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Scaled Vehicle for Interactive Dynamic Simulation (SIS)

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Abstract - This paper describes a development of a **S**caled vehicle for **I**nteractive dynamic **S**imulation or **SIS**. The **SIS** is a scaled vehicle that engineered to have dynamic behaviors equivalent to those of real vehicle. The main purpose is to use SIS in a scaling environment interactively with human operator. SIS prototype equipped with sensors, instrument, wireless communication system, controller, and vision on board. Several measurement devices were developed for measuring moment of inertia, and cornering stiffness coefficients. The simulation and experiment is provided.

Index term –Scaled Vehicle, Simulation, dimensionless analysis, similarity, human vehicle interface

I. Introduction

Computer simulation is an essential tool to design, analyze, and develop a product such as vehicle prototype. This technology mainly relies on mathematical models to predict the physical behaviors. Since, none of mathematic model can completely represent a real physical system; the non-exact model will result in some simulation error. Thus, in practice especially in the automobile industry, a series of real expensive prototypes were built to test their dynamics and performance.

To reduce developing cost and time, recently, many researches have developed scaled vehicles. Scaled vehicles are proportionally similitude vehicles that have similar dynamic behavior of those full size vehicles. There are several advantages of using the scaled vehicle over a full-size vehicle. The scaled vehicle is more simple and inexpensive. No drivers or pedestrians are risk during testing. In addition, it is relatively simple to change testing conditions and environment (ex. road surface). This makes the testing safe, fast, and repeatable.

Brenanl [1] developed a scaled vehicle testing on a moving road surface (treadmill). The position and orientation of the vehicle on the treadmill were measured using a mechanical link attaching to the vehicle. Maren and Sika constructed 1:5 scaled vehicles using a camera to measure position and orientation [2]. Hoblet modified a 1:10 scaled vehicle [1] and used external camera to measures planar positions as well [3]. Later, Glumac [5] has constructed 1:10 scaled operating on a tilting treadmill which can create a 25 deg in rolling axis. Verma also studied longitudinal response [6] using 1:10 scaled vehicle.

All works mentioned above utilizes a scaled vehicle as a test bed for study dynamics behaviour. There is no direct interaction from human operators. All vehicles are commanded to follow paths and then collected data for analysing later on.

Here we developed a “SIS” or **S**caled vehicle for **I**nteractive dynamic **S**imulation. This scaled vehicle not only use to follow command and collect data but can be directly interact with human operator in the same control loop.

II. A Scaled Vehicle Test bed

SIS prototype was built from a 1:10 scaled vehicle platform that powered by an electric motor with four speed transmissions. The prototype consists of microprocessor module, sensor module, vision module, and communication module.

The microprocessor module processes command received from the external controller via a wireless communication module. We installed inertia sensors (Xbow) for measuring vehicle states, accelerations, yaw rates, and GPS signals. In addition, the vehicle equipped with positioning and hall sensors to measure steering angle and wheel velocities. Another important element is an on borad wireless video camera system that sends a live motion picture to the controller or operator. The camera on SIS had been placed in the driver’s vision position.

The host computer can control the vehicle in path planing mode or in operator interactive mode. The command structure includes acceleration, breaking, gear shifting and steering. All system transmits and receives at 100 Hz sampling rate

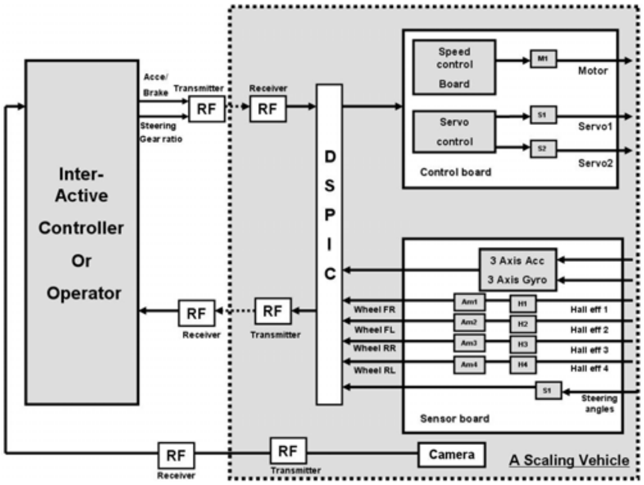


Fig. 1 Overall Schematic

All of these elements must be carefully installed and positioned according to the dimensionless analysis and PI's Group requirements which will be described later.

