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Feasibility Based Design of Hybrid Electric Vehicles for Public Transportation in the Philippines

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***Abstract*— The research is about the feasibility of adopting a novel parallel-series hybrid drive train for public transportation in the Philippines. The drive train will initially be designed to meet the performance requirements of existing public utility jeepneys. The design will then be evaluated against both a technical and an economic feasibility criterion. The technical criterion includes simulating the performance of the hybrid vehicle in the context of local PUV drive cycles, to arrive at estimates of fuel economy, battery requirements and refinements in gearing, motor and engine sizing. The economic feasibility will then be analyzed based on potential fuel savings checked against current fuel prices, prevailing interest rates, operating routes and schedules, maintenance costs and the market prices of the power train components. Discussion of the feasibility of the hybrid PUV will include possible changes in the design, acquisition, and operation of the drive train. Mentioned also are the implications on individual driver income, national economy, environment, and local industries.**

Keywords— parallel series hybrid, public transportation, feasibility, total cost of ownership, life cycle analysis

1. INTRODUCTION

The Philippines consumes over 300,000 barrels of oil per day. [1] Almost two thirds of this is guzzled down by the transportation sector. Statistics also show that over 80% of vehicle-kilometers-travelled (VKT) are borne by buses and jeepneys in the country [2]. Given that the amount of fuel energy consumed is proportional to the distance travelled and the weight of the payload, the public transportation sector would easily comprise the biggest chunk of fuel consumption in the country. Any viable technology that would reduce the amount of fuel consumed and improve the efficiency of oil usage would be extremely important. The impact would be so pervasive, including the nation's dependency on imported fuel, the quality of the environment, growth of new supporting industries for transportation, increased income to bus and jeepney operators and drivers, and even the market prices of local agricultural products.

This paper does not discount other modes of public transportation. Mass rail transport and electric vehicles already have a strong presence in the Metro Manila area. Technically, better use of rail and electric vehicles over conventional buses and jeepneys would be very beneficial. However, the current number of commuters already cannot be accommodated by current train services. While efforts are made to expand the capacity of the train systems, it could only be up to a certain extent, and be very expensive. Buses and jeepneys would still be needed to transport the majority of commuters. They would also be needed to service the huge network of transport routes where rail lines cannot go. While electric jeepneys can have flexible routes, they are limited to shorter inner city routes. Current electric jeepney operators are also reported to have sustainability issues. Trains, buses and jeepneys all have their roles in public transportation. Hence, alongside developments in rail and electric vehicles, improvements for buses and jeepneys are not only relevant, but should be considered as part of any comprehensive plan for public transportation. [3]

This research is about the feasibility of adopting a novel parallel-series hybrid drive train for public transportation in the Philippines. Specifically, the study starts with analyzing the performance requirements of public utility jeepneys (PUJs), that operate in metropolitan areas. Then, a new hybrid drivetrain will be designed around these requirements. The design will then be evaluated against both a technical and an economic feasibility criterion.

2. HYBRID TECHNOLOGY

A hybrid vehicle is roughly defined as a vehicle that utilizes different energy sources.[4] The most common example of a hybrid vehicle uses an internal combustion engine and an electric motor. Other energy sources such as solar, fuel cell, hydrogen, LPG, CNG, etc may be considered as hybrids when combined with electric power. The most ubiquitous examples of hybrids are diesel-electric locomotives. Hybrid technology is an established technology already seen in cars, trucks, buses, locomotives, motorcycles, ships, and submarines.

There are several types of hybrid vehicle configurations. As a baseline, a hybrid vehicle will be compared to an electric vehicle (EV). An EV is a vehicle whose only energy source on the road is a battery. The battery powers an electric motor that drives the wheels. Electric vehicles are already being used for public transportation in the Philippines in the form of electric mini-jeepneys and tricycles. The main disadvantages of using electric vehicles are the current lack of infrastructure for battery charging, long charging time and the high cost of batteries. While these three disadvantages can be delicately balanced, EV owners and operators would have to compromise by having at least one of the following setbacks: high initial cost, high recurring cost, limited driving range, and/or poor vehicle performance.

