

# Design and Control of Vehicle Trailer with Onboard Power Supply

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## ABSTRACT

Typically, when someone needs to perform occasional towing tasks, such as towing a boat on a trailer, they have two choices. They can either purchase a larger, more powerful vehicle than they require for their regular usage, or they can rent a larger vehicle when they need to tow something. In this project, we propose a third alternative: a trailer with an on-board power supply, which can be towed by a small vehicle. This system requires a means of sensing how much power the trailer's power supply should provide, and an appropriate control system to provide this power. In this project, we design and model the trailer, a standard small car, and the control system, and evaluate the concept's feasibility. We have selected a suitable power source for the trailer, a DC motor, coupled directly to the trailer's single drive wheel, which allow us to dispense with the need for a differential. The trailer hitch is designed to include force sensing capability, to determine whether the trailer is moving under its own power or being towed by the vehicle. There is a control system, designed to maintain a zero force in the hitch, thus ensuring that the trailer is providing enough power. This system will enable someone with occasional towing needs to perform these tasks with their standard vehicle, and avoid the need for a larger vehicle.

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## INTRODUCTION

In this project, we propose and analyze a concept for a trailer with its own on-board power supply. This allows the trailer to be towed by a relatively small vehicle, which would not be able to tow a non-powered trailer. The purpose of this design is to allow someone with occasional towing needs to avoid the need for a larger vehicle, either rented or purchased, to serve those occasional needs.

This concept includes two significant innovations. The first is the inclusion of the power source on the trailer. There are many trailers available for towing a variety of different types of loads, but they are designed to be propelled by the engine or other power source of the towing vehicle. Some trailer designs do include unique features, such as the steerable trailer proposed by Ryu et al. [1], but no existing trailer moves under its own power, with the towing vehicle providing primarily guidance. The second innovative concept is the use of a load-sensing trailer hitch to provide a feedback signal to the trailer's controller. Some similar prior art exists in this regard, e.g. a load sensing trailer hitch used for detecting problems with alignments/towing, but these existing hitch designs are not used for our purpose. There are also trailer hitches including shock absorption, but they do not include sensing [2, 3, 4, 5].

Some modeling work has been done on vehicle-trailer systems as well, e.g. [1, 6, 7, 8, 9], and there has been some work on control systems for trailers in order to incorporate braking for safety purposes [10]; however, these models focus on the trajectory tracking problem and

directional control, rather than power control, and so significant modeling was required in order to carry out this project. This modeling work was the focus of the first phase of the project; the second phase was the design of a control system, and the third and final phase involved some preliminary optimization work on the model.

This paper is organized as follows: first, the modeling of all the systems is presented. This includes the models of the small car, trailer, on board power supply for the trailer and the hitch. Each is modeled as an individual system, and then they are connected to each other using the Mathworks® software Simulink.

In the next section of the paper, the control system is selected and designed for maintaining the trailer's motion in proportion with the small car's motion. The controller chosen is a proportional controller. This controller was selected to be the simplest possible controller. Although the proportional controller does have significant limitations, including the presence of a steady state error, we are using this to check the feasibility of the design. Future work will include a more sophisticated controller.

After this, the model is optimized and the system performance is evaluated for some simple maneuvers. While further optimization is desirable, along with more extensive analysis, this does show the basic feasibility of the concept.

Following the description of the work, a summary of key findings and conclusions is given, and future work is noted.

## Modeling of the System

Modeling and design have been performed for the four basic parts of the system which are,

1. Model of the standard small car
2. Model of the trailer
3. Model of the On Board power supply system
4. Model of the hitch

These parts were then combined into a complete system model. Each part of the system is modelled using Mathworks® software Simulink. The detailed description of the modelling and design of various components of the system are discussed below.

