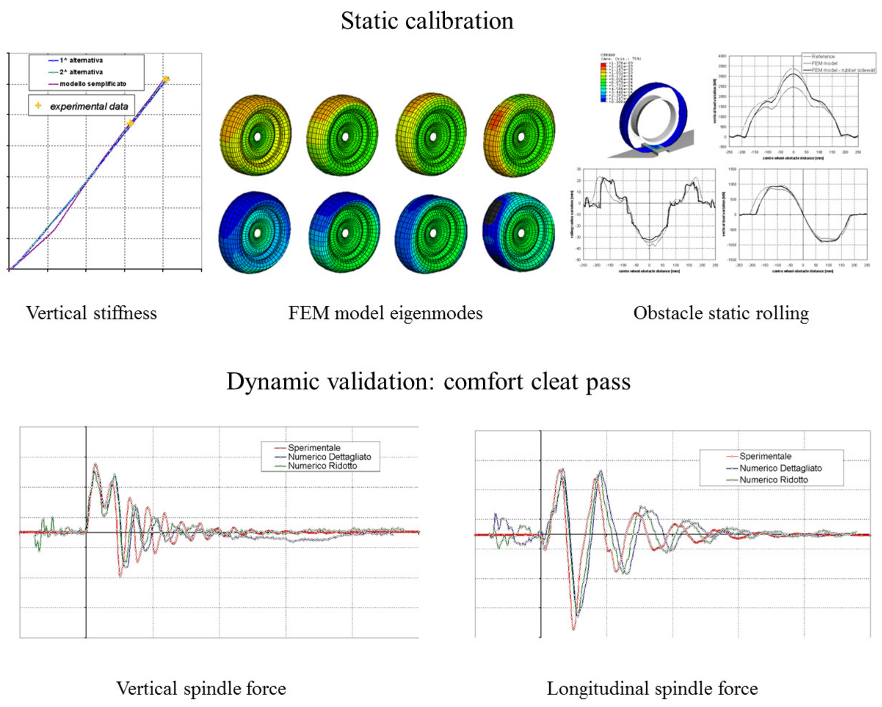

Figure 2. Finite element tire model validation method

characteristics have to be fixed as a balance between an acceptable total time of simulation and a good accuracy of results. In (Duni, 2003) and (Duni, 2010), the construction of a reliable tire finite element model of moderate complexity was described. It is validated over several obstacles using quasi-static, static and dynamic analysis (as shown in Figure 2).

In addition to static and dynamic validation, some issues related to mesh size, element integration order and integration accuracy order have been investigated, making the model able to be stable and accurate along all simulation length. Model developed in (Duni, 2003) and (Duni, 2010) has been used for the work presented in this paper.

2.2 Fatigue road digitalization

All car companies have their own targets for durability assessments that are generally based on reference tracks representing all life conditions of a vehicle. FIAT has two main reference tracks:

- “Balocco”, 400m long, used for passengers car testing;
- “Mandria”, 900m long, for commercial vehicle testing.

These tracks have different roughness and are associated to different testing conditions and targets. The possibility of a numerical description of the track surface makes possible to simulate realistic testing conditions, so an optical measurements of the tracks was made: the output of these measurements is a grid of vertical coordinates with a 5x5 mm resolution in horizontal spacing. In Figure 3 a graphic output of a small portion of surface is compared to a photography of the same patch.

