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Theoretical and Experimental Analysis on Energy Consumption of Electric Two wheelers with Indian Drive Cycle

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Abstract—*Electric two-wheelers (E2Ws) have become an increasingly popular mode of transportation in India due to their cheap operating costs and zero emissions. As the number of E2Ws on Indian roads increases, for comparison, it becomes necessary to investigate their energy consumption under a standard driving cycle. Reference test scooters available in the Indian market were theoretically and experimentally examined for their energy consumption on IDC in the present paper. The kerb weight, battery capacity, motor capacity, and projected area of the reference test E2W vary, although theoretical findings show a marginal difference of 3.89% in Wh/km for 16.5% difference in weight. Furthermore, test vehicles were subjected to 5 sets of experiments using a chassis dynamometer under the identical IDC. Portable data-acquisition equipment was utilized to test and investigate the energy consumption of E2Ws. Even with the energy consumption pattern matching theoretically, the practical findings indicated substantial variance when compared to the theoretical. The energy consumption of the reference test vehicle with central drive matched theoretical estimates, although there was a deviation in the idle section. In contrast, the instantaneous maximum energy consumption in the test vehicle with flexible drive was more than predicted.*

Total energy consumption was determined to be 34.2 ± 1.87 Wh/km with multiple iterations, with 34.1% deviations from theoretical estimates.

This paper provides a consistent and standardised technique for measuring and comparing the energy consumption of several E2Ws models, emphasising the need of taking energy consumption into account when choosing between different E2Ws.

Keywords: *Energy Consumption, Electric Two Wheelers, Indian Driving Cycle (IDC)*

INTRODUCTION

The road presence of electric two wheelers has increased due to many factors such as government subsidies [1]. Another reason for that is increased competition in electric two wheelers, companies try to compete in market by offering features like high battery capacity, connectivity features, good performance etc.

Electric vehicles (EVs) have been hindered by the high prices primarily attributed to battery production costs. However, a recent study indicates a promising trend in the Indian kWh battery production, suggesting that it will soon reach the global average.[2]

This study provides comparative analysis of theoretical and experimental energy consumption of electric two wheelers. 3 different test vehicles were used for this study.

Standard Drive cycles are crucial for any comparative study as they give standard to compare different vehicles. Several DCs are currently in use, including the Indian Drive Cycle (IDC), the New European Drive Cycle (NEDC), and the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) [3]. These drive cycles simulate real-world driving conditions and consist of specific driving patterns, speeds, accelerations, and decelerations. By subjecting EVs to these standardized drive cycles, manufacturers, researchers, and policymakers can evaluate and compare the performance and emissions characteristics of different vehicles. The Indian Drive Cycle (IDC) is specifically designed to represent typical urban and suburban commuting patterns in India. It takes into account factors such as traffic conditions, and driving behaviour specific to Indian road conditions. The IDC enables the assessment of EV performance and energy consumption in a controlled and reproducible manner.

This study focuses on comparison based on IDC i.e. Indian drive cycle as a standard drive cycle. *Table.1* give the details of operations, acceleration, speed, duration and cumulative time for standard IDC. *Fig. 1* Show the variation of velocity with respect to time for the standard IDC [4].

THEORETICAL ENERGY CONSUMPTION

The Indian Drive Cycle (IDC) has been selected as the benchmark driving cycle for evaluating electric two-wheelers. A velocity vs. time graph for the Indian driving cycle shown in *fig.1* indicates how the speed of a vehicle varies over time under normal Indian driving circumstances. Typically, the graph is made up of several segments that represent the various driving conditions that can be found on Indian roads, including urban traffic, highway driving, and congested areas. Due to variables including traffic congestion, stop-and-go circumstances, and fluctuating road conditions, the graph depicts regular variations in velocity. The slope or steepness of the graph represents the acceleration or deceleration rates that cars undergo during the various stages of the driving cycle.

By subjecting electric two-wheelers to the IDC, energy consumption pattern can be studied in a controlled and standardized manner. The evaluation process involves mathematically calculating the power consumption of electric two-wheelers based on the IDC parameters. This calculation takes into account various factors, such as aerodynamic force, rolling resistance, acceleration force and climbing force.

