Multi-objective Optimization in the Conceptual Phase of Vehicle Development

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Abstract This paper deals with the usage of multi-objective optimization techniques in the early stage of vehicle development. Integration of multi-objective optimization tools with vehicle dynamics simulation tools can provide significant improvements in the development process. Development of the optimization model, based on evolutionary algorithms, that is able to handle a large number of variables, constraints and objectives, and the usage of vehicle dynamics simulation tools, is a precondition for a complete solution for the conceptual phase of vehicle development. Some necessary steps lead to development of optimization models. These steps are identification of influence parameters, selection of criteria for the evaluation of vehicle dynamic characteristics and selection of optimization algorithms. Using a simulation eliminates the need for vehicle prototype in the early stage of development and reduces costs of development. Achieving optimum parameters of the vehicle at this stage of development reduces the possibility of wrong solutions or concepts.

Keywords

Vehicle dynamics, multi-objective optimization, evolutionary algorithms, vehicle parameters

1 Introduction

Competition in the automotive industry imposes a constant improvement of vehicles. Improvements can be achieved through innovations and optimization, reducing development time and costs. Considering only vehicle dynamics, vehicle must meet various requirements related to stability, handling and ride comfort. These requirements are often conflicting, and enhancement of one parameter cannot be achieved, without effect on another, in most cases adversely. The goal is to find a suitable compromise.

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In this research, focus is on the conceptual phase of development, in which physical models of vehicle do not exist, and simulation models are only presentation of vehicle. Nowadays, computer simulations are an indispensable engineering tool in almost all sector of automotive industry. Dynamic simulations of vehicles and their subsystems have become fundamental in the whole development process, and especially in the conceptual phase of development. From the specification of the definition phase, through the concept confirmation phase to the testing phase, dynamic models are used to predict the behaviour of the vehicle and its subsystems. Using dynamic simulations, real driving conditions can be simulated in a virtual environment, meaning that it is not necessary to make an expensive prototype vehicle.

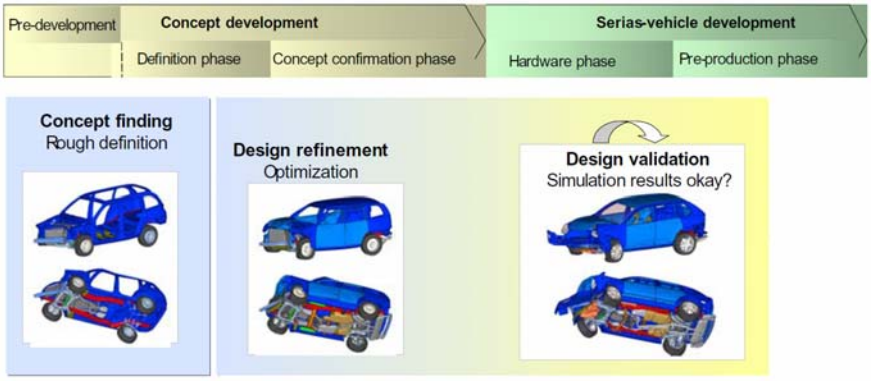


Fig. 1 Vehicle simulation model used in various development phases [1]

Also, dynamic simulation tools serve to understand the influence of main parameters on vehicle behaviour. The next logical step is the ability of optimization of parameters with the goal to improve the behaviour of vehicles still in a virtual environment. Although design process is and probably always will be based on designer intuition, dynamic simulations and optimization techniques can permit significant improvement in the process itself. In that way, many problems can be predicted and many deficiencies can be resolved at early stages of development.

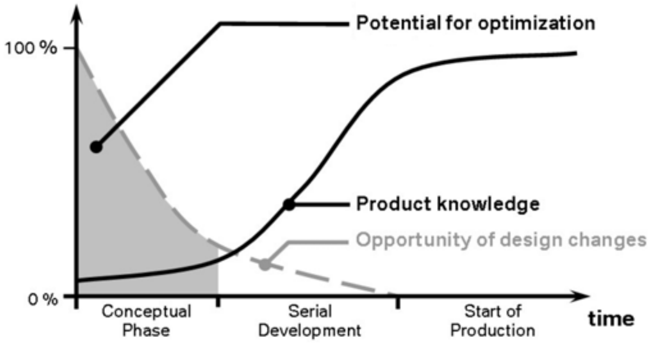


Fig. 2 Huge potential for optimization in the conceptual phase of development [2]

At the conceptual stage of development, knowledge about product is low and there are still many unknowns to be solved. On the other hand, the conceptual phase provides an opportunity to change the design, what is a huge potential for optimization.