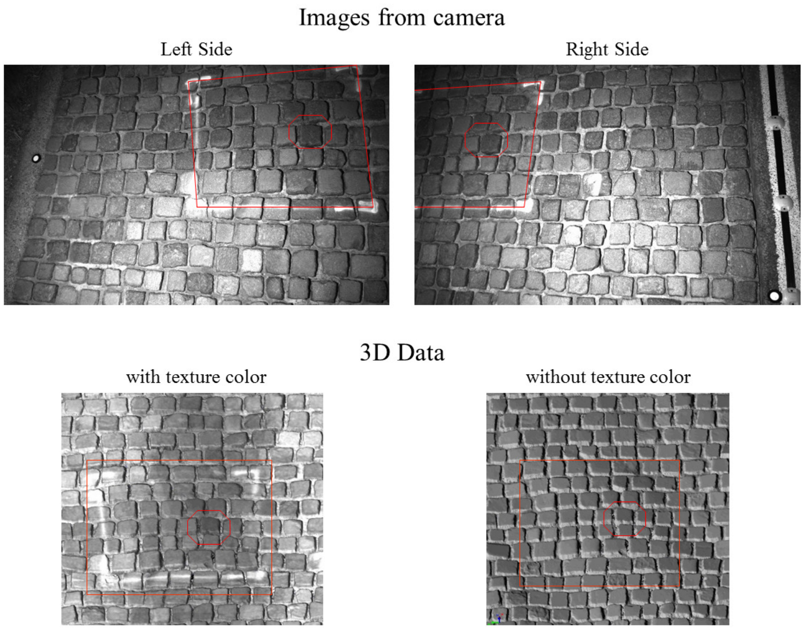

Figure 3. Finite element tire model validation method

Track measurements are implemented in Abaqus/Explicit as rigid elements associated to a rigid body; a Python script translates grid information in Abaqus node cards and a parametric element generation (using the ***ELGEN** card) fills all this nodes network with rigid elements. With this method is possible to select and generate only the elements of the strips involved in contact with tires, removing the rest of the track width and the corresponding nodes. In §4.1 a new track modelization will be presented.

3. Pure Lagrangian method

In current Fiat practice, a pure Lagrangian method is used to perform dynamic maneuvers. A step by step scheme is used, where first steps are performed to find the static equilibrium. Abaqus/Standard is used and the following phases are simulated: tire seating and inflation (for the four wheels of the model); gravity load application and consequent suspensions pre-loading; contact enforcement between wheels and ground; equilibrium between vehicle and ground under the gravity field previously applied. The equilibrium solution found is used as starting point for the transient dynamic analysis, which consists in reproducing experimental conditions. The dynamic analysis is performed whit Abaqus/Explicit.

General contact algorithm is applied to manage interactions between tires and ground, that is modeled as described in §2.2; motion of all nodes of the road, from original to final configuration of the car running on, is evaluated by adopting a Lagrangian formulation. To reduce calculation time, the analysis is divided in many steps, where reduced contact patches are activated or deactivated in general contact definition depending on vehicle position.

A problem related to long time simulations is due to random excitations acting to tires rolling on "pave" road that make difficult to maintain prescribed running velocity and trajectory; in real tests, the driver ensures prescribed conditions by driving action. In numerical finite elements, simulations boundaries and loads are usually applied in passive terms (independent of model response), but the use of this kind of loading to adjust vehicle dynamic response requires a calibration, done using at least a short preliminary simulation. Using Fortran subroutines, it is possible to apply boundaries or loads to the model at every increment of the simulation based on transform functions of outputs of the previous increment. In "pavé" track simulation two active controls are applied: torque on driving wheels (for maintaining prescribed velocity) and position of the steering system (for maintaining vehicle trajectory). As a result, active controls make the numerical solution repeatable and closer to test condition.

This kind of simulation allow to obtain:

- vertical acceleration of the four wheels, representative of dynamic response of unsprung masses;
- vertical acceleration of front and rear strut mounts, representative of vertical loads transmitted from suspension systems to vehicle body;
- relative displacements between wheel centers and corresponding body points;
- loads in the three directions of all suspension attachments.

First three outputs can be used for comparison with experimental data, when available, while last outputs can be used for structural performances assessment of body structures.

4. Mixed Lagrangian Eulerian method

Even though Lagrangian formulation represents a more natural and effective analysis for such kind of problems, it can be convenient to use an Eulerian formulation and focus the attention on the motion of the road through a stationary control volume.

In dynamic simulations as described in previous chapters, calculation time performance is dominated by contact problem solution as the solver has to manage the interaction between big surfaces ("pave" road) and tire external surfaces. Search contact algorithm is not local and involves part of road far away from tires. In order to improve calculation time performance, a new road modeling principle has been developed: instead of using rigid elements, the road mesh is deformable and modeled as a closed roller, whose nodes can be constrained with appropriate amplitude of displacements in order to make a circular movement of the roller, as it can be seen in figure 4, where an example of a longitudinal section is reported. Road profile can then be described trough appropriate amplitudes of vertical displacement; this way, only the needed patch of the road is present in the simulation (the information of the road profile is stored in the time instead in the space).

