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Solar-Battery Car with Four-Wheels Solar-Array Trailers

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Abstract: For some areas of the globe where solar energy is available throughout the year, one is tempted to use solar energy to drive cars. However, solar energy on its own is not sufficient to propel the car due to the low specific surface energy of solar radiation.
In [1], we explored the possibility of using solar-battery cars with solar-array trailers in order to increase solar power input. In order to minimize the weight and drag of the trailers, two wheels were used as support. The use of solar trailers, however, resulted in a decrease in the operating speed due to stability and energy requirements.
In order to increase the operating speed, we resort in this paper to four-wheels solar-array trailers and 1600W solar-arrays.This resulted in the increase in the stability limit of operation as well as a boost in the solar energy harvested.
Keywords: Solar Energy; Solar Car; Solar-array Trailers

I. INTRODUCTION

Attempts at using solar energy in driving cars have been so far limited to the academic field [2-4]. This is due to the low specific surface energy of solar panels when compared to the specific energy of gasoline.
In [1], we considered increasing the solar input energy to the car by increasing the surface area of the solar array through the addition of solar-array trailers. To lower the drag and weight of trailers, we picked two wheels to support the trailers. This, however, reduced the stability speed of operation.

In this paper, we look at using four-wheels per trailer in order to increase the stability speed limit. To increase the solar power input, the total power per array was raised from 1000W to 1600W, i.e., from 13% efficiency to 20% efficiency solar-arrays.

The paper is divided into two sections. In the first section, the average battery powers needed to travel a specified track, at different speeds, with and without solar-array trailers are computed and compared. In the second section, stability speed limit of a car with two solar-array trailers is calculated.

The paper concludes with a summary of results.

II. ROAD DATA AND POWER CONSUMPTION OF BOTH A STANDALONE CAR AND A CAR WITH ONE/TWO SOLAR-TRAILERS

The approach used in [1] is followed here. The energy consumed by a single car is compared to that consumed by a car with one/two solar-trailers when driven during daylight hours, from 9:00AM to 5:00PM. The drive follows a simplified track at a latitude of 24.08^{o}N, near the end of the month of March. The track is assumed to have a constant slope of 0.2%. The calculations are conducted at half-hour intervals with the effects of drag, gravity, rolling resistance and variable sunlight due to time change taken into account.

The simplified approach of [5] for computing the energy required to drive along the track is adopted here. The details of the various components of the car and trailers used in the analysis are as follows: the total mass of the car with passengers is 500kg, 300kg for the car and 200kg for passengers; this accounts for up to four passengers. The mass of the trailer tested is 100kg. The efficiency of power conversion from input power to output power is assumed to be 85%. The power computations are described below:
a) Solar power: The maximum solar power, P_{max}, per car or trailer, is assumed to be 1600W. The solar energy produced by the array while driving depends on the angle φ between the sunlight and the normal to the ground.
b) Aerodynamic force: For a solar-battery car with up to four passengers, the aerodynamic force is calculated based on a drag area AC_d=3.*0.12m^2. For the trailer, the value considered was AC_d=0.12.
c) Rolling resistance: The rolling resistance coefficient for the wheels of the car is as assumed to be 0.01; the rolling resistance coefficient for the wheels of the trailer is assumed to be 0.0055.
d) Gravity resistance: The necessary power to overcome gravity resistance is determined by $P_{gravity}$=weight*sin(α)*speed (W), where α is the angle of the inclined path. For small angles, α is assumed to be equal to the percentage of elevation. During the course of the day trip, the terrain is assumed to be almost flat with a percentage of elevation equal to 0.2%.
e) Necessary power: The total necessary power is obtained by adding the powers of drag, rolling resistance, and gravity: $P_{drag}+P_{rolling}+P_{gravity}$.

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f) <u>Battery power</u>: The battery power required is equal to the power provided by the solar arrays subtracted from the total necessary power: $P_{battery} = (P_{drag}+P_{rolling}+P_{gravity}) - P_{array}$.

To begin, we calculate the battery power required to travel the specified track for a standalone car and a car with one/two solar-trailers:

(a) Car with a mass of 500kg.
(b) Car with a trailer of mass 100kg and a drag area coefficient AC_d equal to 0.12.
(c) Car with two trailers of 100kg each and a drag area coefficient AC_d equal to 0.12 per trailer.

The battery power required for a car without and with one/two solar-trailers is plotted in Fig. 1. Results indicate that up to a speed of 80km/h, a car with two solar-array trailers has advantage over a car with one trailer, which in turn has advantage over a car with no trailers.