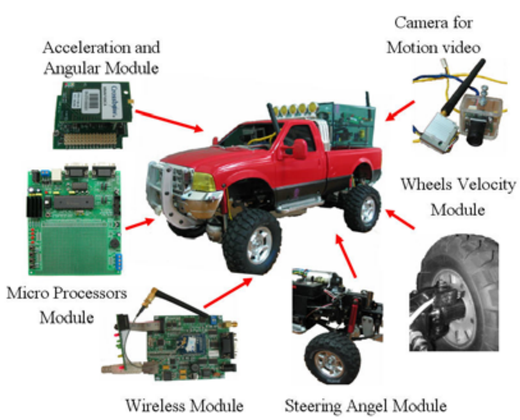


Fig. 2 Sensors on SIS

III. Dynamics model of scaled vehicle

In order to create a dynamically equivalent similar to a full size vehicle, all essential parameters of the scaled vehicle must be matched with those of full size vehicle by using dimensionless analysis and Pi's theorem [1]. Dimensionless parameters of the scaling vehicle and the full size vehicle can be arranged and grouped together. These groups will be adjusted so that they are proportionally similar.

At the beginning, the dynamics model used in this research is a simple model [1,2] called "Bicycle model" as show in Figure 4.

Assumptions:

1. Turning radius equals to wheelbase of the vehicle
2. Left and right steering angles are equivalent. Side slip angles of wheels are less than 10 degrees.
3. Left and right side slip angles of wheels are equivalent.
4. Side slip angle on CG. is $\beta=\tan^{-1}(v/u)$.
5. Friction and wind force are neglected.
6. System is a linear model.

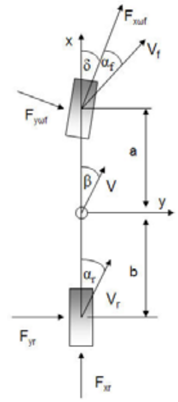


Fig. 3 Bicycle model

From Newton's law :

$$ma_x = F_{xwf}\cos\delta - F_{ywf}\sin\delta + F_{xr} \quad (1)$$

$$ma_y = F_{ywf}\cos\delta + F_{xwf}\sin\delta + F_{yr} \quad (2)$$

$$I_Z\dot{r} = aF_{ywf}\cos\delta + aF_{xwf}\sin\delta - bF_{yr} \quad (3)$$

with a condition of constant longitudinal velocity, force on x-axis is zero. For a small steer angle, $\cos\delta \approx 1$ and $\sin\delta \approx 0$. Thus $F_{ywf}\sin\delta$ =0 . Now we have:

$$\dot{v} = -\omega u + \left(\frac{1}{m}\right)\left(F_{yf} + F_{yr}\right) \quad (4)$$

$$\dot{r} = \left(\frac{1}{I_z}\right)\left(aF_{yf} - bF_{yr}\right) \quad (5)$$

where F_{yf} and F_{yr} in (4) , (5) are lateral forces on front and rear wheels respectively. With all variables substituted, one can write

$$\dot{v} = \left(\frac{2C_{\alpha f} + 2C_{\alpha r}}{mu}\right)v + \left(\frac{2aC_{\alpha f} - 2bC_{\alpha r}}{mu} - u\right)r - \left(\frac{2C_{\alpha f}}{m}\right)\delta_f \quad (6)$$

$$\dot{r} = \left(\frac{2aC_{\alpha f} - 2bC_{\alpha r}}{I_z u}\right)v + \left(\frac{2a^2C_{\alpha f} + 2b^2C_{\alpha r}}{I_z u}\right)r - \left(\frac{2aC_{\alpha f}}{I_z}\right)\delta_f \quad (7)$$

, where subscript f and r associate with front and rear wheels, C_α is Cornering stiffness, α_r is slip angle, m is vehicle mass, I_Z is moment of inertia of vertical axis, u is the velocity in x axis, r is yaw rate, and α is slip angle.

