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Investigation on Chassis Dynamometer with Capability to Test Regenerative Braking Function

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ABSTRACT

An investigation-based approach to a bidirectional power flow method for testing regenerative braking function on a chassis dynamometer is presented. The requirements and specifications for capability to test regenerative braking function of Electric Vehicle (EV) emulated by using a bidirectional chassis dynamometer are discussed. The dynamometer emulates road load conditions during testing, and regenerative braking is able to test their function while the vehicle is in deceleration condition. Performances of power requirement are illustrated and translated into sequence diagram. It is shown that the proposed topology is particularly advantageous in generating and regenerating power for energy consumption. The overview of conventional chassis dynamometer and the proposed chassis dynamometer is compared to investigate the parameter in the development of regenerative braking test.

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1. INTRODUCTION

The increasing world population soars the demand for fossil fuels in electricity energy generation [1], which subsequently influences the growth of Energy Efficient Vehicle (EEV). EEV is defined as vehicles that meet a set of defined specifications in terms of carbon emission level (g/km) and fuel consumption (l/100km) [2], which include electric vehicle (EV) and hybrid electric vehicle (HEV) technologies. EV and HEV consists of a very different powertrain compared to that of a conventional automobile, hence vehicle performance test should be applied not only to the engine, but also to the complete powertrains [3]. Vehicle performance must be measured using chassis dynamometer, a device for determining the overall delivered torque and power of a vehicle from its wheel's propulsion. The performance produced by the whole powertrain (the engine, motor and transmission) is collectively measured by the continuous readings of the rotational speed (rpm) and torque on the wheel(s).

In recent years, the usage of chassis dynamometer for performance testing of EV has rapidly increased as a consequence of the development of EVs. Typically, chassis dynamometer utilizes either eddy current brake or DC generator brake as the power absorber. However, the actual use of eddy-current dynamometer has been rather limited due to its accuracies that produce imperfect results [4]. DC generator brake, on the other hand, converts the mechanical energy from the Vehicle under Test (VUT) to electrical energy. The energy from the DC generator is then stored, utilized or dissipated as heat using a variable load. The main advantage of DC generator brake over eddy current brake is its capability to emulate the changes in the dynamic load, hence test the VUT's dynamic performance. Thus, DC generator brake is more appropriate for testing EEV.

The challenge in emulating road conditions on a dynamometer is caused by the differences in the characteristics of road load and dynamometer's load, which produce inaccuracies in the performance results. To measure the performance of the VUT, the force and the inertia on the vehicle and the dynamometer drum must be considered. Force is known as the tractive effort and is commonly measured on a drum-type dynamometer by a load cell indirectly connected to the rollers [3]. Thus, speed and force are two important parameters for power performance test of the VUT.

Typically, emulating road condition in a chassis dynamometer would enable the test on a specific real road tracks, called drive cycles, be carried out [4-5]. Vehicle performance test conducted on conventional chassis dynamometer focuses on power and torque developed by the VUT in a range of speed [3] but little attentions are being paid to the VUT performance during deceleration [4]. This is because in traditional internal combustion engine (ICE) vehicles, the deceleration is just a state where the vehicle is slowing down with the vehicle's momentum. However, the situation is different with EV and HEV as deceleration usually involved regenerative braking [8-9].

In this paper, attempting to overcome the problem, the possibility of a new design of chassis dynamometer that emulates the VUT's deceleration inertia, and consequently assess the regenerative braking function, is investigated. This investigation considers the use of chassis dynamometer for three functions; (1) determining power performance, (2) emulating road condition, and (3) testing the regenerative braking. Section II describes the chassis dynamometer, which includes operation and power performance. Section III proposes a solution of a new design of chassis dynamometer for EV with regenerative braking testing capability. Section IV discusses the classifications of chassis dynamometer and identifies further research to improve performance.

2. PRINCIPLE OF THE CHASSIS DYNAMOMETER

2.1. Operation of Conventional Chassis Dynamometer

Performance of a VUT can be measured through simultaneous operation of load variation and parameter measurement. Load variation refers to the process of manipulating dynamometer drum's inertia to emulate road load condition, while parameter measurement is about the power, torque and speed measurements using various sensors; mostly installed at the load cell. Chassis dynamometer implicates an absorbing power output from the test vehicle's engine to allow different loads to be applied on drum for various testing procedures [3].

