**Vuslat Odabaşı**
Department of Mechanical Engineering
Hacettepe University
Turkey

**Stefano Maglio**
Vehicle Design Division
Onda Solare Association
Italy

**Alberto Martini**
Department of Industrial Engineering
Alma Mater Studiorum University of Bologna
Italy

**Silvio Sorrentino**
Department of Engineering 'Enzo Ferrari'
University of Modena and Reggio Emilia
Italy

# Static Stress Analysis of Suspension Systems for a Solar-Powered Car

*Suspension systems are designed aiming at providing adequate handling, road holding, comfort and vibration control to a terrestrial vehicle. Being an important issue not only for regular road models, suspension design is a matter of concern that also regards solar electric cars, in which, due to limited power supply, stabilization and energy conservation are of utmost importance. Considering three basic types of suspension widely adopted in road vehicle design, this study presents a preliminary comparison among MacPherson, double wishbone and leaf spring systems, aimed at pointing out the most appropriate design for the solar-powered vehicle hereby considered. It includes a finite element static stress analysis, performed with parametric values for a quarter-car model.*

***Keywords:*** *Solar car, Suspension system, Leaf spring, MacPherson, Double wishbone, Finite element method, Stress analysis.*

## 1. INTRODUCTION

The interest in solar-powered vehicles arose as a topic of study mainly developed by academic institutions [1] with the aim of promoting sustainable mobility [2,3]. Students, engineers and researchers were encouraged to develop the most energy-efficient cars [4,5], evaluating their performances through competitions held worldwide [6,7]. The main challenges of designing such cutting-edge vehicles [8] consist in battery selection, electrical systems, solar array design [9,10], structural materials [11], aerodynamics [12,13] (involving computational fluid dynamics calculations [14]), safety [15] and mechanical sub-systems such as suspensions [11].

Regarding vehicle mechanical and structural design, it is possible to say that solar-powered cars represent an exciting test bench, considering the large amount of particular functional and technical aspects able to distinguish them from other competition vehicles (e.g. Formula E, Formula 1, Rally). Hence this vehicle category demands specific and innovative design solutions.

Focusing on suspension systems, the load due to passengers, electric batteries and solar panels can be even higher than the total weight of the remaining parts of the vehicle, making the choice of suspension stiffness and weight distribution quite challenging in order to get good performances in terms of vehicle dynamics.

These technical demands becomes extreme in the case of the 'cruiser' category, multi-passenger vehicles recently introduced in solar-powered car competitions. In fact, compared to more traditional single-seater solar cars, cruisers present a total weight from four to five times higher, as well as higher center of gravity.

The solar-powered car considered in this study and displayed in Figure 1 was designed and manufactured for racing by the University of Bologna. It is equipped with a solar-electric powertrain developed for efficiently transporting four passengers weighing 80 kg each. With a monocoque, structural and non-stuctural parts in carbon fiber reinforced polymer (CFRP), a roll-cage in titanium alloy, and some other distinct technical features, it represens one of the lightest multi-occupant solar cars ever built [16]: a vehicle with total mass of 300 kg allows to transport 320 kg due to four occupants. Using 5 $m^2$ of monocrystalline silicon photovoltaic panel on the roof, 64 kg of lithium-ion batteries, two electric engines coupled directly to the rear wheels and further solutions for optimal energy control, either a range of 600 km at cruising speed, or velocitiy peaks of 120 km/h can be achieved [16].

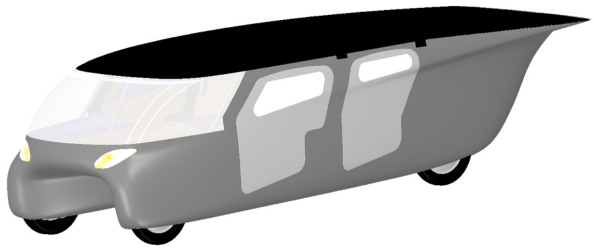

**Figure 1. CAD model of the University of Bologna solar car.**

During its first contest (American Solar Challenge 2018) this vehicle travelled 1.762 miles (2835 km) in the Unites States with four passengers, without other energy sources than the sun, winning at a cruising speed of about 55 km/h [6]. Such public exhibition also represented a functional test on several aspects, which led to the conclusion that this vehicle still needs futher mechanical improvements.