As a comparison, the first kind of hybrid vehicle was a series hybrid configuration. Similar to an EV, a battery delivers energy to a motor which drives the wheels. However, an internal combustion engine (ICE) is connected to a generator that can replenish the battery. The ICE acts as a range extender allowing for fewer required batteries. Despite its simplicity, a series hybrid suffers from energy conversion losses that cascade from the engine to the generator to the battery to the inverter to the motor. [5] It also requires a large motor to solely drive the vehicle.

In contrast, a parallel hybrid configuration has both an ICE directly driving the wheels like a conventional car, and a small-to-medium size electric motor. While this minimizes energy conversion losses, the speed control of the motor tends to be complicated, and engine operation is inefficient.

3. PROPOSED HYBRID DRIVETRAIN

This study is about the implementation of the third kind of hybrid configuration, the parallel-series hybrid. Also called a power-split hybrid, part of the mechanical power from the engine is directed to the wheels, and the rest toward an electric generator, as shown in Figure 1. The generator charges a battery which, in turn, powers an electric motor that also drives the wheels. Hence, the engine and motor provide complementary power to the wheels like a parallel configuration, while the engine-generator-battery-motor sequence behaves like a series hybrid.

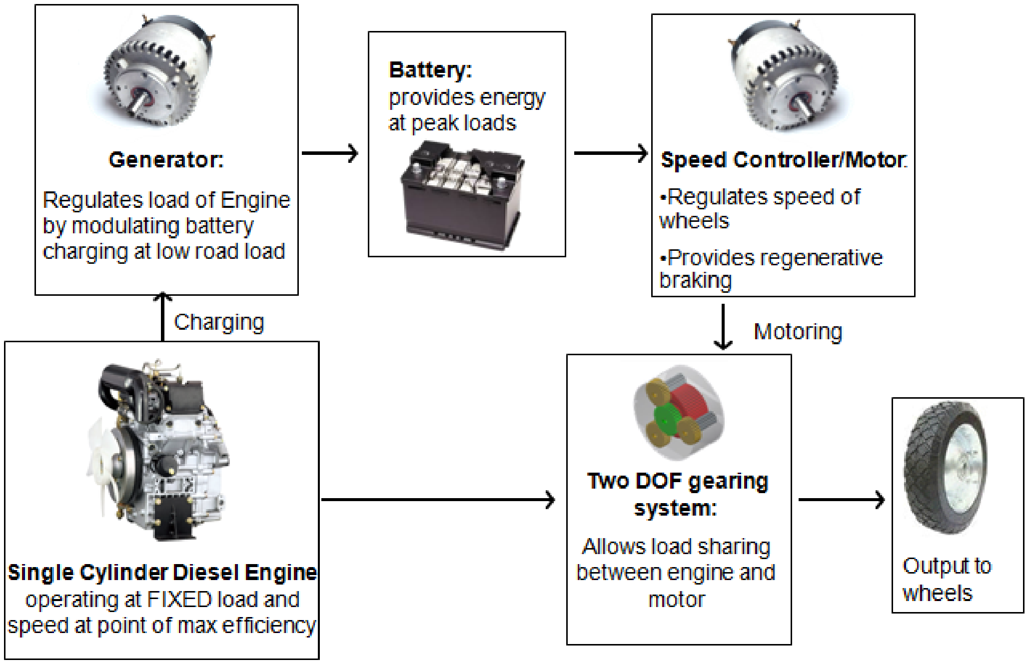

Figure 1. Proposed Parallel-Series Hybrid Drivetrain

The initial design for the drivetrain will be for a jeepney of approximately 3000kg of gross vehicle weight. This kind of vehicle can carry 20 passengers plus the driver. The typical jeepney would have a conventional internal combustion Diesel engine delivering up to 65kW. [6] According to the Philippine PUV drive cycle, developed by the UP National Center for Transportation Studies, jeepneys achieve a typical top speed of 46 kph. Shown in Fig. 2 is the Philippine PUV drive cycle showing the vehicle speed versus time. As a matter of comparison, also shown are the Japanese 10-15 drive cycle (Fig. 3), the US Highway Fuel Efficiency Test drive cycle (Fig. 5) and a drive cycle derived from local jeepneys servicing the University of the Philippines, Diliman campus (Fig 4).