IV. Dimension analysis

We adopted PI-Bucking ham's theory [1] together with Bicycle model to arrange dimensionless groups (called "PI's-Groups"). These Pi's groups of the scaled vehicle later will be adjusted to compatible with those of real vehicle. Here we have 5 dimensionless groups as:

$$\Pi_1 = \frac{a}{L},\ \Pi_2 = \frac{b}{L},\ \Pi_3 = \frac{C_{\alpha f}L}{mu^2},\ \Pi_4 = \frac{C_{\alpha r}L}{mu^2},\ \Pi_5 = \frac{I_z}{mL^2} \tag{8}$$

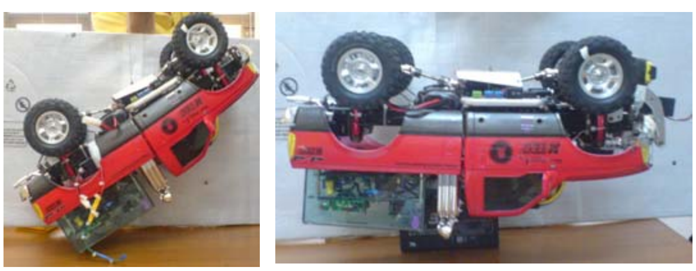
Substitute parameters of the scaled and real vehicles to eq (8). Now we have 2 sets of PI's groups (one for scaling vehicle and the other for real vehicle). To make an equivalent dynamic behaviour, we must adjust the scaled vehicle parameters to match those of real vehicle.

V. Measurement and parameter adjustment of scaled vehicle

From data of NHTSA [7], we selected "Ford 1 Driver + 3 Passengers + Rear Cargo" as a full size vehicle. This model has overall geometry matching well with our testbed vehicle. The parameter adjustment process based on dimensionless analysis can be explained step by step as follow:

A. Center of gravity

We acquired the position of CG form NHTSA, and calculate parameters in the 1st and 2nd dimensionless group. Then, we hang a scaling vehicle in the CG location as shown in Figure 4. After that, we carefully relocated all elements in the vehicle to adjust the CG.



(a) before (b) after

Fig. 4 Central gravity adjustment

Figure 4(a) and (b) display the vehicle before and after CG adjustment. Table 1 shows the result of the Pi's Group associated with CG adjustment.

Table 1. compare equivalent of dimensionless group 1st and 2nd

Description	a(m)	b(m)	L(m)	Π_1=a/L	Π_2=b/L
Full size	1.1700	1.5200	2.690	0.4349	0.56506
Scaled	0.1212	0.1588	0.280	0.4329	0.56714

B. Moment of inertia

To adjust a moment of inertia, we built a simple device shown in Figure 5, called three-string torsional pendulum, to measure rotational inertia. Here we can measure period of oscillation and calculate inertia values using formula in Eq. 9-10.

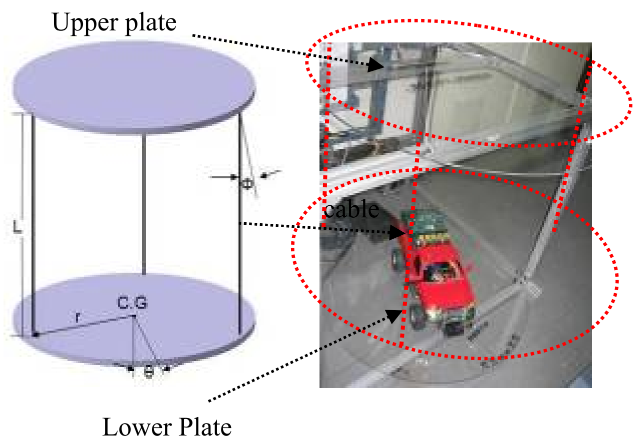


Fig. 5 Moment of inertia measurement

From Figure 5

$$\sum M_z \ :\ -r(m_o + m_p)gsin\phi = (I_p + I_p)\ddot{\theta} \tag{9}$$

Since the angle $\varnothing$ is small, one can write

$$l_{sc} + l_p = \frac{(m_o + m_p)r^2 g}{l}\left(\frac{\tau}{2\pi}\right)^2 \tag{10}$$

When placing the scaled vehicle on the lower plate, the central gravity of the vehicle must coincide with the center of the plate. Here the angle $\varnothing$ must be less than 5 degree. We collected 20 experiment data to determine an average period of oscillation. Initially, the moment of inertia of the scaled vehicle was too much. Thus we adjusted by relocating elements toward the center of gravity to decrease moment of inertia. The adjusted result is shown in the Table 2.