A conventional dynamometer operates by absorbing the power and energy produces from the vehicle and dissipates the absorbed power usually as heat. The absorbing power flow is shown in Figure 1, where the flow originated from the VUT on a chassis dynamometer drum to the load. Conventional chassis dynamometer is focused on measuring power delivered by vehicle that is dependent on road condition. Several chassis dynamometer that could emulate the physical system configuration, inertia and friction calibration techniques, and control software have been developed; however the testing is applicable for Internal Combustion Engine (ICE) vehicles.

2.2. Power Requirement/Driving Resistance Simulation of Chassis Dynamometer Testing

This section investigates the limitation of a conventional chassis dynamometer. The direction of force applied during chassis dynamometer testing is illustrated in Figure 1(a). The inertia from the vehicle and the force on the chassis dynamometer assist in the emulation of actual road condition on chassis dynamometer drum. As different vehicles have different mass, inertia simulation must be employed to provide realistic loading during transient proceedings [7]. The force acting on the vehicle can be calculated using equations (6) to (8), where m_{car} is the weight of the vehicle to be calculated, with acceleration and gravitational forces taken into account. The gravitational force is equal to the net force, expressed in Equation (3), because the directions of the two forces are in parallel.

$$F_{car} = m_{car}a \quad (1)$$

$$F_g = m_{car}g \quad (2)$$

$$F_n = F_g \quad (3)$$

Equation (4) expresses the friction force, $F_{roadload}$, in which its direction is opposite to the applied force as shown in Figure 1. Friction force is due to the traction of the vehicle, while applied force is due to the propulsion of the vehicle.

$$F_{roadload} = \mu F_n \tag{4}$$

Since $F_{roadload}$ is derived based on frictional force, then the values for vehicle force, F_{car}, or applied force, $F_{propulsion}$, can be defined using equations (5):

$$F_{car} = F_{propulsion} - F_{roadload} \tag{5}$$

Based on equations above, the total road-load of the vehicle is calculated using Equation (8), and then road condition emulated by the wheels is then delivered to the chassis dynamometer. Torque is generated to provide realistic load and consists of forces that are constants, F_c, or dependent on acceleration, F_a, or vehicle velocity, F_v. The total force applied on wheels is translated as in Equation (8). The acceleration force can be expressed as $F_a = M_v \frac{dv}{dt}$, and the constant force $F_c = A_c$. Setting, $A = A_c + A_v$ [7], the total load can be expressed as:

$$F_w = F_a + F_v + F_c \tag{6}$$

$$F_v = A_v + Bv + Cv^2 \tag{7}$$

$$F_{total(load)} = A + Bv + Cv^2 + M_v \frac{dv}{dt} \tag{8}$$

The chassis dynamometer emulates the total road load to make vehicle experiences road condition, and consequently, power performance of the vehicle can be measured. The instantaneous dynamometer power is defined as in Equation (9):

$$P = \tau\omega = F.V \tag{9}$$

where P is the power produced by the vehicle and τ is the associated torque. The power required must be considered to determine how much torque should be added when conducting the test [4]. From equations (10) and (11), the parameters of chassis dynamometer, including drum radius, distance of load cell and moment of inertia, can be determined from the structure, while angular frequency, ω and force, F is obtained from measurement method.

$$F_{propulsion} = \left(m \times \frac{\partial(V)}{\partial t} + F_{roadload}\right) \times V \tag{10}$$

$$F_{dyno} = F_{total(load)} \times V_{dyno} \tag{11}$$

As a case study, the scope of force calculation is sufficient for conventional chassis dynamometer test but is limited when testing the performance of EV. On the other hand, the bidirectional chassis dynamometer is proposed as a new method to test the capability of regenerative braking function of EV.