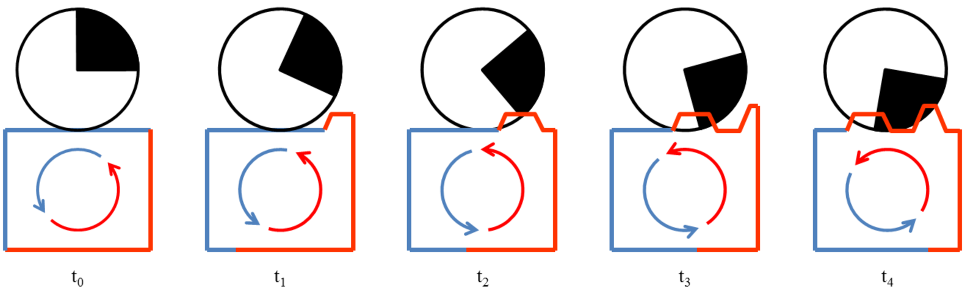

Figure 4. Example of a longitudinal section of the roller at different instants

This new approach reduce the number of contact interactions managed by general contact algorithm and the number of nodes and elements of the model; in addition, it is not necessary anymore to perform the solution using a step by step strategy; one step solution is adopted instead. Other aspects of the simulation remain the same compared to pure Lagrangian method: vehicle modelization, general contact algorithm and active controls.

Abaqus cards for nodes, elements and amplitudes of displacement are created with a Python routine.

4.1 Modelization

For every tire, it is modeled only the surface strictly necessary, as shown in figure 5. Road mesh has to be deformable and membrane elements (M3D3) are used. All degree of freedom of element nodes are constrained trough amplitude of displacements, so it is not important to assign a section to this elements; since Abaqus does not accept deformable elements without a section assignment, a thickness and an elastic material have been chosen in order to not influence the minimum time increment of the simulation.

The Python routine requires input data as wheel position and roller dimension, in order to create nodes and elements in the right position.

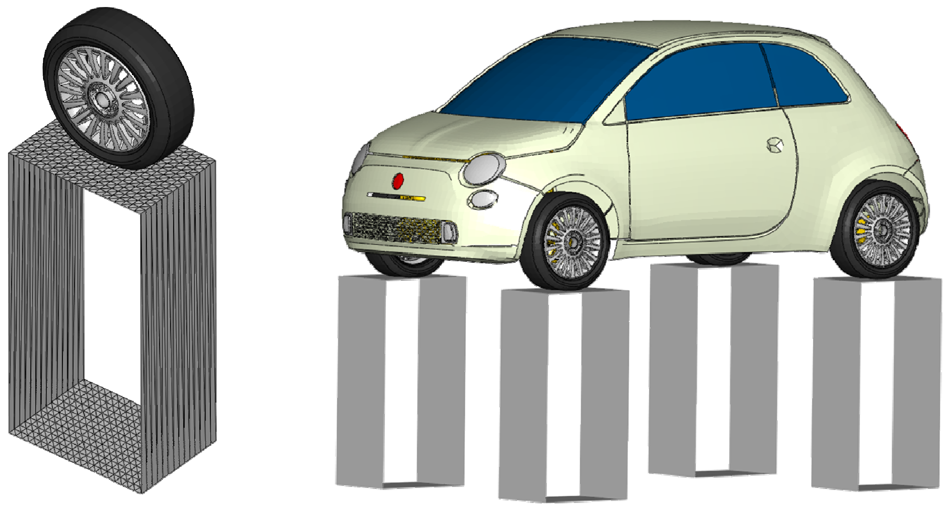

Figure 5. Roller modelization and its placement under vehicle wheels

4.2 Amplitude

Relative displacement between wheels and ground is created moving road nodes with appropriate amplitude of displacements; for each node, it must be defined a longitudinal and a vertical amplitude of displacement (the transversal position is held constant with a **`*BOUNDARY`** card). Every amplitude can be considered made by a sequence of similar unit, each of them representing a complete run of the roller; the number of units is function of the entire track length.