1. Aerodynamic Force (F_{aero}): The aerodynamic force is the resistance encountered by the vehicle due to its interaction with the surrounding air. It is calculated using the equation:

   $$F_{aero} = \frac{C_d \rho A V^2}{2} \qquad (1)$$

   Where, A is the frontal area of the vehicle, V is the velocity, Cd is the drag coefficient, and ρ is the air density.

   The aerodynamic force depends on the square of the vehicle's velocity and the aerodynamic characteristics of the vehicle design.

2. Rolling Resistance (F_{rr}): Rolling resistance is the force that opposes the motion of the vehicle's wheels as they roll on the road surface. It is influenced by factors such as tire type, tire pressure, and road conditions. The rolling resistance force can be calculated using the equation:

3.

   $$F_{rr} = \mu m g \qquad (2)$$

   Where, μ is the coefficient of rolling resistance, m is the mass of the vehicle, and g is the acceleration due to gravity.

4. Acceleration Force (F_{acc}): The acceleration force is the force required to accelerate the vehicle. It depends on the mass of the vehicle (m) and the desired acceleration (a). The equation for acceleration force is:

   $$F_{acc} = ma \qquad (3)$$

   During the IDC, the acceleration force varies as the vehicle accelerates, decelerates, or maintains a constant speed.

5. Climbing Force (F_{gra}): The climbing force is the force required to overcome a gradient or slope in the road. However, in the IDC, as it does not contain any gradients, the climbing force can be ignored.

To calculate the theoretical power consumption of the electric two-wheeler, the traction force at a discrete time interval of the IDC needs to be determined. This can be achieved by segmenting the IDC into one-second intervals and calculating the velocity at every second. The IDC consists of 108 seconds, and the total distance covered in one IDC cycle is approximately 658 meters.

Using the formulas mentioned above, the traction force at a discrete time interval of the IDC can be calculated by summing the aerodynamic force, rolling resistance force, and acceleration force:

$$F_{traction} = F_{aero} + F_{rr} + F_{acc} \qquad (4)$$

This represents the total driving force required by the vehicle during discrete time interval of the IDC.

Once the traction force at discrete time interval is determined, the power consumed by the vehicle can be calculated by multiplying the traction force by the corresponding velocity:

$$Power = F_{traction} \times \text{V}elocity \qquad (5)$$

To obtain the energy consumed per kilometre (Wh/km), the power in watts (W) is divided by

3600 (to convert from seconds to hours) and then divided by the distance covered in kilometres: Energy consumed per km (Wh/km) is given by:

$$\left(\frac{Wh}{km}\right) = \left(\frac{Power}{3600 \times Distance}\right) \qquad (6)$$

By following this method, it becomes possible to estimate the theoretical energy consumption of an electric two-wheeler based on the IDC. This calculation provides valuable insights into the energy requirements of the vehicle under specific driving conditions and serves as a benchmark for comparing and evaluating the energy consumption of different electric two-wheelers.