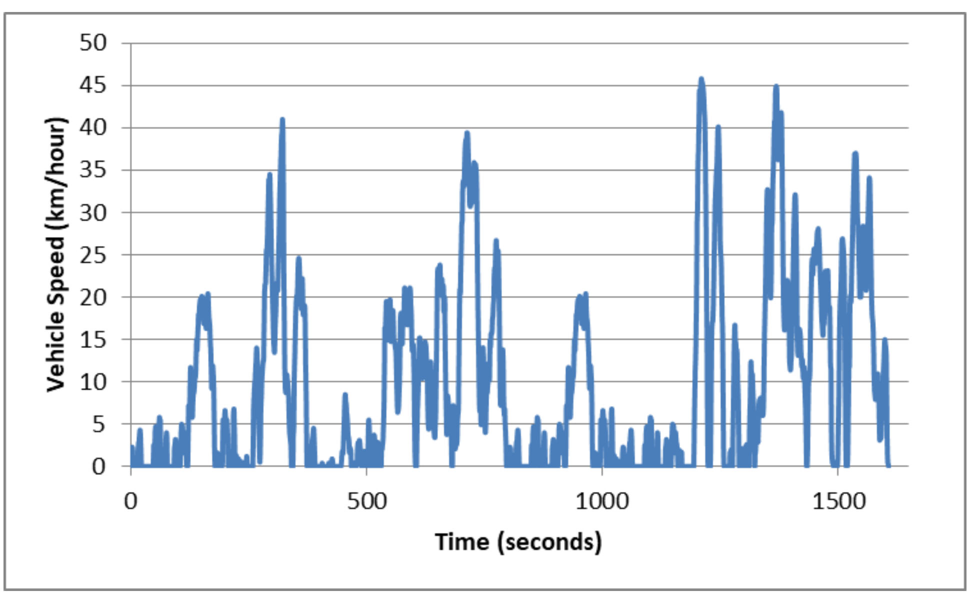

Figure 2. Philippine Public Utility Vehicle Drive Cycle by the UP NCTS

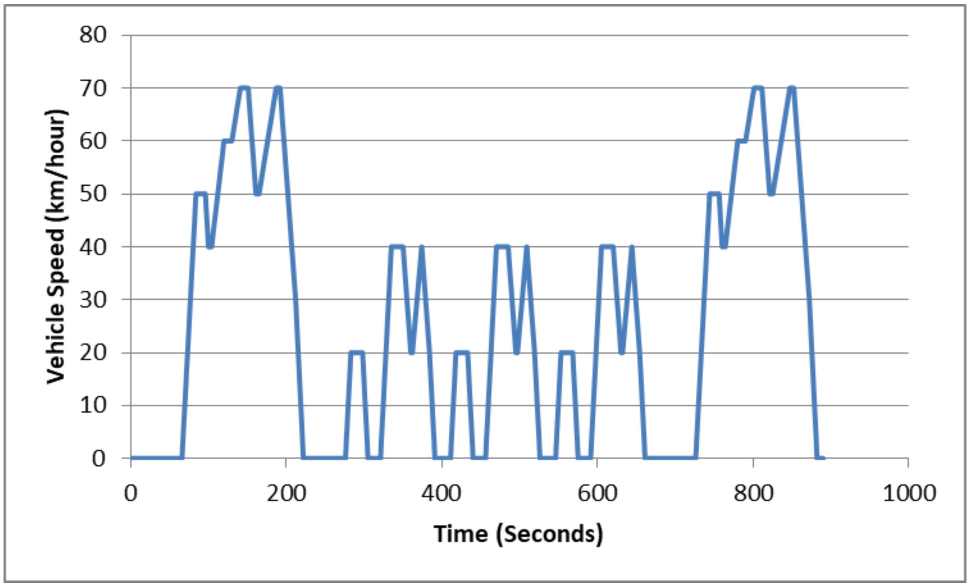

Figure 3. Japanese 10-15 Drive Cycle

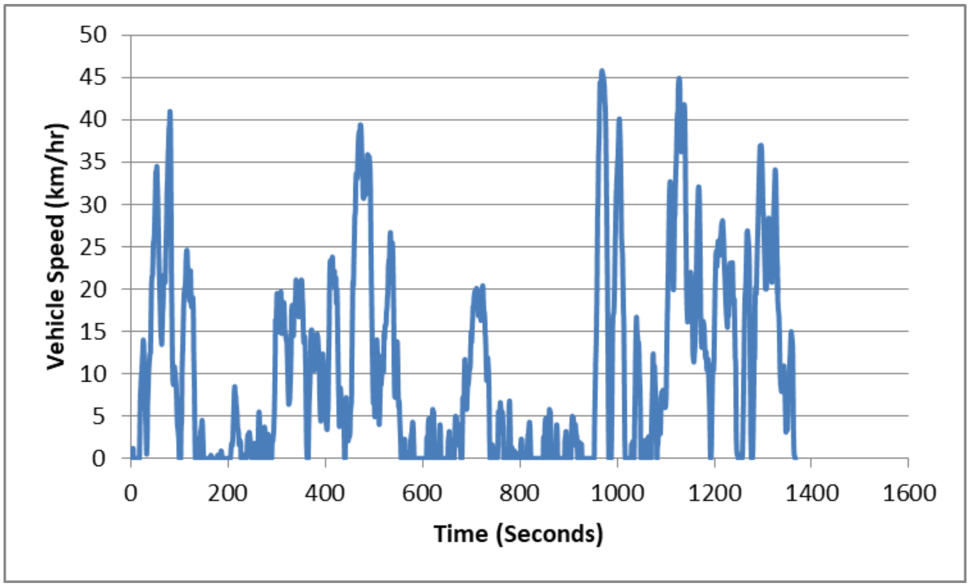

Figure 4. PUV Drive Cycle in UP campus

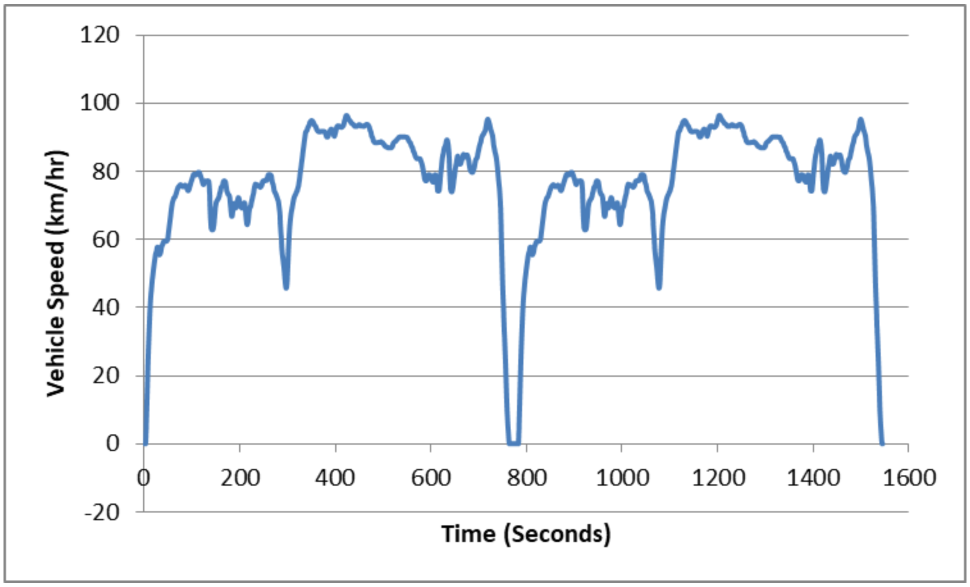

Figure 5. US Highway Fuel Efficiency Test

Unlike most hybrid drivetrains available in the market, the proposed parallel-series hybrid drivetrain will only require a much smaller engine. The remaining power needed will be delivered by larger electric motors. The theoretical engine size needed to complete the PUV drive cycle would correspond to the average power across the entire cycle. The drivetrain design takes advantage of the long periods of idle or low speed operation within the PUV drive cycle to use the excess engine capacity to charge the batteries. Conversely, when the power demanded is greater than the engine power, energy is taken from the batteries to drive the motors.