The main objective is to increase the average speed of the race vehicle up to 75 km/h, a necessary condition to successfully take part in further competitions [7]. Such objective requires a thorough revision of different technical possibilities, expecially those regarding vehicle dynamics. The suspension system in particular has to be designed considering the necessity to provide adequate

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Correspondence to: Vuslat Odabaşi
Mechanical Engineering Dept., Hacettepe University,
Beytepe, 06800, Ankara, Turkey
E-mail: vuslat.odabasi@hacettepe.edu.tr
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levels of handling, road holding, comfort and vibration control. Moreover, specific requirements related to competition solar-powered cars also have to be addressed, such as the optimization of energy efficiency in terms of weight of components, stiffness and dissipated energy.

Currently, the suspension system is based on a novel design consisting of longitudinal arms with leaf springs (Figure 2) in which arms, springs and wheels are made in CFRP [16]. Figure 3 shows how the transversal leaf spring is mounted.

With the aim of investigating alternative solutions for the suspensions, this study presents a preliminary comparison between the current system and two basic types of suspension widely adopted in road vehicle design: MacPherson and double wishbone [17,18]. It includes a finite element static stress analysis, performed with parametric values for a quarter-car model, using the code Catia V5.

a) (b) (c)

**Figure 2. Current suspension system: a) front suspension; b) rear suspension; c) set-up and control.**

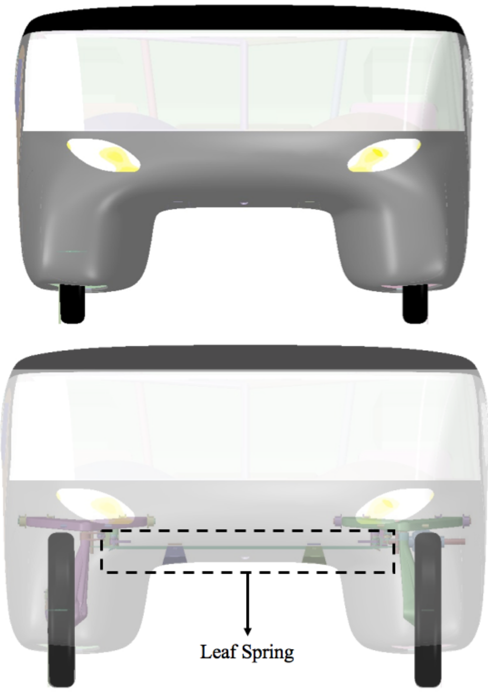


**Figure 3. Front view of the vehicle and front suspensions.**

## 2. SUSPENSION SYSTEMS

Suspension design is generally focused on optimization of ride and handling [19,20], however also the energy efficiency target is of great importance, as for the vehicle under study [21,22].

In general, suspensions are classified as dependent, semi-dependent and independent [24-26]. In dependent suspensions (like Panhard rods or Watt's linkages [27], commonly employing leaf springs), the wheels of a same axle are connected to each other by a shaft. That means that their motions (except travelling rotation) are rigidly linked (giving, in particular, same camber angles variations on the two wheels). Dependent suspensions are simple and robust with low manufacturing costs, however they usually carry higher unsprung masses with respect to other suspension systems. Therefore they were not considered for the application under study.

In semi-dependent suspensions, the rigid connection between the wheels is replaced by a compliant link, like in the twist beam suspension [28] which has low cost, simple assembly but limited kinematic possibilities. Therefore they were disregarded as well.

Independent suspensions (like trailing and semi trailing arm, longitudinal arm, MacPherson, double wishbone and multi-link) are the most widely adopted in automotive industry and racing cars, due to their superior capabilities with respect to ride and handling optimization, togheter with lower unsprung masses.