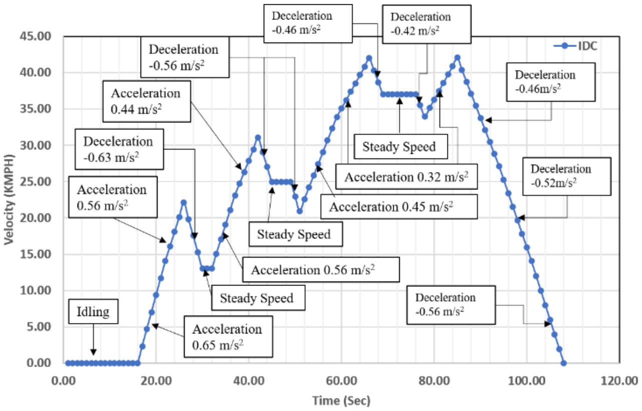

Figure 1: Indian Drive Cycle (IDC) Velocity vs Time

Table 1: Standard IDC

No. of operation		Acceleration (m/sec2)	Speed (Km/h)	Duration of each operation (s)	Cumulative time(s)
1	Idling	--		16	16
2	Acceleration	0.65	0-14	6	22
3	Acceleration	0.56	14-22	4	26
4	Deceleration	-0.63	22-13	4	30
5	Steady speed	--	13	2	32
6	Acceleration	0.56	13-23	5	37
7	Acceleration	0.44	23-31	5	42
8	Deceleration	-0.56	31-25	3	45
9	Steady speed	--	25	4	49
10	Deceleration	-0.56	25-21	2	51
11	Acceleration	0.45	21-34	8	59
12	Acceleration	0.32	34-42	7	66
13	Deceleration	-0.46	42-37	3	69
14	Steady speed	--	37	7	76
15	Deceleration	-0.42	37-34	2	78
16	Acceleration	0.32	34-42	7	85
17	Deceleration	-0.46	42-27	9	94
18	Deceleration	-0.52	27-14	7	101
19	Deceleration	-0.56	14-00	7	108

TEST VEHICLES.

Reference Vehicles T-1, T-2, and T-3 were used as benchmarks for the tests conducted in this research. Each vehicle possesses unique parameters that are critical in evaluating its energy efficiency, acceleration, handling performance, and driving range. *Table 2* highlights the elements such as mass, projected area, battery capacity, and claimed range. Open source image scanning software was employed to determine the projected area for each vehicle.Based on the references, the test vehicles' coefficient of drag is assumed to be 0.6 [5].

Mass:

The mass of Reference Vehicle T-1 is 133 kg, Reference Vehicle T-2 is 111 kg, and Reference Vehicle T-3 is 108 kg. Mass is an essential parameter that affects the amount of energy required to propel the vehicle, its acceleration, and overall performance. A lower mass generally results in better energy efficiency, acceleration, and handling performance.

Projected Area:

Reference Vehicle T-1 has a projected area of 0.33 m², Reference Vehicle T-2 has a projected area of 0.34 m², and Reference Vehicle T-3 has a projected area of 0.35 m². The projected area affects the aerodynamic drag force experienced by the vehicle, which can impact its energy efficiency.

Cd (Coefficient of Drag):

Reference Vehicle T-1, T-2, and T-3 all have a Cd value of 0.6. The coefficient of drag represents the aerodynamic efficiency of the vehicle. A lower Cd value indicates better aerodynamics, reducing air resistance and improving energy efficiency.

Battery Capacity:

The battery capacity of Reference Vehicle T-1 is 3.04 kWh, Reference Vehicle T-2 is 3.70 kWh, and Reference Vehicle T-3 is 3.24 kWh.

Battery capacity is a critical factor as it determines the amount of energy that can be stored and used to power the electric vehicle. A higher battery capacity generally allows for a longer driving range.

Claimed Range:

Reference Vehicle T-1 has a claimed range of 90 km, Reference Vehicle T-2 has a claimed range of 146 km, and Reference Vehicle T-3 has a claimed range of 150 km. The claimed range represents the distance that the vehicle manufacturer estimates the vehicle can travel on a single full charge, providing an indication of the vehicle's energy efficiency and ability to meet the user's driving needs.

Table 2: Test Vehicles Parameters

Parameters	**T1**	**T2**	**T3**
Mass (Kg)	131-135	109-113	106-110
Projected Area(m^2)	0.33	0.34	0.35
Cd (co-efficient of drag)	0.6	0.6	0.6
Battery Capacity(kwh)	3.04	3.7	3.24
Claimed Range(km)	80-95	135-150	140-155

EXPERIMENTAL METHODOLOGY

The experiment conducted for this research aimed to assess the energy consumption and performance characteristics of two reference vehicles using a Chassis Dynamometer. The Chassis Dynamometer provided a controlled environment for testing and allowed for the simulation of road load conditions and inertial values.

The experimental setup began with the calibration and coast down of the dynamometer. This process involved conducting tests with the vehicle and a rider to establish accurate baseline measurements and ensure that the dynamometer's performance aligned with real-world conditions. By accounting for the presence of the rider and the vehicle's weight, the dynamometer's readings could be calibrated to provide reliable results.