3. PROPOSED BIDIRECTIONAL CHASSIS DYNAMOMETER

3.1. Chassis Dynamometer for Regenerative Braking

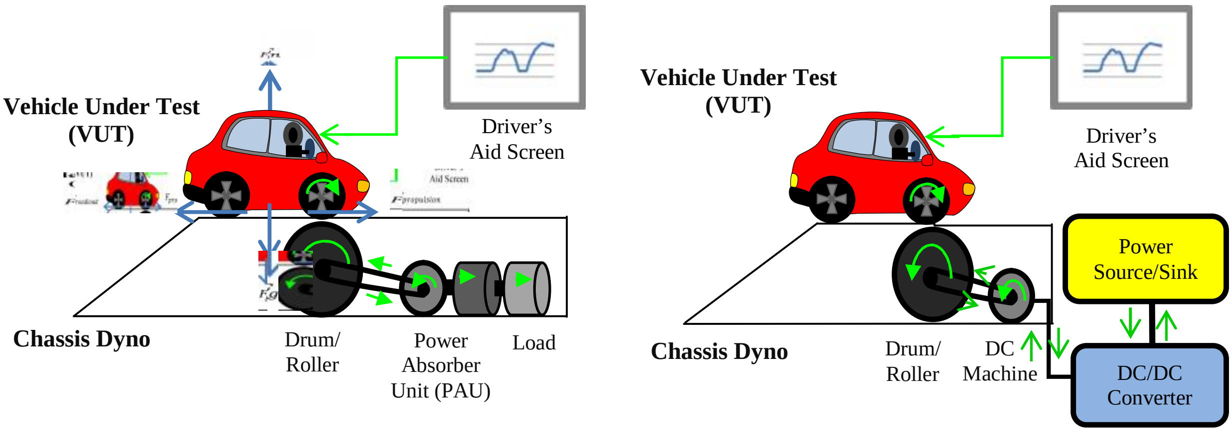
The working principle of bidirectional chassis dynamometer with the associated devices is illustrated in Figure 1(b). It should be noted that the system is similar to the conventional chassis dynamometer in Figure 1(a). The only difference between the two systems is conventional chassis dynamometer utilize Power Absorption Unit (PAU) to dissipate the power from VUT, whereas the proposed system use a new subsystem called Power Absorption and Delivery Unit (PADU). PADU consists of a DC machine, a bidirectional DC-DC converter and a power sink/source. Unlike PAU which can only absorb VUT's energy, PADU can operates in two modes; Mode 1 – absorbing energy from VUT and Mode 2 – delivering energy to VUT.

Mode 1 is when VUT is in normal motoring condition. Once VUT starts accelerating, the rotating wheels force the drum to turn. Due to higher starting torque of the DC machine which is directly coupled to the shaft of the drum, the VUT need to provide additional power for relatively hard accelerations [8]. The rotational force put DC machine in generating mode, where it convert the mechanical energy into electrical energy. DC-DC converter transfers the electrical energy into another form of electrical energy, suitable for storage in the power source/sink. In practical application, this power source/sink might be an energy storage system like battery and ultracapacitor or, it might be a bidirectional grid-tied inverter.

Mode 2 is exclusive to HEV or EV as the VUT, operating in regenerative braking mode. For most HEV and EV, regenerative braking happens when acceleration pedal is released. In this mode, HEV and EV harvest the mechanical energy from the rotating wheels to charge the main battery pack, thus slowing down the vehicle. In the proposed bidirectional chassis dynamometer, this Mode 2 demands an opposite energy transfer as compared to Mode 1. In this condition, power source/sink transfers energy to DC machine through the bidirectional DC-DC converter. Upon receiving the energy, DC machine starts operates as motor and rotates the drum. This subsequently rotates the wheel of VUT, hence allowing the VUT to test its regenerative braking operation.

The main purpose of PADU in the proposed system is to vary the system's inertia to closely resemble the real VUT's inertia. By controlling the power transfer in magnitude, the system is able to control the inertia of the drum, make it lighter or heavier to turn. With bidirectional capability, the system is able to control the direction of the power transfer, make the drum turns even without the power from the VUT. This variation of the drum's inertia emulates the real VUT's inertia during both motoring mode and regenerative braking mode of VUT. Moreover, with precise control of the inertia's variation, the system is capable to emulate road condition and is capable of testing the regenerative braking of HEV and EV.