Clearly, each suspension layout presents its own advantages. In the case under analysis, however, the targets are mass reduction, adequate vehicle ride and handling, and low manifacturing costs. Consequently, in the present study three different independent suspension systems are considered, which may be adopted for the solar electric car under study: longitudinal arms with leaf springs (mounted on the current vehicle; simplest geometry, reduced control of kinematic parameters), MacPherson and double whishbone (most complex geometry, highest possibility of control of kinematic parameters, such as camber, caster, toe, scrub radius, etc. [33]).

## 3. METHOD AND MATERIAL

A preliminary comparison is presented in terms of static analysis due to weight loading among selected elements of the above mentioned three different suspension systems. Static analysis for preliminary structural suspension assessments is a common practice also in academic projects involving prototypic, conceptual and even competition terrestrial vehicles. Double-wishbone arms, for instance, were studied by Gadade et al. [29], who performed a finite element analysis aimed at calculating the components' working life under static loading; by Vivekanandan et al. [30] and Kakria et al. [31], who dealt with the design of a double-wishbone arm for an all-terrain vehicle and for a formula SAE car, respectively. More closely to the present work, Hurter et al. [32] analyzed the specific case of a solar electric vehicle, defining the optimal design of a suspension link and evaluating the usage of carbon fibre as structural material, given its lightweight and enhanced resistance.

Notice that the currently adopted leaf spring system allows alternative solutions, since it could be assembled in different layouts: longitudinally or transversally (mounted between the two wheels of the same side or between the wheels of the same axle, respectively). Another solution would be the adoption of individual springs for each wheel, so it is important to clarify the assembly method considered. In the current version of the solar-powered car [20], the transversal layout was adopted, but in the present analysis the case of individual leaf springs for each wheel is studied, for investigating the possibility of a further overall weight reduction.

Aluminum is adopted in all cases for comparison purposes and for being low-cost and light, having desirable characteristics for this case-study (Table 1).

**Table 1. Mechanical properties of Aluminum** [34]

| Young Modulus (GPa) | Poisson Ratio | Density (kg/m$^3$) | Yield Strength (MPa) |
|---|---|---|---|
| 7.01 | 0.346 | 2710 | 95 |

A quarter car model was considered to reduce the computational load of the algorithms, considering a vehicle with sprung mass of 600 kg (accounting for 4 passengers weighing 80 kg each). These models were implemented for each kind of suspension in a finite element code (Catia V5) considering a tetrahedral mesh with 2 mm sized elements. A 1471.5 N load was applied on the wheel hub, for taking into account the weight of the car, setting fixed support boundary conditions for the mounting points of each system.

## 4. RESULTS AND DISCUSSION

Results of Von Mises stress and deformation analysis are reported in Figures 4 and 5, respectively; while Table 2 summarizes the results of the simulations.

**Table 2. Summary of results of Von Mises stress and maximum displacement**

| | Von Mises Stress (MPa) | Displacement (mm) | Mass (kg) |
|---|---|---|---|
| Leaf spring | 21.6 | 0.05 | 2.977 |
| MacPherson | 64.5 | 1.55 | 2.725 |
| Double wishbone | 53.4 | 0.41 | 2.523 |

The highest stress concentration and deformation regions are located either on the mounting spots on the chassis or on the wheel-hub in all cases, and although stress levels might vary up to three times, none of them represent risk conditions.