To compute for the power requirements, the following equations are combined with the given vehicle parameters and acceleration and speed values according to the drive cycle.

$$Motor\ Power - Losses = (Rolling\ Resistance + Drag\ Force + mass \times acceleration) \times Speed \qquad (1)$$

Rolling resistance is computed by

$$Rolling\ resistance = Cr \times g \times m \qquad (2)$$

where Cr is the coefficient of rolling resistance approximated to 0.15, and m is the gross weight of the vehicle estimated a 3000kg. Aerodynamic drag forces are computed by

$$Drag\ force = \frac{1}{2} \times \rho \times Cd \times A \times V^2 \qquad (3)$$

where ρ is the density of air, Cd is the coefficient of drag, and A is the frontal area the vehicle. The speed and acceleration of the vehicle will be based on the drive cycle data. With a top cruising speed of 45.8 kph, the maximum road load is 50.9kW. In contrast, the average power needed to follow the Phil. PUV drive cycle is theoretically only 3.8kW. Shown in Table 1 are the characteristics of other drive cycles. Note that a lot more power is needed for steady high-speed driving for the HFET drive cycle.

Table 1. Power Requirements of Various Drive Cycles

Drive Cycle	Top Speed	Average Speed	Average Power Needed
Phil. PUV Drive Cycle by UP NCTS	45.8 kph	10.6 kph	3.8 kW
US Highway Fuel Efficiency Test	96.4 kph	76.9 kph	23.1 kW
Japanese 10-15 Test	70.0 kph	25.6 kph	7.8 kW
Jeepneys within UP Diliman campus	37.8 kph	14.3 kph	4.4 kW

The 3.8-4.4 kW range is the theoretical average power needed jeepney drive cycles. Considering conversion losses plus load from the brakes, auxiliary systems, it is recommended to use the smallest 2-cylinder Diesel engine available. Hence, a Changchai EV80 790cc engine was proposed. While rated at 14kW at 3600rpm, manufacturer's data shows that the most fuel-efficient operating point for the engine would only be at 2400 rpm with a torque of 45 N-m, a power of 11.3kW, and a brake-specific-fuel-consumption (BSFC) of 235 g/kWh (Fig. 6).