Table 2. compare equivalent of dimensionless group 5th

Description	M(kg)	Izz(kg.m2)	L(m)	$\Pi_5=I_z/mL^2$
Full size	1857.90	3282.00	2.690	0.2441
Scaled	5.04	0.09748	0.280	0.2466

C. cornering stiffness coefficient

The cornering stiffness of wheel can be calculated by a ratio between cornering force (lateral force) and wheel side slip angle as

$$C_\alpha = \frac{F_y}{\alpha} \tag{11}$$

Since this coefficient results from several factors such as wheel material, wheel structure, and road surface, we have developed an instrument to measure this coefficient.

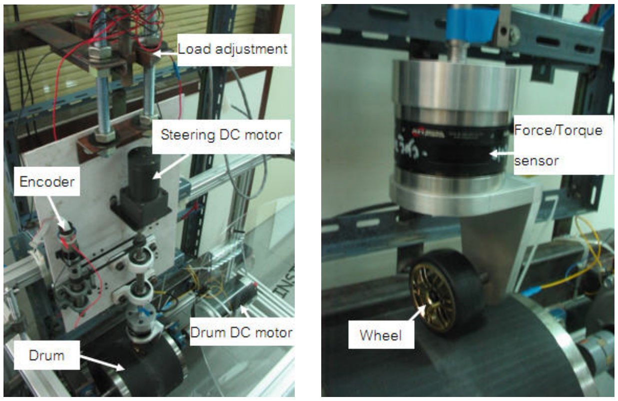


Fig. 6 Cornering stiffness coefficient measurement device

This instrument consists of a drum, steering axis, steering load, and a force sensor. The drum can be surfaced with different materials, and its rotational velocity is controlled by a dc motor. The computer controls the steering axis angle with a preset load, and measures lateral force from the force sensor.

There are two types of wheels in this experiment (with and without inner cushion rubber). We tested road surface up to 6 materials. Each has different roughness. Range of steering angle is ± 4 degree (for linearization system). A cornering stiffness coefficient can be estimated by slope as show in Figure 7.

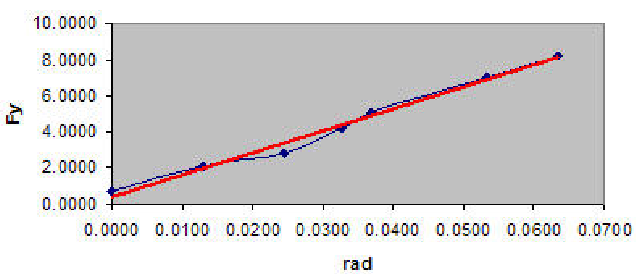


Fig. 7 Steer angle and lateral force relation

We performed several experiments in different configurations. Some of them are listed in the Table 3 with cornering stiffness coefficients.

Table 3. cornering stiffness

Condition	Cf(N/rad)	Cr(N/rad)
Wheels 1,Surface 1 (Inner)	72.77	78.81
Wheels 1,Surface 1 (Non-Inner)	68.79	70.5
Wheels 1,Surface 2 (Inner)	55.49	47.45
Wheels 1,Surface 2 (Non-Inner)	32.705	43.21
Wheels 1,Surface 3 (Inner)	44.89	32.12
Wheels 1,Surface 3 (Non-Inner)	37.44	42.77
Wheels 1,Surface 4 (Inner)	44.38	43.12
Wheels 1,Surface 4 (Non-Inner)	56.11	50.22
Wheels 1,Surface 5 (Inner)	55.06	36.5
Wheels 1,Surface 5 (Non-Inner)	47.82	48.82
Wheels 1,Surface 5 (Inner)	40.96	40.32
Wheels 1,Surface 5 (Non-Inner)	43.66	57
Wheels 2,Surface 1 (Inner)	-	140

From table 3, we take a cornering stiffness coefficient on each configuration, and substitute into dimensionless group 3rd and 4th. We found a good set of parameters. The wheel without inner rubber and surface 3 (table 3 above) has coefficients matching with the real vehicle.