In order to simulate similar loads on the drum of the chassis dynamometer as on real road conditions, the road load forces have to be determined by executing a coast-down testing [9]. The testing is used to determine the target coefficients in Equation 8. These target coefficients (A, B and C) are unique for each vehicle under certain operating condition [7], [10-11]. The target coefficients are needed in the calculation of the total road force on the dynamometer, as expressed in the equation.



a) Conventional chassis dynamometer b) Bidirectional chassis dynamometer

Figure 1. Comparison of proposed and conventional chassis dynamometer

4. SIMULATION AND RESULT

4.1. Simulation parameter

The proposed bidirectional chassis dynamometer is simulated to prove its working concept, as shown in Figure 2. The VUT is resembled by a DC motor as prime mover in the simulation, directly coupled to the DC machine on the chassis dynamometer side. The absence of drum in the simulation simplifies the speed conversion, where it is assumed that the speed of the PADU's DC machine is same as the speed of VUT's wheel. The availability of half bridge bidirectional DC-DC converter is used to allow power flow in both directions, whether in Mode 1 or Mode 2. In Mode 1, the energy from the DC machine (operates as generator) is stored in the battery at the last station. This stored energy is reused for Mode 2 (regenerating braking test), where the DC machine operates as motor. The main focus of the bidirectional chassis dynamometer is to investigate the testing capability of regenerative braking function. In the proposed method, bidirectional DC-DC converter power flow is used to test regenerative braking performance of the dynamometer.

In real-world application, the operation of the bidirectional chassis dynamometer starts when the driver engaged the acceleration pedal to accelerate the VUT, according to the speed trace display on a Driver's Aid Screen. To simulate this, a predefined variation of voltage is supplied to the DC motor, as shown in the left side of Figure 2. The predefined voltage shape is chosen to directly resemble the real-world speed trace. As a result, the speed of the simulated VUT is identical to the speed trace on Driver's Aid Screen.

DC motor coupled with PADU's DC machine yields a variable voltage supply to the half bridge bidirectional DC-DC converter. Half bridge topology has been chosen because less complexity and simple for bidirectional power transfer. This topology is using hysteresis current control method for controlling power transfer of bidirectional chassis dynamometer where the inductor, I_L as control signals of current changes. The direction of current flows from PADU's DC machine to the Battery is in Buck Mode while current flows from battery to PADU's DC machine are in Boost Mode. In Buck Mode the bidirectional DC-DC converter transfers power from PADU's DC machine to the Battery. Meanwhile power is transfer from the Battery to the PADU's DC machine when PADU's DC machine demands an energy to turn as motor. Summary of bidirectional chassis dynamometer mode with acceleration pedal variation is tabulated in Table 1.

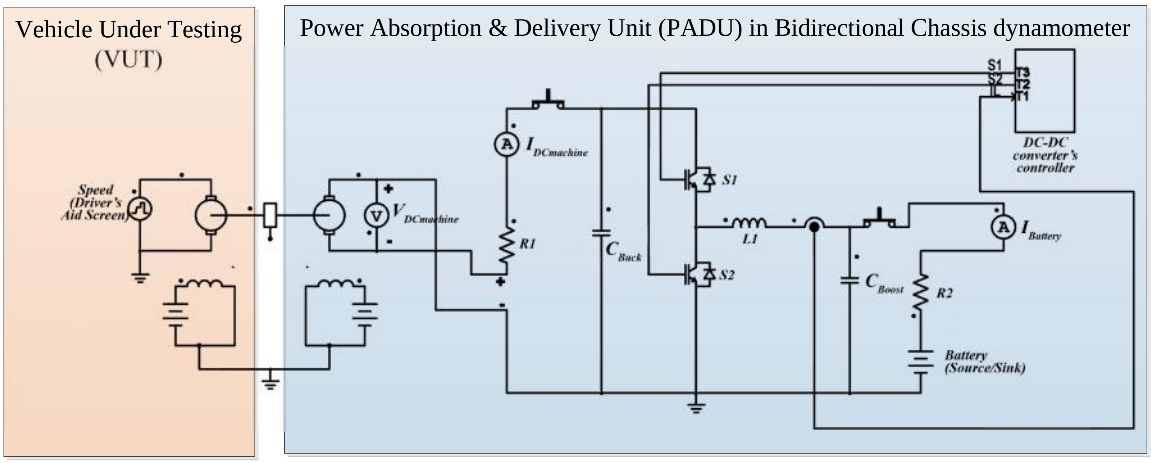
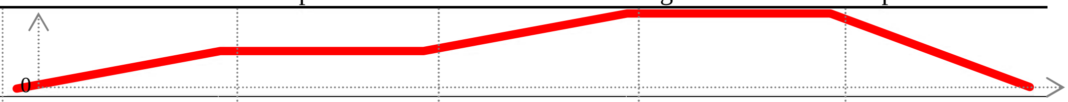