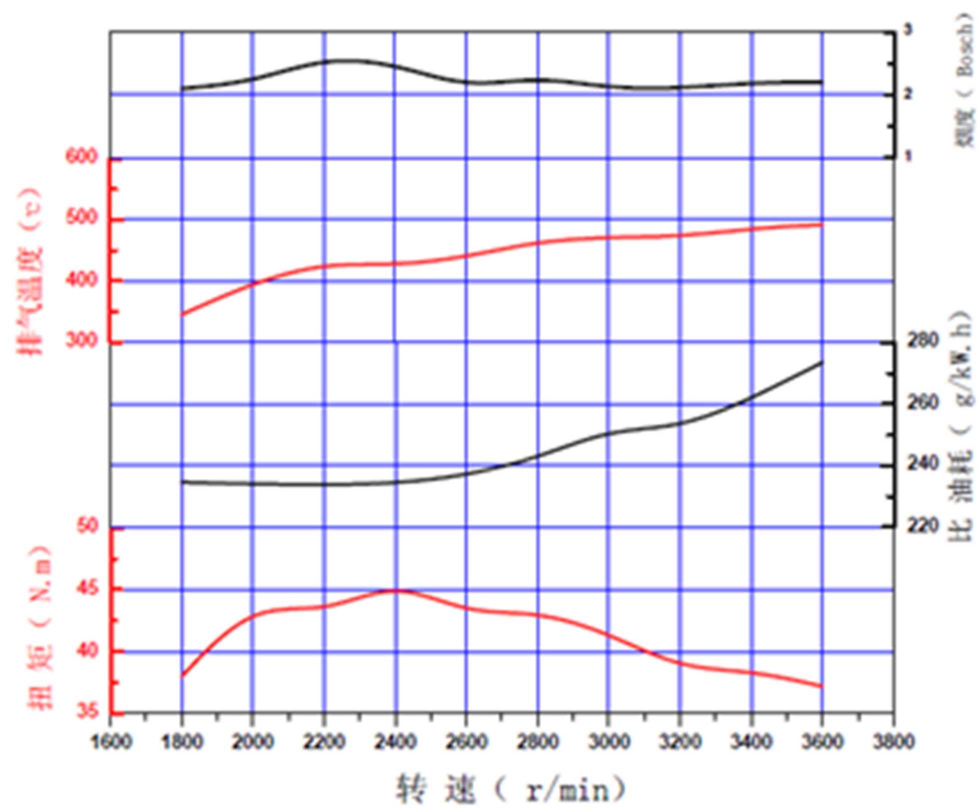

Figure 6. Engine Characteristics

The engine would be coupled to a Motoenergy ME1004 DC motor. Running as a motor or generator at 48volts, it can deliver or absorb 15.9 kW of peak power. This will serve as the speed controller to the engine by channeling surplus engine power to charge the batteries when road load demand is low. When the road load demand is high, this motor will provide additional mechanical power and prevent the engine speed from dropping . Two more similar motors coupled in tandem will serve as the variable-speed main drives. This would give a total drivetrain capacity of 59.1 kW of power and 410 Nm of torque. This is comparable to the engines typically used by jeepney, that are in the 55~65kW power range.

4. FEASIBILITY CRITERION

The design will then be evaluated against both a technical and an economic feasibility criterion. The technical criterion includes simulating the performance of the hybrid vehicle in the context of local PUV drive cycles, to arrive at estimates of fuel economy, battery requirements and refinements in gearing, motor and engine sizing. The economic feasibility will then be analyzed based on potential fuel savings checked against current fuel prices, prevailing interest rates, operating routes and schedules, maintenance costs and the market prices of the power train components.

5. TECHNICAL FEASIBILITY

After the drive train components have been sized, the entire drivetrain will be simulated against PUV drive cycles. The reference cycles would be the Philippine PUV drive cycle developed by the UP National Center for Transportation Studies, and the Ikot Jeep route travelled within the University of the Philippines, Diliman campus. It is noteworthy that, while both cycles were patterned after jeepney behavior, the campus route has a higher average speed and farther daily travel.

The simulation of the fuel economy of the hybrid vehicle will require knowledge of the battery storage capacity. Using the total of 48 kW of peak motor power at 48 volts, AGM-type batteries should be able to provide the necessary ampacity if battery banks of at least 124 ampere-hours are used. This gives a total storage capacity of about 10,700 kJ. More batteries will allow longer operations under full electric mode, but at a higher weight and recurring cost. Shown in Figure 7 is the graph of the State-Of-Charge (SOC) of the batteries simulated against several iterations of the drive cycle. Included in the graph are the power output (kW) of a conventional engine with a 4-speed transmission, and the power output of the engine in the hybrid setup. Shown in Table 2 is the power distribution between the engine-generator (E+G) and the motor (MG) at different speeds.

Other iterations were made including changing motor voltage to 72 volts, but resulted in the same number of batteries required. Engine power could be reduced, but would require bigger motors, or sacrifice acceleration and gradeability. The drivetrains for this simulation were sized to handle grades of 13%.