### 1. Model of Standard Small Car

While complex vehicle models can be created, for the purposes of this work a simple model was used. The vehicle dynamics of the small car are assumed to be adequately represented by a bicycle model, which has only three degrees of freedom. Since the focus of this work is on the trailer, the drivetrain of the vehicle was not modeled; it was assumed to be able to achieve the specified speeds and paths used in the analysis.

#### Bicycle Model

Generally a vehicle is associated with lots of degrees of freedom. But for making it simple and considering only the lateral and the yaw motions of a vehicle and the angle associated with it, we consider only three degrees of freedom and thus the vehicle can be considered in two wheels as illustrated below. This is called the bicycle model in vehicle dynamics.

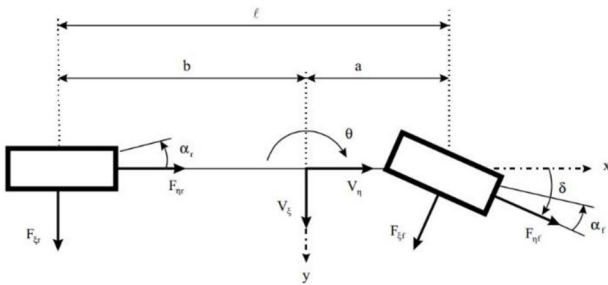


Figure 1. Three degree of freedom model [11]

#### Equations

Thus, from the bicycle model, we can be able to obtain the equations which determine the various parameters of the standard small car. The equations for the different parameters, taken from [12], are listed below:

$$\dot{v}_x = \frac{F_x}{m} + r v_z$$

$$\dot{v}_z = \frac{1}{m v_x} (-a_1 C_{af} + a_2 C_{ar}) r - \frac{1}{m v_x} (C_{af} + C_{ar}) v_z + \frac{1}{m} C_{af} \delta - r v_x$$

$$\dot{r} = \frac{1}{I_z v_x} (-a_1^2 C_{af} - a_2^2 C_{ar}) r - \frac{1}{I_z v_x} (a_1 C_{af} - a_2 C_{ar}) v_z + \frac{1}{I_z} a_1 C_{af} \delta$$

Thus we will be able to obtain our  $\dot{v}_x$ ,  $\dot{v}_z$  and  $\dot{r}$  for the standard small car and can put them into Simulink.

The model of the car has been simulated in Simulink using the above equations, such that the velocity of the car ( $\dot{v}_x$  and  $\dot{v}_z$ ) and the yaw rate ( $\dot{r}$ ) can be obtained for further processing. The inputs to be given are the steering angle ( $\delta$ ) and the force in the forward direction ( $F_x$ ).

### 2. Model of the Trailer

We have designed a three wheel trailer, which has a single front wheel. This front wheel is the drive wheel, which is coupled to the onboard power source. By using a single drive wheel, we eliminate the need for a differential, which produces a simpler design. The trailer's center of gravity will be designed to fall between the line of axis of the front wheel and the center of the rear axle.

#### Free Body Diagram of the Trailer

The free body of the trailer is shown below,

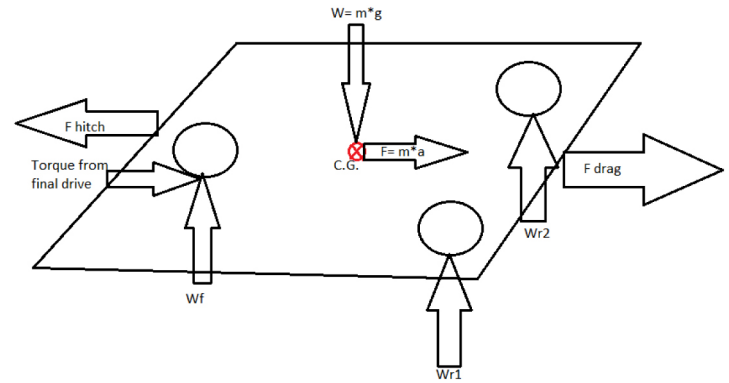


Figure 2. Free body diagram of the trailer

#### Equations of the Trailer

The equations of the trailer, describing the linear and angular acceleration and velocity, were derived based on the free-body diagram in Figure 2. The initial equations are given below, followed by the necessary equation development to construct the model.