Figure 2. Half-Bridge bidirectional DC-DC converter topology on chassis dynamometer

Table 1. Classifications of mode operation for each section according to the acceleration pedal level

Acceleration Pedal					
Mode	Mode 1	Mode 1	Mode 1	Mode 1	Mode 2
PADU	Absorbing power from VUT	Absorbing power from VUT	Absorbing power from VUT	Absorbing power from VUT	Delivering power to VUT
VUT	Motoring	Motoring	Motoring	Motoring	Regenerative braking
DC Machine	Generator	Generator	Generator	Generator	Motor
DC-DC converter	Buck	Buck	Buck	Buck	Boost
Power source/sink	Sink	Sink	Sink	Sink	Source

4.2. Results of Performance Test Sequence

Simulation performance of the bidirectional chassis dynamometer with PADU is carried out using PSIM. The inductor, resistance and IGBT are not considered in this simulation. For the proposed half bridge bidirectional DC-DC converter topology input voltage is consider as variable from PADU's DC machine while the Battery voltage is fixed to 30V. Figure 3 shows two performances test sequence is available, which is Mode 1 and Mode 2. The slope of the speed and current (power) of VUT and PADU is the main test parameter of the bidirectional chassis dynamometer. Mode 1 operation is labeled as A in Figure 3. Mode 1 in region A indicates when the acceleration pedal is pressed and the brake pedal is disengaged. During this, speed from DC motor prime mover is increased consequent from level acceleration pedal pressed. Regarding the *Speed* performance in Figure 3, it should be noted that $I_{reference}$ is take part as reference at the bidirectional DC-DC converter controller for control current flows during Mode 1 and Mode 2 from the *Speed* trace. Meanwhile, the *Speed* response during Mode 1 is simultaneous with $I_{reference.}$ This simulation is observing the power performance of bidirectional chassis dynamometer, however current performance is analyzed for perceive the power flows. Mode 1 still occurs at A1 as delays before achieve to Mode 2.

As expected, $I_{DCmachine}$ shows the performance of current is opposite the results from $I_{reference}$. This occurs when DC machine turn as generator resulting $I_{DCmachine}$ in negative value while VUT's in motoring mode. DC machine emulates VUT's speed thus generating input voltage for bidirectional DC-DC converter. $I_{DCmachine}$ flows through half bridge bidirectional DC-DC converter to be stored at the Battery right side of PADU. The Battery is charging during interval A in Mode 1. On the other hand, Mode 2 performance is shown at interval B (trace) where the performance is exactly as Mode 1; slope is opposite between $I_{DCmachine}$ and $I_{reference}$. Mode 2 starts when the acceleration pedal is released. After $I_{reference}$ signal is approaching zero to negative values, Mode 2 is activate. During this situation, the Battery is discharging and power transfer is change opposite Mode 1. According to Figure 3, $I_{Battery}$ plotted at positive value to transfer current from the Battery to PADU's DC machine. $I_{DCmachine}$ approaches to zero earlier than $I_{reference}$ resulting from *Speed* performance to test regenerative braking from VUT.

It was observed that, for bidirectional chassis dynamometer, the performance of VUT is exactly as that of the chassis dynamometer. The main purpose of this investigation is to emulate road condition during testing of EV with the ability to test regenerative braking of EV.