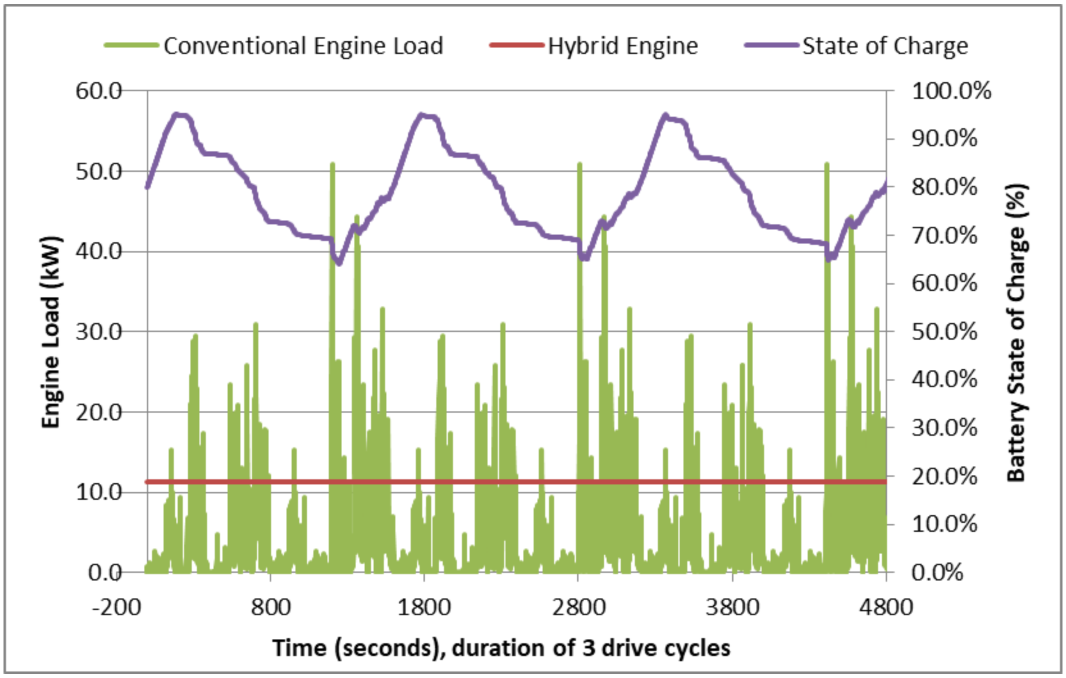

Figure 7. Comparison of Simulated Engine Load of Conventional and Hybrid Systems and Battery State of Charge for three concatenated PUV drive cycles

Based on the simulation, it was calculated that a conventional drivetrain applied to the PUV drive cycle would have a mileage of 6.37 km/L. Compared to the estimated mileage of 5.69 km/L by Vergel and Tiglao [7], the simulation differed by twelve percent. More importantly, the hybrid vehicle would have a simulated mileage of 9.52 km/L. Hence, approximately 49.3 percent fuel savings could be obtained. While this number is very encouraging and shows technical feasibility, the economic feasibility has to be examined to see if the technology should actually be adopted.

	Load	Output		Engine+Generator		Main Drive MG		E+G	MG	out	current
V car	P road	w shaft	T shaft	w sun1	T sun1	w MG	T MG	P s1	P c	P s2	@48v
kph	kW	rpm	Nm	rpm	Nm	rpm	Nm	kW	kW	kW	amp
0	0.0	0	0.0	2400	0.0	-2817	0.0	0.0	0.0	0.0	0.0
15	17.7	411	-410.9	2400	108.1	-982	92.1	27.2	-9.5	-17.7	166.2
30	35.3	822	-410.1	2400	107.9	853	91.9	27.1	8.2	-35.3	625.2
45	52.6	1233	-407.2	2400	107.1	2688	91.2	26.9	25.7	-52.6	1075.2
50	58.9	1371	-410.1	2400	107.9	3300	91.9	27.1	31.8	-58.9	1238.3

Table 2. Simulation of Power Distribution of Engine, Motor and Generator at Different Speeds with road slope

Table 3. Simulation of Power Distribution of Engine, Motor and Generator at Different Speeds with road slope

	UP Campus Drive Cycle	NCTS PUV Drive Cycle
Average speed	14.3 kph	9.64 kph
Max speed	37.8 kph	45.8 kph
Conventional drivetrain mileage	7.03 km/L	6.37 km/L
Hybrid drivetrain mileage	9.64 km/L	9.52 km/L
Difference	37.2%	49.3 %

6. ECONOMIC FEASIBILITY

The electric motors and controllers are the most expensive components in the drive train. If a 48volt system is used to reduce the number of motors needed, the total initial investment needed for the retrofit would be 124,500 pesos. If this were to be amortized for 3-years with a prevailing rate of 15.38% for bank loans, the PUV operator would have an additional 4,952.33 pesos a month of additional expenses.