To replicate the road load conditions specified by the Indian Drive Cycle (IDC), an IDC profile was displayed on a screen positioned in front of the dynamometer setup. The IDC profile consisted of a series of speed and time intervals that represented the typical driving conditions of two-wheelers in India. Importantly, the IDC profile included prescribed error margins to account for minor deviations from the ideal path. The rider then operated the vehicle on the dynamometer, striving to replicate the path dictated by the IDC profile while staying within the specified error margins.

During the experiment, the vehicles were equipped with instrumentation to collect essential data for analysis. Current Transformers (CTs) were installed to accurately measure the battery pack's output voltage and current. The CTs provided valuable information regarding the electrical power consumption of the vehicles during the IDC simulation. Additionally, a Hioki Power Analyzer was utilized to measure and log voltage, current, and power characteristics at specific intervals.

To ensure precise measurement, the CT ratio and VT ratio of the instruments were set at 1 for both reference vehicles. This allowed for accurate conversion of current and voltage values into real-world units. The sampling rate of the data acquisition system varied between the reference vehicles. For Reference Vehicle 1, the sampling rate was set at 1 second, providing data points at regular intervals. For Reference Vehicle 2 and 3, a higher sampling rate of 50 milliseconds (ms) was used to capture more detailed information. To facilitate comparison between the vehicles, the data from Reference Vehicle 2 and 3 were interpolated using a MATLAB code to match the 1-second sampling rate of Reference Vehicle 1. This ensured consistent data resolution and improved comparability between the two vehicles.

The collected data, including voltage, current, and power measurements, were analysed to evaluate the energy consumption and performance characteristics of the reference vehicles during the IDC simulation. By examining the variations in power consumption, energy efficiency, and other parameters, insights into the vehicles' performance under standardized conditions could be gained.

The experiment was designed to provide comprehensive and accurate data on the energy consumption and performance of the reference vehicles during the IDC simulation. The detailed analysis of the instrumented data helps in assessing the efficiency and suitability of the electric two-wheelers in real-world scenarios, providing valuable insights for further research and comparison.

RESULTS AND DISCUSSION

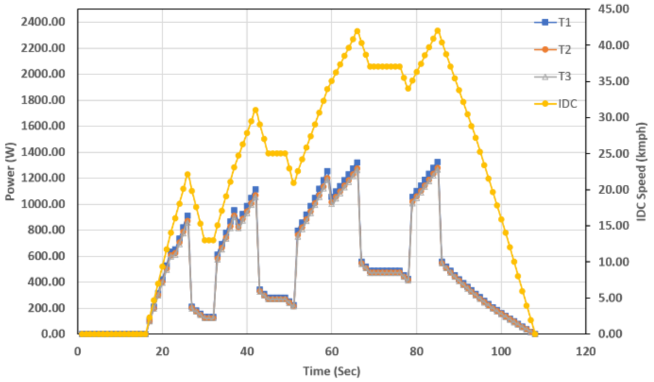

Figure 2: Theoretical power consumption for India dirve cycle (IDC)

The data for theoretical power usage are presented in the fig.2. Based on the corresponding power consumption rate, this data offers insights into the energy efficiency of various test vehicles during the Indian driving cycle.

The figure clearly depicts a strong correlation between power consumption and IDC velocity trend. As the acceleration in IDC increases, the power consumption also shows a corresponding increase, which is followed by a sudden drop in power consumed during deceleration. Intriguingly, changes in acceleration rates are found to result in two distinct power consumption rates at 60 seconds. Furthermore, the steady velocity in IDC is associated with a constant power consumption rate, indicating that power consumption increases with higher steady velocity. Theoretically Test vehicle 3 estimated better than the others by estimating less energy, at a rate of 21.71 Wh/km. Compared to test vehicle 3, test vehicle 1 estimated 4.97% more energy, and test vehicle 2 estimated 1.06% more energy.