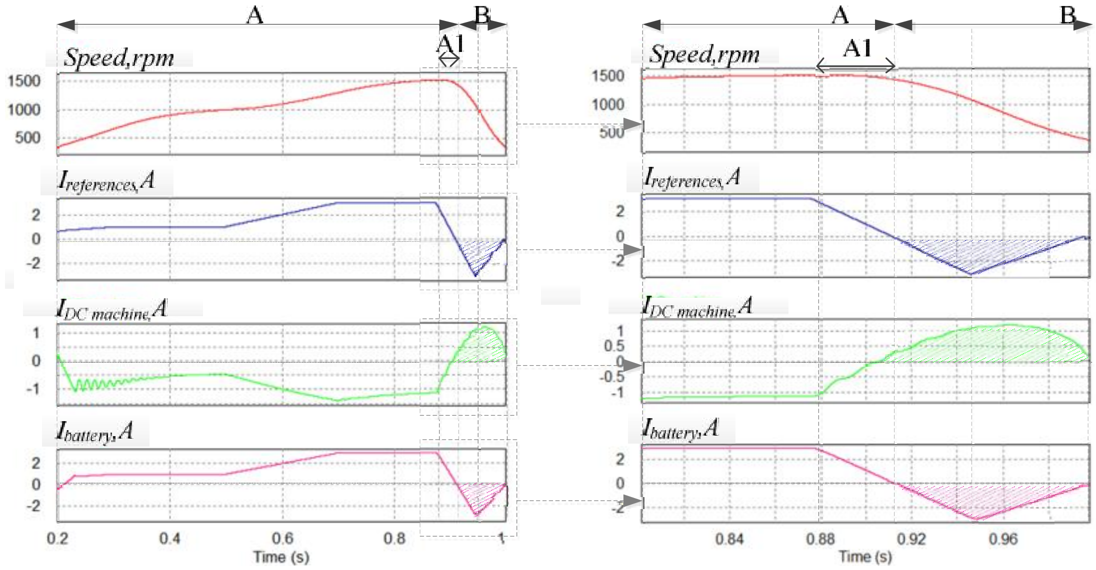


Figure 3. Simulation results during motoring and regenerative braking at controller with enlarged figure at regenerative braking interval.

5. DISCUSSION

As presented above, the performance of Mode 1 and Mode 2 of bidirectional chassis dynamometer power transfer is to vary the capability of regenerative braking of EV at VUT as well as the road load condition. Hence, it can be concluded that the performance of the bidirectional DC-DC converter is important to controlled DC machine emulates VUT performance with bi-direction power transfer. Also, it is observed that drive cycle is change with $I_{reference}$ to measured power performance is applicable and variation between $I_{reference}$ and $I_{DCmachine}$ in bidirectional DC-DC converter is satisfactory. On the other hand, the bidirectional chassis dynamometer significant to be perform than the conventional chassis dynamometer for measuring others than ICE due to the capability to testing regenerative braking which available in HEV and EV.

Based on the investigation, the study is classified as conventional chassis dynamometer and bidirectional chassis dynamometer. The testing method for both types of chassis dynamometer type is listed in Table 1; included in the table are the testing method parameters for accelerating test and braking test. Also, the chassis dynamometer achieves the power performance during regenerative braking test as a result of using the bidirectional dc-dc converter.

Table 2. Classification methods of conventional and bidirectional chassis dynamometer test

	Conventional dynamometer	Bidirectional chassis dynamometer
Testing Methods	Constant vehicle (horizontal speed) test Power/torque measurement -	Constant vehicle (horizontal speed) test Power/torque measurement Regenerative braking test
Acceleration Test	Load or flywheels attached works to emulate dynamometer speed similar to road condition.	Current direction is change by bidirectional dc-dc converter to emulate dynamometer speed similar to road condition.
Inertia	Inertia from drum and flywheel.	Inertia from drum, flywheel and additional force from positive-torque from DC machine.

Despite the advantages offered by bidirectional chassis dynamometer, further research is needed to improve performance and overall control and management of the chassis dynamometer. In addition, to improve braking on dynamometer drum, precautionary measure is needed while conducting the regenerative braking test.

6. CONCLUSION

This paper has investigated certain practical challenges that are associated with the regenerative braking of a modern chassis dynamometer. In the study, the results obtained has showed that the performance of the chassis dynamometer present a significant sequence due to the motoring and regenerative braking mode covered on bidirectional dc-dc converter control. The power performance is influenced by the force applied. The application presented in this paper proposes that significant benefits may be achieved by utilizing chassis dynamometer with bidirectional dc-dc converter as controller for regenerative braking tested capability. The model based on the bidirectional dc-dc converter is an effective and practical method for testing the capability of chassis dynamometer in investigating the regenerative braking from EV present in the conventional chassis dynamometer. Further research is required in attempting to increase the capability and performance of bidirectional chassis dynamometer.

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