$$\sum F_x = F_{hitch} - T_{final\ drive} - F_{drag}$$

$$\sum F_y = W_f + W_{r1} + W_{r2} - mg$$

### Velocity of the Trailer

During a turn,

$$v_x = V \cos\theta$$

$$v_z = V \sin\theta$$

At straight roads,

$$V_x = V$$

$$V_z = 0$$

### Acceleration of the Trailer

At straight roads,

$$\Sigma F_x = ma_x$$

$$a_x = \frac{\Sigma F_x}{m}$$

$$a_z = 0$$

During a turn,

$$a_z = \frac{v^2}{R}$$

Where,

R- Radius of the turn

Angular Velocity of the Trailer:

$$\omega = \frac{V}{r}$$

Angular Acceleration of the Trailer:

$$\alpha = \frac{\Sigma \text{Moment}_{C.G.}}{I_z}$$

Where,

$$\Sigma \text{Moment}_{C.G.} = (F_{\text{hitch}} \cdot e) - T_{\text{final drive}} + (a \cdot W_f) + (2b \cdot W_r)$$

The dynamics of the trailer can be studied using Simulink from the above derived equations. Then a model of the trailer is generated in Simulink. The velocity of the trailer, acceleration of the trailer, angular acceleration and angular velocity of the trailer are the outputs taken from the trailer model. A sample structure of the trailer and the car is depicted below.

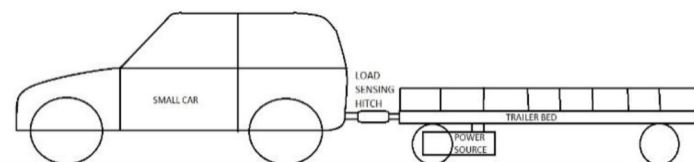


Figure 3. Model of the trailer and the car connected

### Dimensions of the Trailer

In order to analyze the motion of the trailer, its dimensions must be specified. The values of parameters describing the trailer are given in Table 1, below

Table 1. Dimensions of the trailer

| DESCRIPTION                                                  | PARAMETER | VALUE    |
|--------------------------------------------------------------|-----------|----------|
| Trailer's length                                             | l         | 3.048 m  |
| Trailer's width                                              | b         | 1.8288 m |
| Distance from front wheel center to C.G.                     | a         | 1.524 m  |
| Distance from rear wheel center to C.G.                      | b         | 1.524 m  |
| Height of C.G. from the ground                               | h         | 0.360 m  |
| Unloaded mass of trailer                                     | Mul       | 1000 kg  |
| Diameter of the trailer's wheel                              | w         | 0.381 m  |
| Distance between front wheel center and front tip of trailer | f         | 0.1905 m |
| Loaded mass of trailer                                       | MI        | 1500 kg  |

The dimension  $e$  is assumed to be zero; it is included in the equations for possible future work.

### 3. Model of the on- board Power Supply

Although there are many suitable power systems which can be used to power the trailer, such as a conventional internal combustion engine or a motor, we have chosen to use a DC motor. This selection was made due to its advantages in terms of emission, simplicity of the drive train, and the simplicity of modeling. The equations used for the modeling were taken from Reyer & Papalambros [13].

$$\dot{i} = -\frac{L_a}{J_a} \cdot i - \frac{R_a}{J_a} \cdot \omega + \frac{1}{J_a} \cdot z$$

$$\dot{\omega} = \frac{R_a}{K_m} \cdot i + \frac{B}{K_m} \cdot \omega - \frac{1}{K_m} \cdot \tau_L$$

The above equations fully describe the motor, including its power requirements, and are modeled in Simulink and connected with the other subsystems in the model. Thus when the feedback comes from the hitch the controller controls the power to the motor, thus controlling the whole trailer.