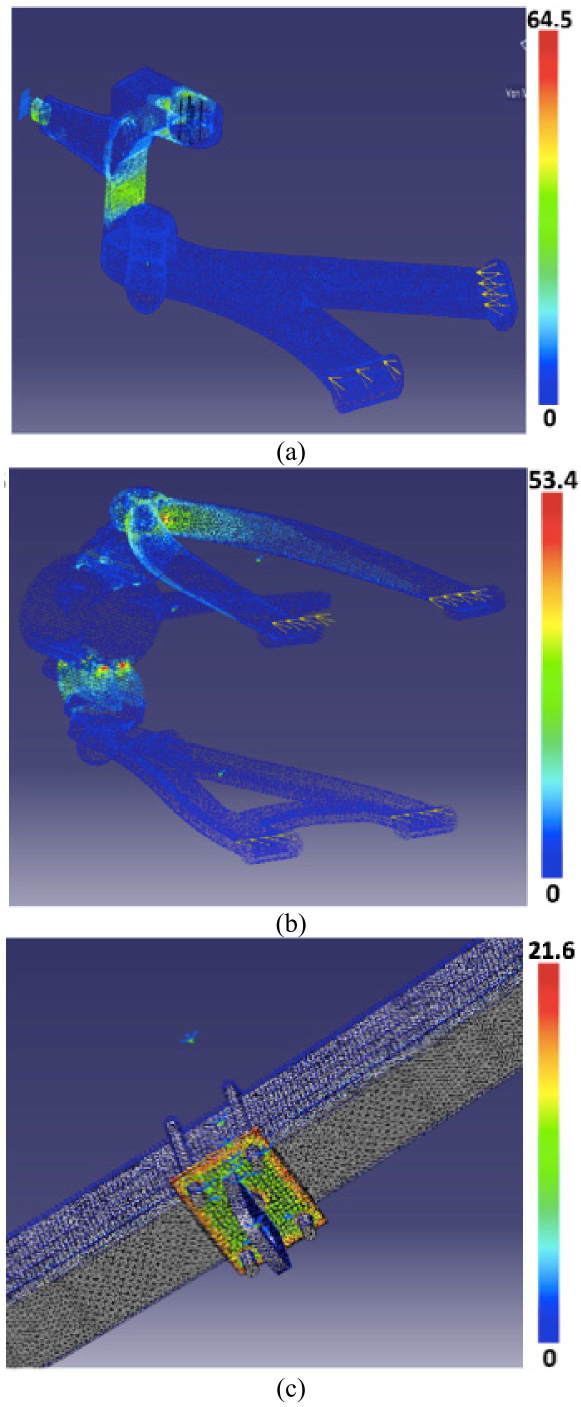


**Figure 4. Von Mises stresses on MacPherson (a), double-wishbone (b) and leaf spring (c) [MPa].**

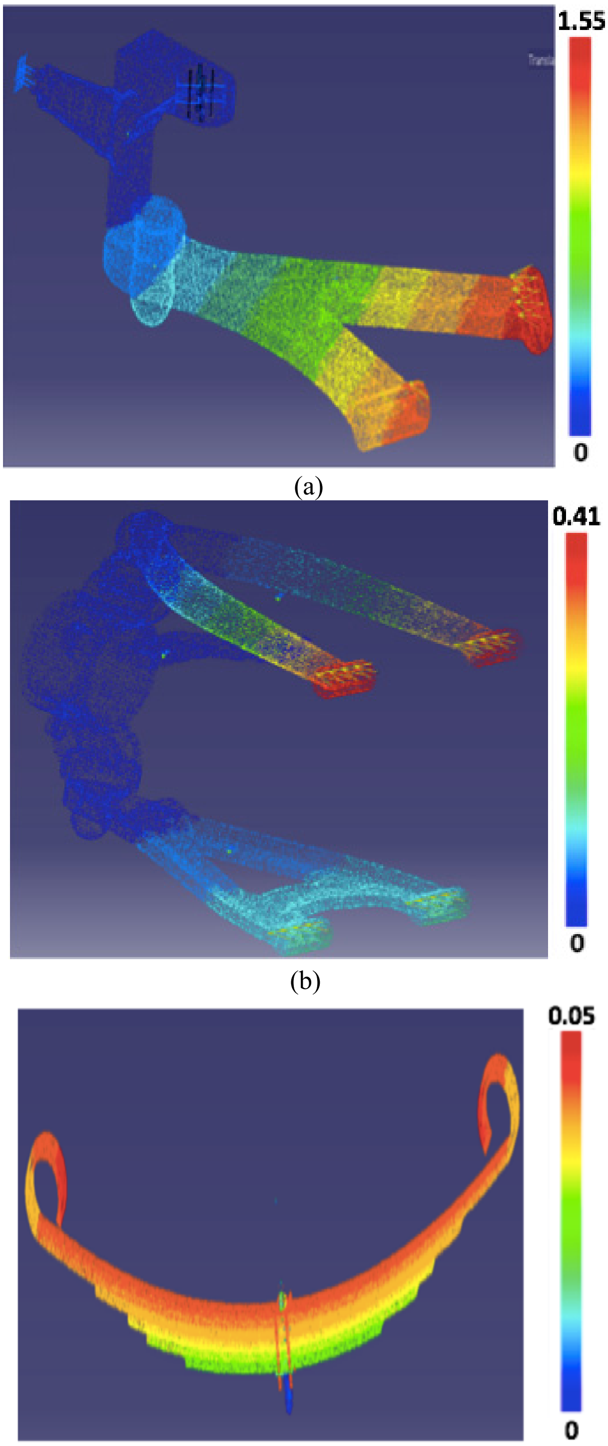


**Figure 5. Deformation displacement of MacPherson (a), double-wishbone (b) and leaf spring (c) [mm].**

The leaf spring suspension proved to be the most rigid system with lowest deformation, although the disad–vantage is its elevated weight. The highest levels of stress and deformation were found on the Mac–Pherson, with an intermediate weight. Intermediate values of stress and deformation were found on the double-wish-bone, which is the lightest among the compared elements.

Given that the selection of a suspension system for a solar electric car is light-weight-focused, it is possible to infer from this preliminary assessment that the main disadvantage of leaf spring systems is their weight. Nevertheless, due to their simple geometry, it would be possible to laminate the leafs out of CFRP in order to significantly reduce their weight without affecting sub- stantially their mechanical properties [35]. This enhan- cement would hardly be attainable at low cost for both wishbone and MacPherson, due to complex geometries.

Other than representing a more suitable material, CFRP would give the additional possibily of tailoring the necessary resistance required by the leafs of the spring [36] with optimization of their geometry.

These factors, combined with the possibility of easily adding local reinforcements, makes the design of specific leaf springs particularly effective in terms of both weight reduction and good performances.