Optimization problems in the development of vehicles, which can be solved only by a one well defined objective are exceptions. Most of optimization problems are multi-objective and often include several conflicting objectives. Instead of one global optimal solution, there are usually numerous solutions for these problems on Pareto front, which all are equally good solutions [3]. Pareto front is a set of solutions where no further improvement is possible in one objective without at the same time worsening another objective. Generally, the ideal multi-objective optimization method that allows obtaining a set of optimal solutions does not exist. Classical methods of obtaining solutions on Pareto front use the principle of weight factors. Another approach to solve multi-objective optimization problems is the use of algorithms that will provide a wider Pareto front. Since evolutionary algorithms are using a population of solutions in each optimization step of optimization process, these algorithms are imposed as a better choice. The goal is to find solutions either on Pareto front or close to Pareto front. Also, the goal is to find as many solutions as possible. In this way, the designer who will make the decision, has a better overview of all possible optimal concepts and can choose between many high quality solutions.

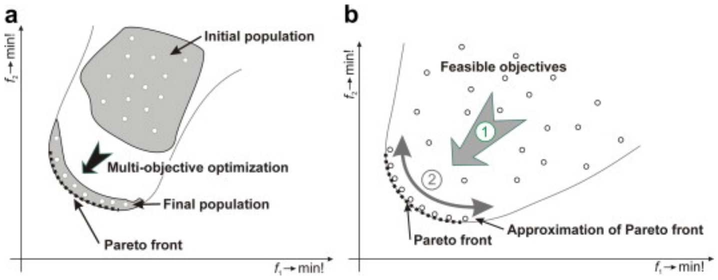


Fig. 3 Pareto front

2 Motivation

The motivation for this research were two projects of vehicle development at the Chair of the IC Engines and Motor Vehicles, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. One project dealt with the development of low-floor minibus and the other with the development of a racing vehicle for Dakar Rally competition. Both vehicles were developed from first sketch to the conceptual stage. For both of these vehicles it was necessary to determine parameters of vehicles and its subsystems, e.g. parameters of suspension system.

Vehicle development was based on the conventional approach, numerical analysis and usage of CAD tools. Optimization method (Nelder-Mead method - modified simplex method) was used only for the particular parameters of steering system of minibus [4].

Main goal of this research is to expand this conventional approach by using modern simulation tools and advanced optimization algorithms at the early stage of development.

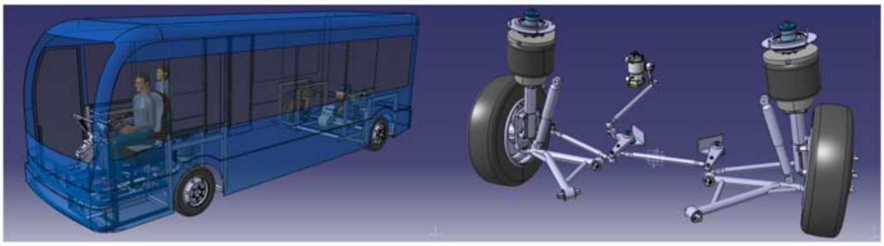


Fig. 4 Concept of low-floor minibus and its front suspension and steering system

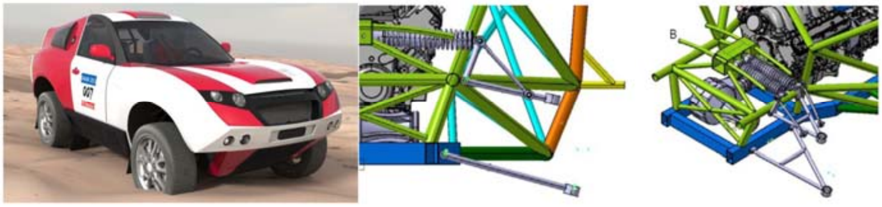


Fig. 5 Concept of racing vehicle for Dakar Rally competition and its front suspension system