It is not possible to force the position of a node, but only the displacement, so there are different archetypes of amplitude unit depending on the initial position of the node considered. Nodes of the roller can be divided between upper and lower (considering the initial position) and then between rear, middle and front position; in figure 6 the twelve unit archetypes are shown. The amount of displacement for each amplitude is calculated by the Python routine considering roller size and, for vertical displacements, also from road digitalization database. For longitudinal displacements, amplitude unit is repeated many times as needed to complete the entire track length; for vertical displacements, amplitude is made by units similar in shape, but with different height in order to describe the road profile.

Examples in figure 6 are shown for a longitudinal section of the roller: longitudinal amplitude are always the same for any section, while vertical amplitudes are all different as they have to describe road shape in transversal direction. Figure 7 reports an example of the road profile as it results after application of amplitudes calculated by the Python routine.

Time definition in the amplitudes determines the velocity of the road profile under the wheels; **`SCALEX`** parameter in **`*AMPLITUDE`** card allows to change test velocity with no need of running again the Python routine.

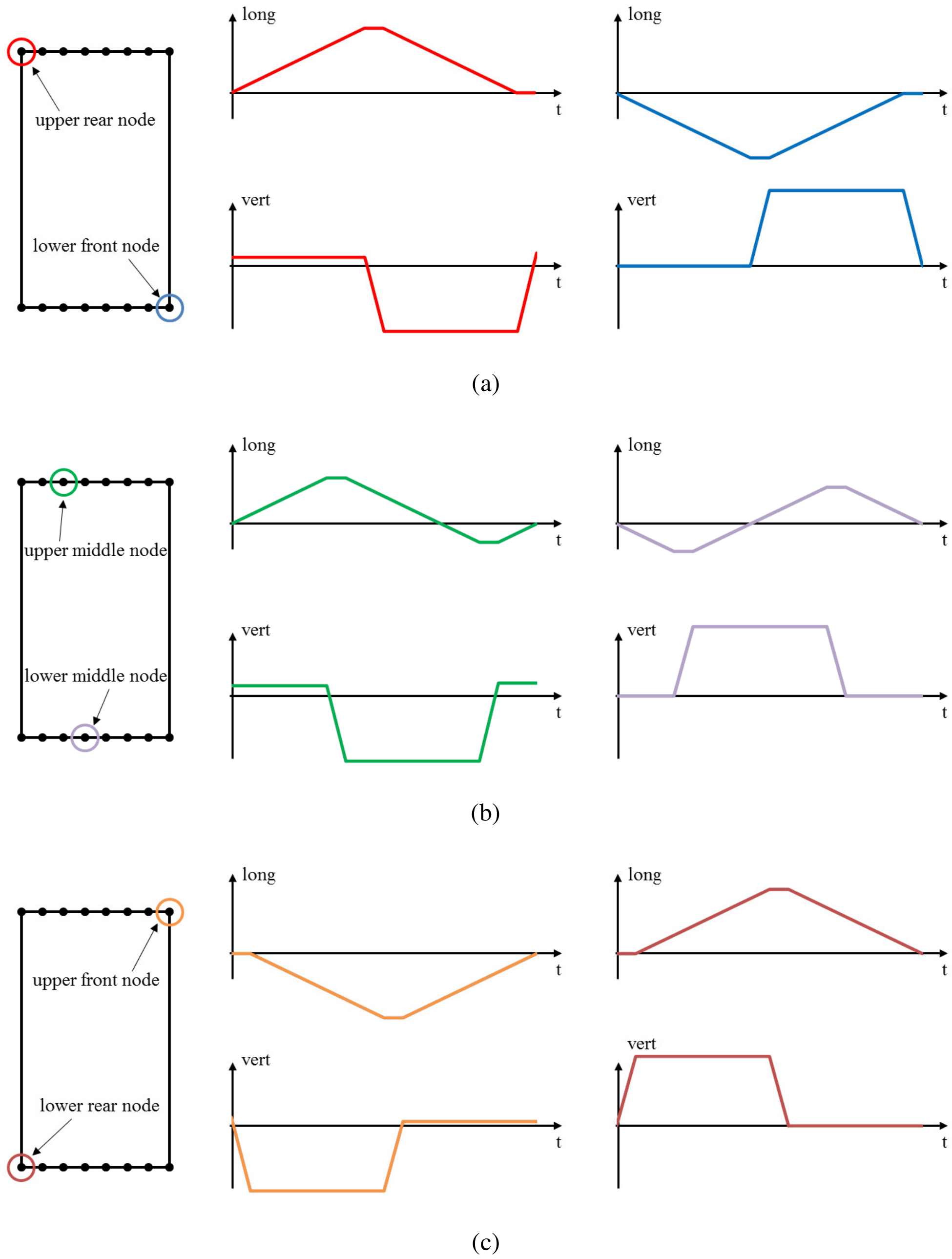

Figure 6. Amplitude unit archetypes

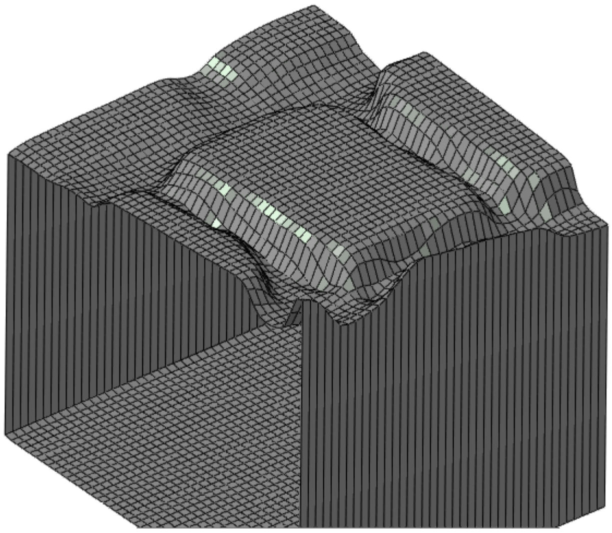

Figure 7. Road profile created by displacement amplitudes

5. Results

Simulation made with pure Lagrangian method and with mixed method must provide same results.

In figure 8 is reported a comparison of front strut mount acceleration with the two different methods: there is a quite perfect overlapping. A better comparison can be done in terms of statistical parameters: in figure 9 the comparison of some typical vertical acceleration and body loads for both methods is reported using level crossing graphs. There is a very good overlap between both results.