## 5. SUMMARY

In this study a preliminary comparison was presented among longitudinal arms with leaf springs, MacPherson and double wishbone, aimed at pointing out the most appropriate design for the solar-powered vehicle hereby considered, considering its its specific demands for low-weight and efficient structures. The MacPherson layout was disregarded for the present application, while in future studies a more specific dynamic analysis will be conducted between the two remaining systems, to deter-mine whether or not the high rigidity of the leaf springs system can be more convenient than the low mass and optimal ride and handling performances of double-wishbones, in terms of energy efficiency.

However, preliminary conclusions that can be drawn confirm the good performances also in terms of stress-strain analysis of the already adopted leaf-spring system (although with individual springs applied to each whell and not transversally to the vehicle), in addition to those due to a simple and adaptable construction.

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## СТАТИЧКА АНАЛИЗА НАПОНА СИСТЕМА СУСПЕНЗИЈА ЗА ВОЗИЛО СА СОЛАРНИМ ПОГОНОМ

**В. Одабаси. С. Маглио, А Мартини**

Системи за суспензију су дизајнирани са циљем обезбеђивања адекватног управљања, држања, комфора и контролисаних вибрација у традицио–налном возилу. Као проблем који прелази редовне моделе, дизајн суспензије је забрињавајућа ствар која обухвата и соларне електричне аутомобиле, где су стабилизација и заштита енергије од изузетног значаја за возило у којем је извор енергије ограничен. Анализирајући три врсте суспензија које се обицно користе у аутомобилској индустрији, представљни рад намерава да се супротстави МакФерсон-у, системима са двоструким опругама и лиснатим са циљем да истакне најприкладнији дизајн за ово соларно возило. Истраживање се састојало од статичне анализе напона спроведене у софтверу Catia V5 кода коначних елемената, усвајајући параметарске вредности за четвртину модела аутомобила.