3 Related Works

Handling, stability and ride comfort play an important role in the performance of a vehicle, and the task of the designer is to attain a well balanced suspension. Numerous papers deal with vehicle dynamics problems, especially with topics such as vehicle handling, stability and ride comfort. Similar situation is in topic of evolutionary algorithms. However, the number of papers that deal with both topics is relatively small. Usually, these papers deal with solving partial problems of vehicle dynamics.

Several important papers that deal with analysis of influence of suspension system parameters on the behaviour of the vehicle and with optimization of those parameters for different types of suspension system by using evolutionary algorithms, are described below. Fujita et al. [5] showed optimization of multilink suspension parameters with the goal to improve vehicle handling and stability. In this research a simple genetic algorithm was used and a hierarchical categorization of design characteristics and influential parameters was presented. Multi-objective optimization of the geometric parameters of double wishbone suspension using a genetic algorithm, with goal to improve vehicle handling and stability were shown by Hwang et al. [6]. Khajavi et al. [7] showed multi-objective optimization of suspension parameters to improve vehicle handling and ride comfort. In research NSGA-II (Non-dominated Sorting Genetic Algorithm) algorithm and 8 degrees of freedom vehicle model were used. Multi-objective optimization of vehicle parameters with goal to improve vehicle handling was shown by Fadel et al. [8]. A vehicle passing through three test procedures related to handling was simulated in the research. Results obtained by using evolutionary algorithms were compared with results obtained by Monte Carlo method. Schuller et al. [9] showed multi-objective optimization of vehicle parameters in order to improve vehicle handling. In a complex research 150 input parameters and 18 output vehicle dynamic characteristics were analysed.

Review and comparison of multi-objective optimization methods, including evolutionary algorithms and its application on vehicle development problems was given by Gobbi et al. [10]. According to this survey neither method has been dominated by all criteria for all types of problems. Evolutionary algorithms have been evaluated as a robust algorithm that can manage a large number of objective functions, with appropriate adjustment of several key parameters (population size, mutation probability and crossover, etc.) to achieve the desired convergence.

Overview of criteria for evaluation of vehicle handling, stability and ride comfort was given by Uys et al. [11]. They analysed criteria such as vertical, longitudinal and lateral acceleration, roll, pitch, yaw angle and rate, slip angle, forces at the tire contact surface and test procedures such as double lane change, J-turn, fishhook, crosswind, acceleration and braking on road surfaces with different coefficients of friction.

One of the goals of this research is to combine, extend and improve significant ideas from these papers by use of modern simulation tools and advanced optimization algorithms. In topic of usage of multi-objective optimization methods, especially evolutionary algorithms in vehicle dynamics problems, there is still a lot of room for improvement.

4 Vehicle Model

In this research vehicle model was built in CarSim. The software was chosen because its math models are based on decades of research in characterizing vehicles and reproducing their behaviour with mathematical models.

Also, one of the main reasons for choosing CarSim is the extendibility of vehicle model. The CarSim math models cover the entire vehicle system and its inputs from the driver, ground, and aerodynamics. The models can be extended by using built-in VehicleSim commands or custom programs written in MATLAB / Simulink, Visual Basic and other languages. By using this option it is possible to thoroughly extend the subsystem or the component models such as suspension system, brakes, powertrain, etc.