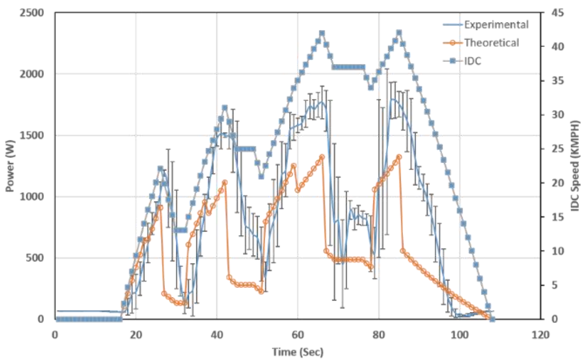

Figure 3: Power Consumption data for Test vehicle 1 comparison with theoretical estimate

The figure presented here (fig.3) provides a detailed comparison of the mean experimental power consumption rate, along with its standard deviation, with the theoretical power consumption rate for test vehicle 1. The results indicate that the experimental power consumption rate follows the expected trend, although it is noticeably higher than the theoretical estimate. Analysis of the initial 16 seconds of idling reveals that the experimental results show a higher power consumption rate, which can be attributed to the auxiliary load. This includes the head light, instrumentation cluster, fan, tail lamp, and other peripherals which are not included in the theoretical model for power estimation. Moreover, the theoretical model does not incorporate energy requirements based on the drive line losses, which explains why the experimental results exhibit higher values than the theoretical estimates. However, during steady velocity, the energy consumption rate drops similar to the theoretical estimate.

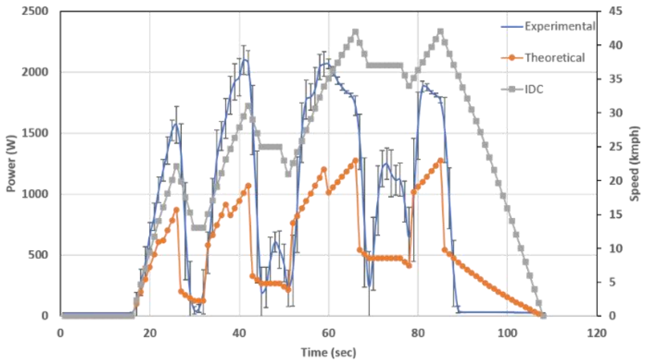

Figure 4: Power Consumption data for Test vehicle 2 comparison with theoretical estimate

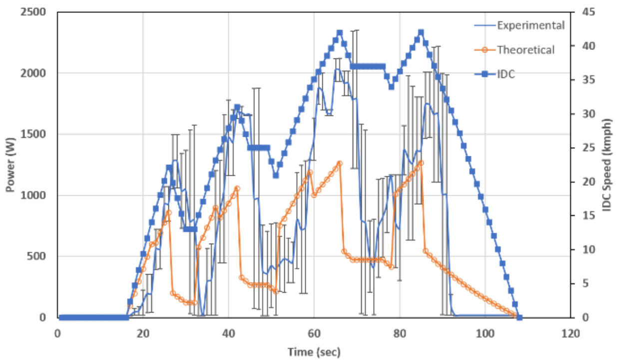

Figure 5: Power Consumption data for Test vehicle 3 comparison with theoretical estimate

The analysis of power consumption for test vehicle 2 and 3, as depicted in fig. 4 and 5, reveals similar trends as observed for test vehicle 1. However, there are noticeable differences in power consumption rates between the three test vehicles. Test vehicle 2 employs a flexible drive from motor to primary sprocket and another flexible drive to the wheel, which could be a factor resulting in higher power consumption. Additionally, in test vehicle 2, power is consumed at a higher rate for a given acceleration, after which it is matched based on the input. This is clearly evident at 80 seconds, where the experimental power consumption reaches its maximum level to achieve a higher speed, and then gradually decreases until the top velocity is achieved. This leads to greater acceleration and punchier ride quality but also costs more energy. In contrast, test vehicle 3 follows the opposite strategy to test vehicle 2, with a gradual acceleration profile resulting in energy savings. It is important to note that experimentation for each vehicle was conducted in their respective "ECO" mode. Overall, these findings highlight the influence of drive train configuration and driving strategy on power consumption rates, and underscore the need for careful consideration of these factors in vehicle design and operation.