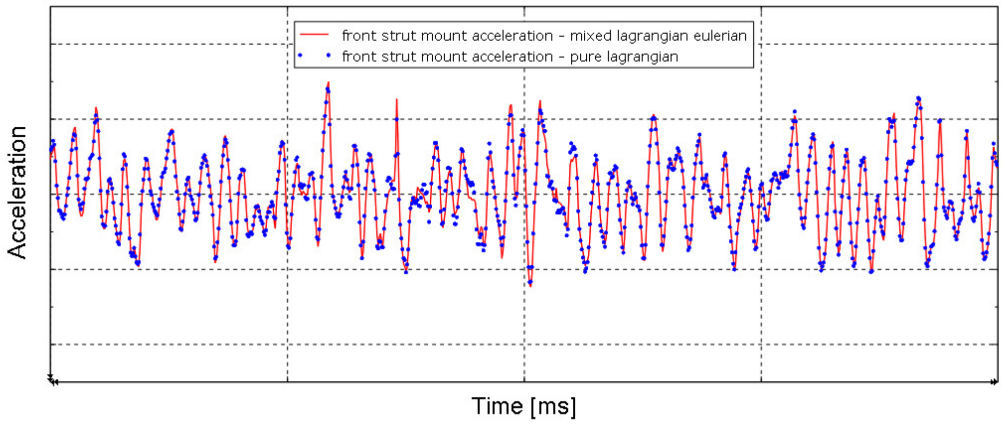

Figure 8. Comparison of front strut mount acceleration

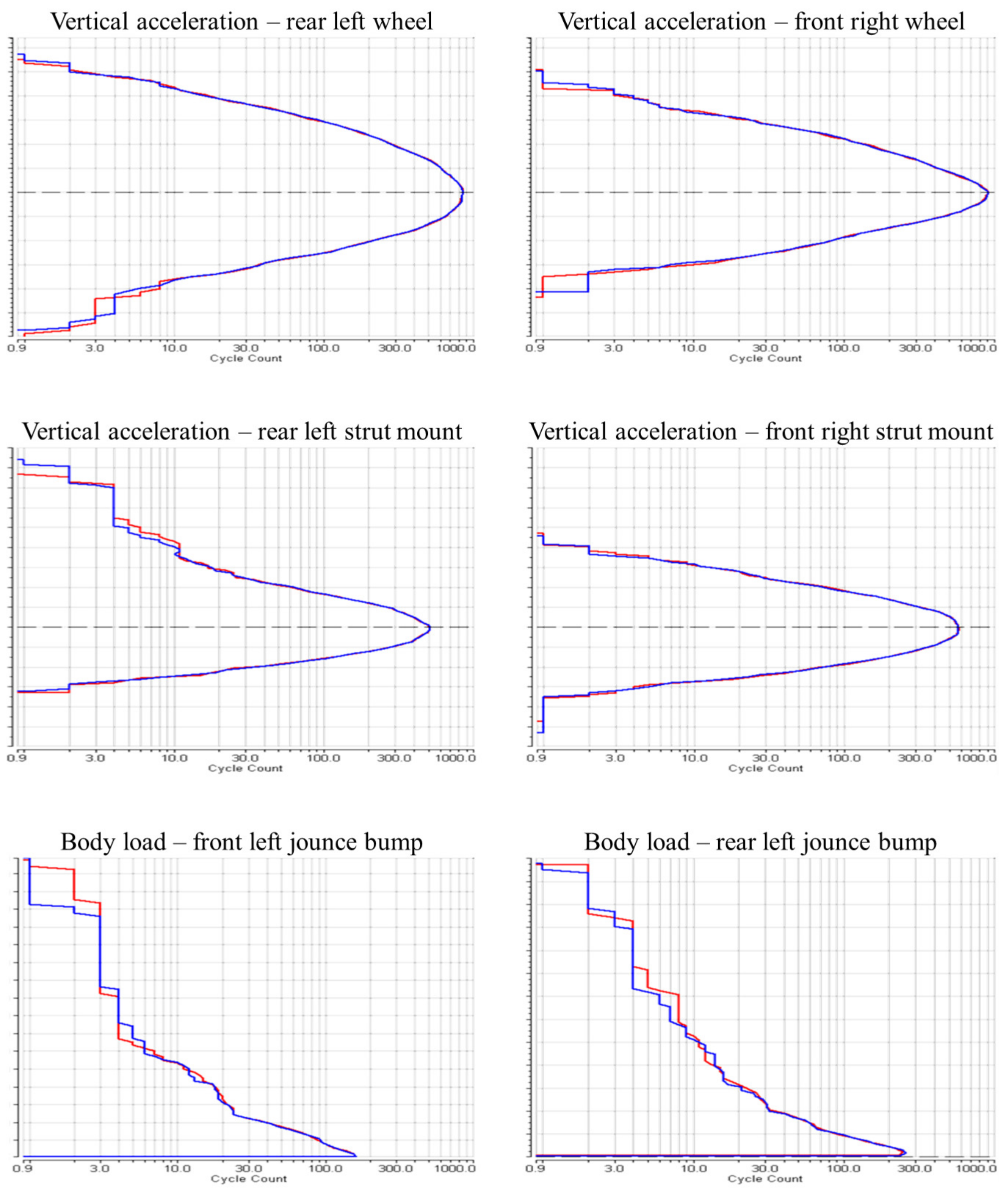

Figure 9. Level crossing comparison of some results
(blue = pure Lagrangian; red = mixed Lagrangian Eulerian)

Calculation time performance has been evaluated considering several number of cpus; figure 10 shows calculation time ratio, defined as the ratio of mixed method calculation time to pure Lagrangian time (using the same number of cpus). The new road modeling principle results in a significant reduction in calculation time. Increasing the number of cpus, the advantage decreases because the improvement due to the reduction of simulation problem size is negatively balanced by performance reduction due to parallelization of small models.