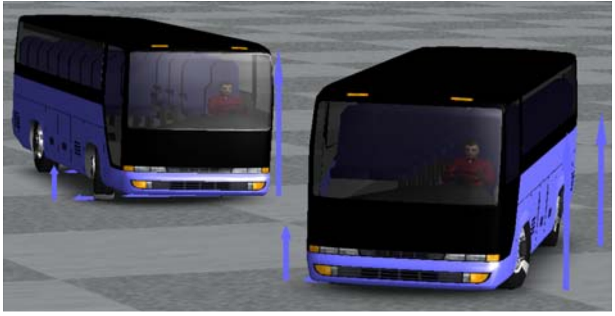
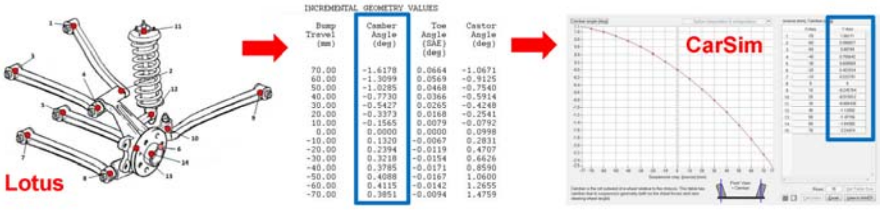


Fig. 6 Minibus model

CarSim uses a parametric suspension model. This model defines the kinematic characteristics of the suspension, such as gradients or curve (table), data of wheel rotation angle (camber, caster, toe, etc.) in terms of the vertical motion of the wheel centre. This type of modelling approach is suitable for fast simulation, but does not provide insight into the suspension system geometry, or the position of suspension system hard points.

Lotus, kinematics analysis program, is used to generate kinematic curves using suspension system hard points data. Its camber, caster, toe, and other kinematic curves are implemented in CarSim model.



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INCREMENTAL GEOMETRY VALUES

     Bump        Camber        Toe      Castor
   Travel         Angle      Angle       Angle
     (mm)         (deg)      (SAE)       (deg)
                             (deg)

    70.00       -1.6178     0.0664     -1.0671
    60.00       -1.3099     0.0569     -0.9125
    50.00       -1.0285     0.0468     -0.7540
    40.00       -0.7730     0.0366     -0.5914
    30.00       -0.5427     0.0265     -0.4248
    20.00       -0.3373     0.0168     -0.2541
    10.00       -0.1565     0.0079     -0.0792
     0.00        0.0000     0.0000      0.0998
   -10.00        0.1320    -0.0067      0.2831
   -20.00        0.2394    -0.0119      0.4707
   -30.00        0.3218    -0.0154      0.6626
   -40.00        0.3785    -0.0171      0.8590
   -50.00        0.4088    -0.0167      1.0600
   -60.00        0.4115    -0.0142      1.2655
   -70.00        0.3851    -0.0094      1.4759
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Fig. 7 CarSim model extended with a detailed model of suspension system created in Lotus

With this approach to modelling, the intention is to analyse suspension system, whose parameters are changed during simulation and optimization process, within the framework of complete vehicle. All other vehicle parameters remain constant during the process.

5 Test Procedures (Manoeuvres)

Test procedures (manoeuvres) will be the basis for the evaluation of dynamic characteristics of vehicles. There are different tests for the assessment of stability, handling and ride comfort of vehicles. Some of the test procedures are standardized, and some are required by ECE regulations (UNECE Transport Division - Vehicle Regulations), the EU directives and regulations of FMVSS (Federal Motor Vehicle Safety Standards) and others are recommended by NHTSA (National Highway Traffic Safety Administration). Some of the test procedures to determine the dynamic characteristics of the vehicle are: double lane change, understeer or oversteer on circle, sine with dwell, J-turn, fishhook, bounce sine sweep, cross slope sine sweep, small sharp bump, crosswind, etc.

For example, typical handling test procedure double lane change can provide valuable information about the handling of a vehicle in a highly transient situation. A double lane change is a path following (avoidance) manoeuvre that frequently occurs in the real world. Handling is measured in terms of yaw, roll, yaw rate and lateral acceleration.