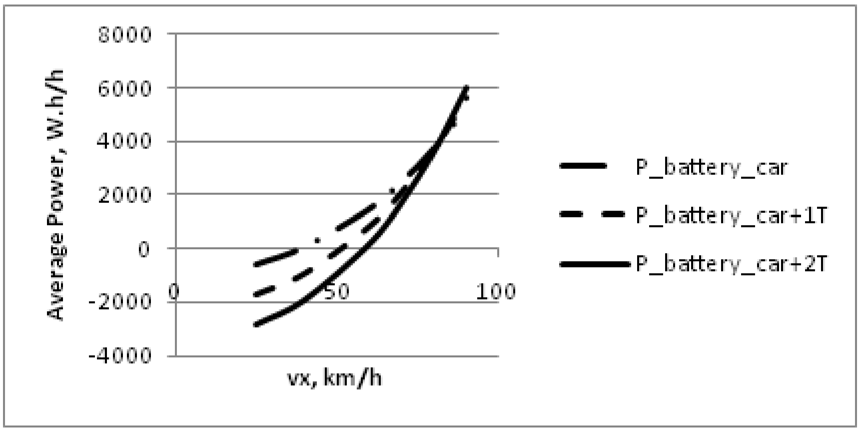

Fig. 1 Average battery power required for a multi-passengers car, car with one solar-array trailer and a car with two solar-array trailers versus speed Vx

III. LINEARIZED EQUATIONS OF MOTION OF A SOLAR-BATTERY CAR WITH DOUBLE SOLAR-ARRAY TRAILERS

To study the dynamics of cars with solar-array trailers, the approach adopted in [1,6-10] is followed here. However, in this case the trailer has a set of four wheels.

Using linearization of the equations, the accelerations, lateral forces, and equations of motion of the car and the two trailers for small angular rotations can be written as shown below. The nomenclature is described in Table 1.

A. Accelerations at center of masses

$$a_y = \dot{v}_y + \omega * vx; \quad (1)$$

$$a_{y1} = \dot{v}_y - (a_2 + a_3 + b_1) * \dot{\omega} + b_1 * \ddot{\theta} + \omega * vx; \quad (2)$$

$$a_{y2} = \dot{v}_y - (a_2 + a_3 + b_1 + b_2 + b_3 + c_1) * \dot{\omega} + (b_1 + b_2 + b_3 + c_1) * \ddot{\theta} + c_1 * \ddot{\alpha} + \omega * vx \quad (3)$$

B. Lateral Forces at the wheels

$$F_{yf} = caf * (\delta - (v_y + a_1 * \omega) / v_x); \quad (4)$$

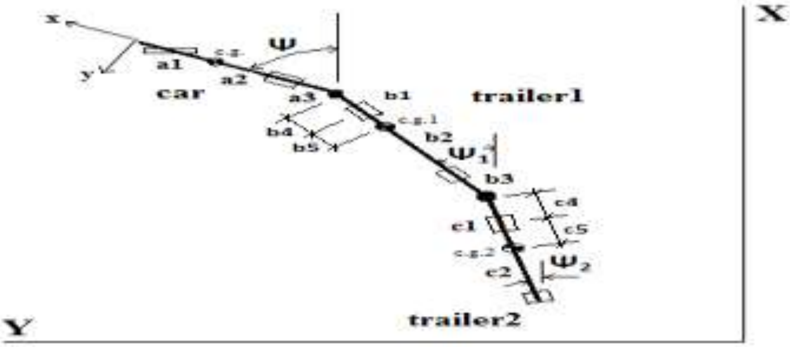

Fig. 2 Line model of a solar-battery car with two solar-trailers and four-wheels per trailer

$$F_{yr} = -car*(v_y - a_2*\omega)/v_x; \tag{5}$$

$$F_{yr1} = -car_1*(v_y - (a_2 + a_3 + b_1 + b_2)*\omega + (b_1 + b_2)*\dot{\theta} + vx*\theta)/v_x;$$

$$F_{yf1} = -caf_1*(v_y - (a_2 + a_3 + b_4)*\omega + b_4*\dot{\theta} + vx*\theta)/v_x; \tag{6}$$

where $a_{23}=a_2+a_3$, $b=b_1+b_2+b_3$ and $c_{12}=c_1+c_2$. Thus, we obtain:

$$F_{Yr2} = -car_2*(v_y - (a_{23} + b + c_{12})*\omega - (b + c_{12})*\dot{\theta} + c_{12}*\dot{\alpha} + vx*\theta + vx*\alpha)/v_x; \tag{7}$$

$$F_{Yf2} = -caf_2*(v_y - (a_{23} + b + c_4)*\omega - (b + c_4)*\dot{\theta} + c_4*\dot{\alpha} + vx*\theta + vx*\alpha)/v_x. \tag{8}$$

C. *Linearized equations of motion (neglecting product terms) [8-10]*

1) *Car:*

$$m*ay = F_{yf} + F_{yr} + T_y; \tag{9}$$

$$I_z\dot{\omega} = F_{yf}*a_1 - F_{yr}*a_2 - T_y*(a_2 + a_3). \tag{10}$$

2) *Trailer 1:*

$$m_1*a_{y1} = F_{yf1} + F_{yr1} + S_y - T_y; \tag{11}$$

$$I_{z1}*\dot{\omega}_1 = F_{yf1}*b_5 - F_{yr1}*b_2 - S_y*(b_2+b_3) - T_y*b_1. \tag{12}$$