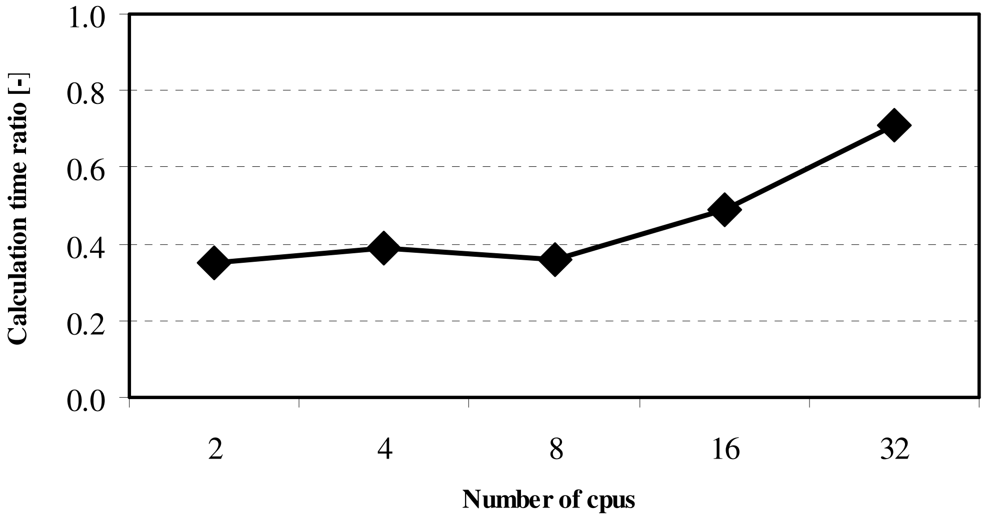

Figure 10. Calculation time ratio

6. Conclusions

In recent years, Fiat has developed a virtual environment to simulate dynamic maneuvers and calculate loads transmitted to the vehicle running on fatigue reference roads for structural performances assessment. Fundamentals parts of the method are the employment of a finite element tire model, fatigue reference track digitalization, its implementation as a rigid body and some issues related to tire/road interaction.

A new mixed Lagrangian-Eulerian approach for tire/road interaction has been developed: this new methodology is based on a different road modeling principle, where the road profile is described in time domain rather than space domain. A Python routine has been written to create all Abaqus cards needed for the new approach.

Comparisons between current practice and new approach have been done: the new method shows a significant reduction of calculation time without any appreciable changing in simulation outputs, making shorter the virtual test phase.

7. References

1. Duni E., Saponaro R., Monfrino G, Caudano M., Urbinati F., Spinelli M, Pizzuto A., "Numerical Simulation of Full Vehicle Dynamics behavior based on the interaction between Abaqus /Standard and Explicit Codes," Abaqus Users' Conference, Munich, 2003.
2. Duni E., Saponaro R., Monfrino G, Caudano M., Urbinati F., Spinelli M, Pizzuto A., "An integrated approach for numerical simulation of full vehicle behavior during transient dynamic maneuvers on arbitrary obstacles and road surfaces," IMECE2003 - 41374, ASME Proceedings, Washington, 2003.
3. Duni E., Toniato G., Saponaro R., Smeriglio P., "Vehicle Fatigue Load Prediction based on Finite Element TIRE/ROAD Interaction implemented in an Integrated Implicit-Explicit Approach," Abaqus Users' Conference, Newport, 2008.
4. Duni E., Toniato G., Saponaro R., Puleo V., Smeriglio P., "Vehicle Dynamic Solution Based on Finite Element Tire/Road Interaction Implemented through Implicit/Explicit Sequential and Co-Simulation Approach", SAE 2010 World Congress, Detroit, 2010.