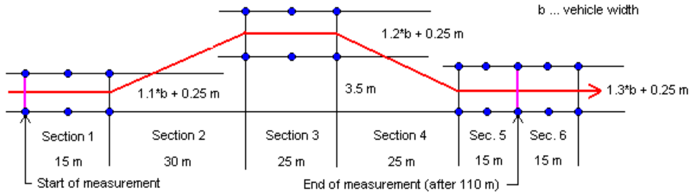

Fig. 8 Double Lane Change test procedure

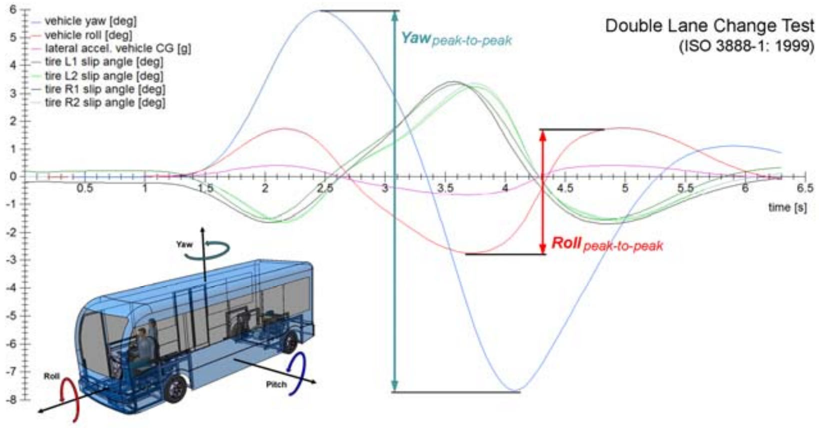

Fig. 9 Typical Double Lane Change test procedure results

Some manoeuvres mentioned before are a sample of various scenarios to which a vehicle can be subjected. The goal is to use several manoeuvres to assess a specific dynamic behaviour of a vehicle. Each manoeuvre requires the evaluation of different dynamic characteristics. For example, dynamic characteristics for typical stability test procedure such as J-turn or fishhook test are: yaw rate, roll rate, lateral and longitudinal acceleration, vehicle slip angle, etc. Dynamic characteristics for typical ride comfort test procedures are: pitch, pitch rate, vertical acceleration, root mean square (RMS) value of the vertical acceleration, etc.

6 Optimization Algorithms

Multi-objective optimization algorithms can be divided into classical gradient based algorithms and stochastic heuristic algorithms. The former is known to be fast and accurate but lacking in robustness, while the latter is very robust but requiring several steps to reach convergence. In this research the emphasis is on usage of evolutionary algorithms belonging to the heuristic optimization algorithms.

Evolutionary algorithms are popular approaches to solving multi-objective optimization problems. Evolutionary algorithms use mechanisms inspired by biological evolution: reproduction, selection, recombination and mutation.

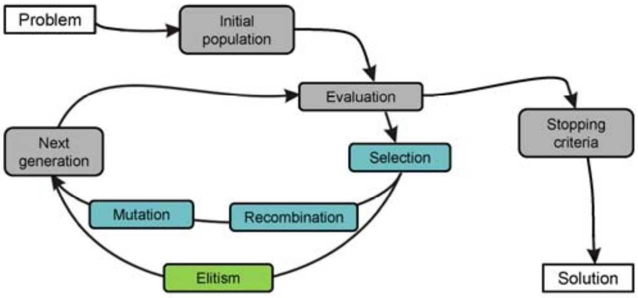

Fig. 10 Scheme of evolutionary algorithm

Currently most modern evolutionary optimizers apply Pareto-based ranking schemes. The main advantage of evolutionary algorithms, when applied to multi-objective optimization problems, is the fact that they simultaneously optimize sets of possible solutions (population). That allows finding several members of the Pareto optimal sets in a single run of the algorithm, instead of having to perform a series of separate runs as it is with the traditional mathematical programming techniques. The main disadvantage of evolutionary algorithms is much higher computing time consumption. Evolutionary algorithms can be divided into four classes: genetic algorithms, evolution strategies, genetic and evolutionary programming.

Genetic algorithms are the most popular type of evolutionary algorithm. Genetic algorithms such as the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-objective Genetic Algorithm-II (MOGA-II) have become standard approaches. Efficiency of NSGA-II and MOGA-II algorithms is ruled by its operators (probability of crossover, mutation and selection) and by implementation of elitism concept. Elitism increases performance of genetic algorithms, because it guarantees that the best solutions remain in the population.