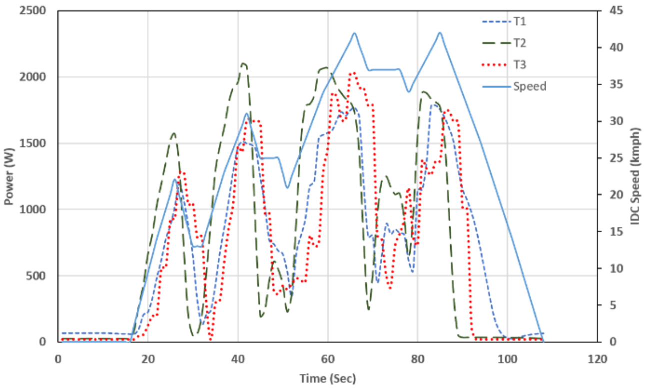

Figure 6: Power consumption of all 3 test vehicles with respect to IDC

resented above (fig.6) illustrates the comparison of power consumption among the three test vehicles discussed earlier in relation to the Indian driving cycle (IDC) speeds. It is evident that there are notable variations in the energy consumption profiles of these vehicles throughout the IDC. These variations can be attributed to the unique logic and characteristics of each vehicle, as they are individually tuned to serve different purposes. In this study, our primary focus is on analysing the energy consumption of these vehicles during their performance in the IDC.

Table 3: Results

Test Vehicle	**Theoretical Energy Consumption (Wh/km)**	**Theoretical Energy consumption adjusted for auxiliary power**	**Experimental Energy Consumption (Wh/km)**
1	22.79	25.88	34.27±1.87
2	21.94	25.03	35.88±0.73
3	21.71	21.71	32.06±1.04

The experimental energy consumption rates for the test vehicles revealed that test vehicle 3 exhibited the lowest energy consumption, while vehicle 1 demonstrated a 7% higher consumption rate, and vehicle 2 displayed an 11.7% higher consumption rate. These variations in energy consumption can primarily be attributed to the distinct performance tuning of each vehicle. Notably, vehicle 2 was tuned for higher acceleration, whereas vehicle 3 was tuned for more gradual acceleration. Additionally, the differences in powertrain arrangements and auxiliary systems among the vehicles contributed to the observed variations between the theoretical and experimental energy consumption values. The theoretical energy consumption values adjusted for Aux loads differed by 24.4%, 30.2%, and 22.6% from the corresponding experimental values for test vehicles T1, T2, and T3, respectively which is also shown in *fig.7*.

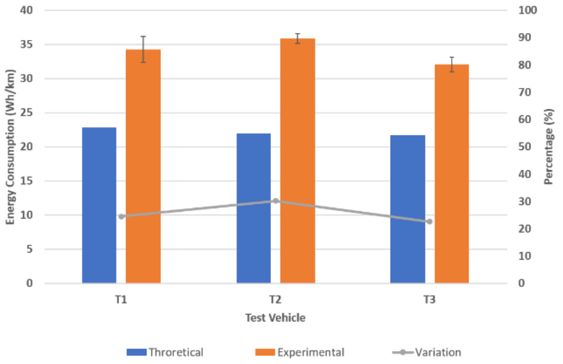

Figure 7: Theoretical and Experimental Variation

CONCLUSION

The analysis of energy consumption during the Indian driving cycle (IDC) for the three test vehicles provided valuable insights into their performance and efficiency. Test vehicle 3 demonstrated the lowest energy consumption, indicating its superior energy efficiency compared to vehicles 1 and 2. The variations in energy consumption among the vehicles were primarily attributed to their unique performance tuning, with vehicle 2 optimized for higher acceleration and vehicle 3 prioritizing gradual acceleration. Furthermore, the variations between the theoretical and experimental energy consumption values were influenced by factors such as powertrain arrangement and auxiliary systems. The adjusted theoretical energy consumption values exhibited notable differences from the corresponding experimental values for all three vehicles. These findings underscore the importance of considering vehicle-specific characteristics and configurations when evaluating energy consumption, thereby enabling the development of optimized vehicle performance and enhanced energy efficiency in real-world driving scenarios. Future research in this area should focus on creating a close to real mathematical model to estimate the energy consumption with least variation, thus saving cost and time required for the extensive testing.

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