Now, we have matched all essential dimensionless groups as summarized in the Table 4. In principle, the dynamic behaviour of our scaled vehicle will be closely equivalent with a real vehicle. In this research, we are using this scaled vehicle for advanced interactive control.

Table 4. Compare dimensionless groups between the scaled and real vehicles.

Description	Π_1	Π_2	Π_3	Π_4	Π_5
Full size	0.4393	0.5607	2.0800	2.3761	0.2468
Scaled	0.4349	0.5651	2.0804	2.5725	0.2441

VI. Dynamic simulation

After adjusting process, we used parameters from the scaled and real vehicles to simulate dynamic behaviour using MATLAB. These parameters are shown in Table 5, The simulation results showed good dynamical equivalent as display in Figure 10-12.

Table 5. Vehicle parameters

Description	Full size	Scaled
M(kg)	1857.90	5.04
Iz(kg.m2)	3282	0.0975
A(m)	1.170	0.124
B(m)	1.520	0.157
L(m)	2.690	0.280
$C_{\alpha f}$(N/rad)	107462	37.44
$C_{\alpha r}$(N/rad)	132880	42.77
U(m/s)	8.648	1

From Fig 8 thru Fig 10, we found the trajectory of scaling vehicle and real vehicle are different in magnitude but have same trend and characteristics.

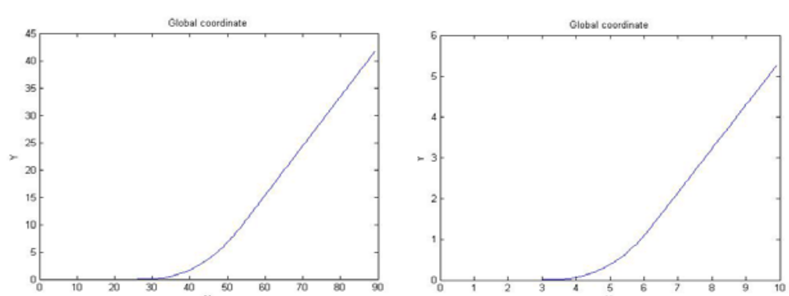


Fig. 8 Trajectory (simulation)
real vehicle-Left , scaling vehicle-right

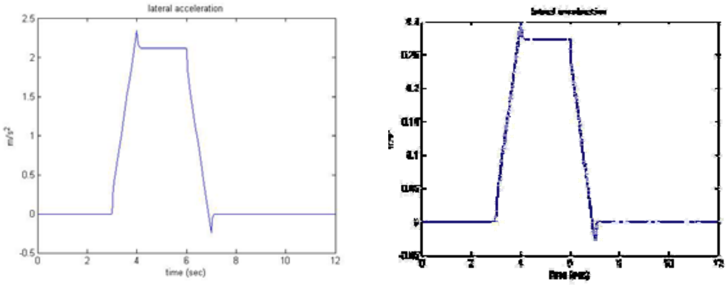


Fig. 9 Lateral Acceleration (simulation)
real vehicle-Left , scaling vehicle-right

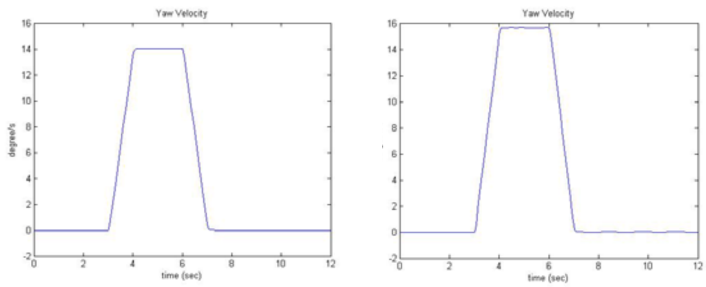


Fig. 10 Angular Velocity (simulation)
real vehicle-Left , scaling vehicle-right

Consider Fig 10. Responses of angular velocities are similar in both magnitude and characteristics because their units associate with radian. Although there are slightly different in magnitude, this because the adjustment parameters are closely matched but not exactly matched.