7 Optimization Model

To obtain a better insight into the behaviour of the vehicle, a vehicle whose suspension parameters should be optimized passes through a series of test procedures (manoeuvres) related to the stability, handling and ride comfort. Scheme of the optimization model is shown in Figure 11.

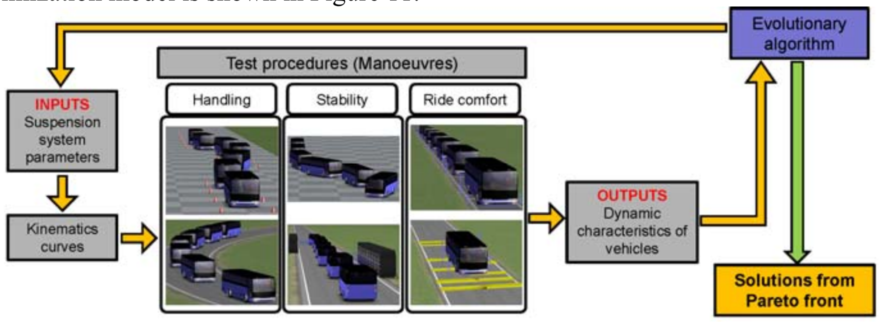

Fig. 11 Scheme of optimization model

Optimization model is built in software modeFrontier. To create the model it was necessary to couple simulation software for analysing suspension kinematics (Lotus) and vehicle dynamics (CarSim) with modeFrontier. This is made by scripts in Matlab and VisualBasic. These scripts define transfer of data and files between different software packages and define the order of steps in simulation and optimization process. By using these scripts it is also possible to run simulation tools without using the graphical user interface (GUI). That significantly speeds up the process.

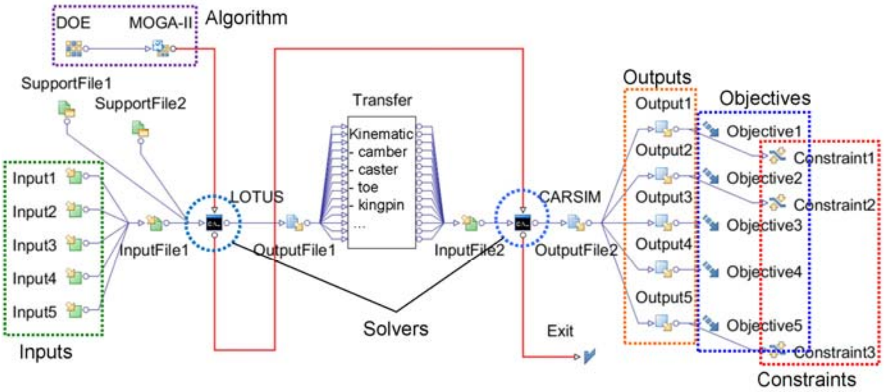

Fig. 12 Optimization model in modeFrontier

Typical layout of optimization model in modeFrontier is shown in Figure 12. ModeFrontier enables graphical modelling, and each icon on the layout represents some type of connection to the specific files of the simulation program, which is usually in the form of ASCII files.

8 Results

The proposed optimization model should enable obtaining a large number of high quality solutions. That number of solutions is much higher than the number of solutions which can be obtained by using conventional design methods.