3) *Trailer 2:*

$$m_2*a_{y2} = F_{yf2} + F_{yr2} - S_y; \tag{13}$$

$$I_{z2}*\dot{\omega}_2 = F_{yf2}*c_5 - F_{yr2}*c_2 - S_y*c_1. \tag{14}$$

Table 1 Nomenclature For Line Model of A Car With Trailers

a_1, a_2, a_3	Distance from the front wheel of the car to the center of gravity (c.g.), and c.g. to the rear wheel, and from the rear wheel to the trailer1 connection, respectively.
b_1, b_2,b_3,b_4	Distance from the connection to the c.g. of trailer1, from c.g. 1 to the rear wheel, from the rear wheel to the connection with trailer 2, and connection to front wheel of trailer 1, respectively.
c_1, c_2,c_4	Distance from the connection to c.g. 2 of trailer 2, from c.g. 2 to the rear wheel, and connection to front wheel of trailer 2, respectively.
a_y, a_{y1}, a_{y2}	The y-accelerations of the car, trailer 1 and trailer 2, respectively.
Ψ, Ψ_1, Ψ_2	The angle between the X-axis and the x-axes of the car, trailer 1 and trailer 2, respectively.
v_x, v_y	The x- and y-velocities of the car.
θ	Ψ-Ψ_1
α	Ψ_2-Ψ_1
δ	Front wheel steering angle.
ω	$d\Psi/dt$
m,m_1,m_2	Masses of the car, trailer 1 and trailer 2, respectively.
Iz,Iz_1,Iz_2	Mass moments of inertia along the z-axis of the car, trailer 1 and trailer 2, respectively.
F_{yf}, F_{yr}	Lateral front and rear forces of the car.
T_x, T_y	The car-trailer 1 connection forces along the x- and y-directions.
S_x, S_y	The trailer 1-trailer 2 connection forces along the x- and y-directions.
caf,car	Lateral stiffness coefficients of the front and rear wheels of the car.

IV. STABILITY OF THE LATERAL DYNAMICS USING A LINEARIZED LINE MODEL

The equations of motion, rearranged as matrices, can be written as follows:

$$A(dx/dt) + Bx = C(\delta(t)), \quad (15)$$

where the vector **x** is given by **x**=$[v_y \ \ \omega \ \ \theta \ \ \alpha \ \ d\theta/dt \ \ d\alpha/dt]^T$. In the absence of a steering input δ(t), the system of equations reduces to:

$$dx/dt + A^{-1}Bx = 0, \quad (16)$$

If $D = -A^{-1}B$, then:

$$dx/dt = Dx, \quad (17)$$

For such a system to be stable, the eigenvalues of D must represent negative real values [8-10].These equations will be used to calculate the eigenvalues of the system described above for a car with one or two solar-trailers. The properties of the car and trailers used in the analyses are shown in Table 2.The cornering stiffness is assumed to depend on the vertical load and the slip, as derived by Roland [6].

TABLE 2 PROPERTIES OF THE CAR AND TRAILERS

	mass (kg)	Iz (kg.m^2)	$a_1/b_1/c_1$ (m)	$a_2/b_2/c_2$ (m)	a_3/b_3 (m)	Two trailers caf/car (N/rad.)
Car	500.	600.	1.5	1.5	0.5	2.*6480./2.*6480.
Trailers	100.	125.	2.0	1.5	0.5	2.*2920./ 2.*2920

Three speeds were tested: v_x=80km/h, 90km/h and 100km/h. The resulting eigenvalues of a car with two solar-trailers are listed in Tables 3.

Table 3 Eigenvalues of a car with two solar-trailers at speeds of vx=80, 90 and 100 km/h

Car+two trailers	Eigen 1	Eigen 2	Eigen 3	Eigen 4	Eigen 5	Eigen 6
vx=80km/h	-2.969	-4.285	-0.211-3.395i	-0.211+3.395i	-6.586-4.563i	-6.586 +4.563i
vx=90km/h	-2.484	-3.827	-0.050-3.648i	-0.050+3.648i	-6.060-4.719i	-6.060 +4.719i
vx=100km/h	-2.145	-3.456	0.112-3.843i	0.112+3.843i	-5.650-4.822i	-5.650 +4.822i

As expected, decreasing the speed increased the damping and thus, increased the stability of the system. Up to a speed of 90km/h all eigenvalues have negative real parts, some eigenvalues are complex-conjugate; consequently, the system is oscillatory but still damped. Above 90km/h, the system becomes unstable. Moving the center of gravity of the trailers backward increases the stability of the system.

V. CONCLUSIONS

This paper updated the concept of using solar-array trailers with solar cars by using four-wheels per trailer. As expected, increasing the array power to 1600W and supporting the trailer on four wheels made the system energy efficient up to a speed of around 80km/h. As far as stability, for a car with two trailers and four-wheels per trailer, the critical speed is around 90km/h.

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