VII. Experiment

The SIS prototype is developed for an interactive system with human operator. Here human can control SIS on a driving simulator via a control program. All signals will transmit to the SIS via wireless communication.

This program runs on a control center between human and the scaling vehicle. The driver can control scaling vehicle through steering wheel, and paddles on the simulator. Signals from driver consist of steering angle, acceleration, deceleration and gear. These data will send to scaling vehicle by wireless communication. At the same time, a scaled vehicle sends state and other dynamic parameters of the vehicle to the program. When the program receives these data, the program will compare data between dynamics calculation data and vehicle state data.

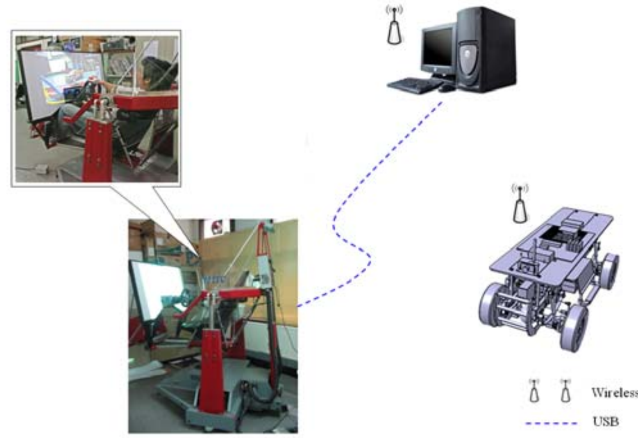


Fig. 11 Overall Control System

We performed an experiment with constant longitudinal speed in) lane change driving as depicted below.

Fig. 12 Trajectory - Lane change (Left)

Fig 13 displays the result lane change driving. We found that lateral acceleration by sensor measurement on scaling vehicle have range about -1.5 m/s^2 or 0.15 g, while the data from model has same trend. However the data is rather noisy and may require additional filtering algorithms.

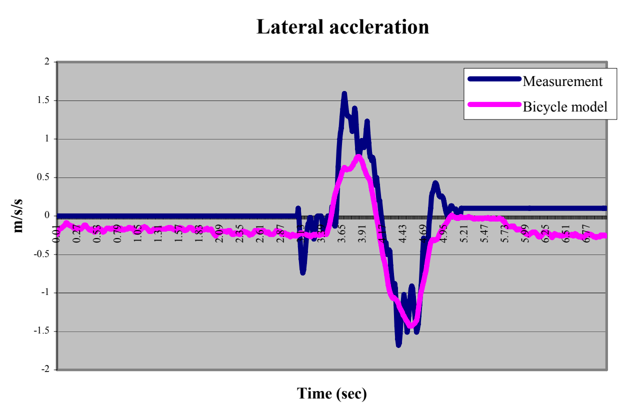


Fig 13. Lateral Acceleration

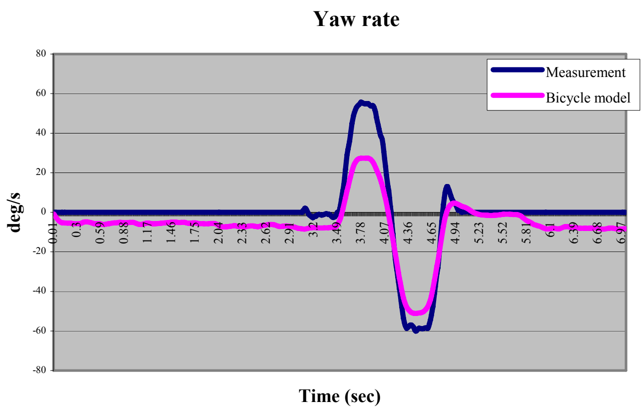


Fig 14. Yaw rate

Yaw rate data from sensor and model have similar characteristics but have different magnitudes.

VII. Conclusion

This paper presents a development of SIS Scaled vehicle for Interactive dynamics Simulation. All dimensionless Pi's group parameters were adjusted to have dynamic similarity to the real vehicle. Experiment and simulation have been proved and verified. The results have been consistent with the model. However there is a margin of improvement, and is under investigation. Furthermore we are now developing a 3D model.

Acknowledgment

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