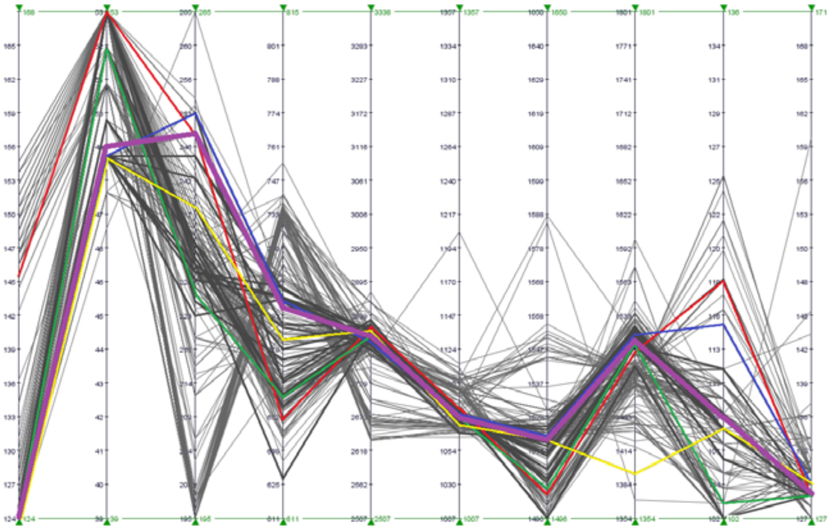

Fig. 13 Family of solutions

Every polyline in Figure 13 represents one solution. On the vertical axis there are the values of certain input parameters. All solutions presented meet the set of requirements, objective functions and constraints. The black lines are the individual solutions near the Pareto front. The colour lines show a few randomly selected solutions near the Pareto front. The fulfilment of these requirements can be achieved for different values of input parameters. The purple line, obtained by statistical analysis of input and output variables, represents a robust solution.

Results shown in Figure 13 present optimization of the model with 10 input variables (suspension system parameters), 22 output variables (dynamic characteristics of vehicle), 21 objectives and 14 constrains. Vehicle model passes through 5 test procedures: (1) Double lane change test (ISO 3888-1: 1999), (2) Sine wave steer input test (ISO 7401: 2003) related to handling, (3) Fishhook test (NHTSA), (4) Sine with dwell test (FMVSS 126, ECE R13H) related to stability and (5) Bounce sine sweep test (ISO 2631: 2004) related to ride comfort of vehicle.

To compute 750 iterations, 50 generations with 15 individuals with MOGA-II algorithm took 45 hours on PC (AMD Athlon 64 X2, 2,6 GHz, 4 GB RAM, ATI Radeon 4800, 512 MB).

Convergence of the solutions is shown in Figure 14.

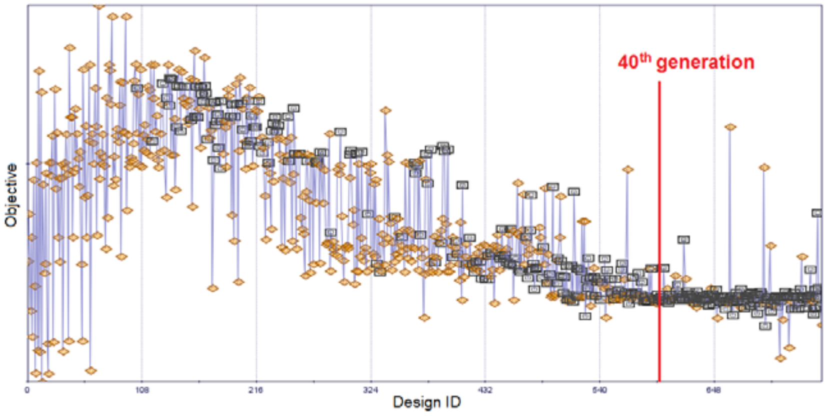

Fig. 14 Convergence (MOGA-II algorithm)

9 Conclusions and Outlook

Research is based on the usage of advanced evolutionary algorithms and modern simulation tools in the conceptual phase of vehicle development. Following results are revealed:

1. Optimization tool coupled successfully with simulation tools for analysing the suspension system kinematics and vehicle dynamics.
2. This approach provides a wide range of numerically verified solutions in short calculation time.
3. Optimization of suspension system parameters simultaneously through stability, handling and ride comfort related test procedures provides insight into influence of certain parameters on vehicle dynamics.

Further research efforts should concentrate on the following topics:

1. Validation of simulation models.
2. Fine adjustment of optimization algorithm parameter values (population size, probability of mutation, crossover or selection, etc.).
3. Analysis of convergence of an evolutionary algorithm.

4. Comparison of the results obtained by evolutionary algorithms with results of other multi-objective optimization method, which follow some mathematical principles.
5. Implementation of proposed optimization model for determining optimal suspension system parameters of low-floor minibus.

10 References

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