We would also have to consider the recurring costs due to battery replacements. If we consider that the batteries are discharged only to a depth of 30%, AGM batteries are estimated to last up to 1800 discharge cycles. The hybrid cycles the battery around twice every hour. If the jeepney is operated 13 hours a day, 22 days in a month, this implies that the battery pack would have to be replaced 4 times a year. If one battery pack consists of three pieces of 12-volt, 42 ampere-hour AGM-type lead acid batteries, it would cost about 63,000 pesos every year. If we include additional cost of maintenance to the motors, we can conservatively round up the total recurring cost to 70,000 pesos a year. At a prevailing interest rate of 7.0 percent for 1-year loans, the monthly amortization would be 6,121.60 pesos. If we include the monthly amortization for the equipment investment, the jeepney operator would have to spend a total of 11,073.93 pesos per month for the implementation of the hybrid drive train.

Table 4. Initial Investment of Components

Engine (Changchai EV80 2cyl Diesel)	32,000 pesos
2x PMDC motors (Motoenergy ME1004)	52,500 pesos
2x motor controllers (Kelly KDZ72551)	40,000 pesos
Total Initial Investment for Retrofit (including fabrication)	**124,500 pesos**

Interest Rate	15.39%
Term	3 years
Monthly Amortization	**4,952.33 pesos**

Table 5. Recurring Cost due to Battery Replacement

Batteries (12pcs, 12-V, 42AH, AGM-type)	63,000 pesos
Maintenance (carbon brushes, etc)	7,000 pesos
Total Recurring Cost	**70,000 pesos**

Interest Rate	7.0 %
Term	1 year
Monthly Amortization	**6,121.60 pesos**

Table 6. Economic Comparison for Campus Jeepney Hybridization

	Conventional Drivetrain	**Hybrid Drivetrain**
Mileage (UP Campus Drive Cycle)	7.03km/L	9.64 km/L
Daily Travel	185.9 kilometers	
Monthly Travel	4089.8 kilometers	
Fuel Price	Assume 30 pesos/Liter	
Monthly Fuel Cost	17,452.92 pesos	12727.59 pesos
Operation	22 days/month @ 13hours/day	
Monthly Fuel Savings	4,725.33 pesos	
Monthly Amortization	11,073.93 pesos	
Monthly Net	-6,348.60 pesos (added cost)	

On the other hand, we would have to consider the effect of the fuel savings. For the UP Ikot and the NCTS drive cycles that were simulated on, there was an improvement in mileage of approximately 37.2% and 49.3% respectively. For the campus jeepney route, the average speed was higher. Hence, for the same 13-hour operation, a total of 185 kilometers could be travelled. Assuming a pump price of 30.00 pesos/L of Diesel fuel, the driver would normally spend 17452.92 pesos a month for a conventional engine jeep. However, the hybrid jeepney would only consume 12727.59 pesos worth of fuel a month, resulting in a savings in fuel equivalent to 4725.33 pesos a month. The monthly added cost to the jeepney operator is 6,121 pesos.

Table 7. Economic Comparison for Phil. PUV Drive Cycle

	Conventional Drivetrain	**Hybrid Drivetrain**
Mileage (NCTS PUV Drive Cycle)	6.37 km/L	9.52 km/L
Monthly Travel	2757.0 kilometers	
Fuel Price	30.00 pesos/Liter	
Monthly Fuel Cost	12,984.49 pesos	8,688.15 pesos
Operation	22 days/month @ 13hours/day	
Monthly Fuel Savings	4,296.34 pesos	
Monthly Amortization	11,073.93 pesos	
Monthly Net	-6,777.59 (added cost)	

For the NCTS PUV drive cycle, a 49.3% improvement in fuel mileage was seen. However, due to the lower average speed, the total distance travelled was only 125 kilometers in a day. With the same computation as before, the monthly fuel savings is only now 4,296.34 pesos. The monthly added cost to the jeepney operator is 6,777 pesos.

7. DISCUSSION

The differences in numbers are mainly due to the amount of fuel consumed by each route. The longer the distance travelled and the more fuel consumed, the greater is the potential fuel savings. Unfortunately, the current numbers do not seem economically viable for the typical jeepney driver.

On the other hand, there is a lot to be noted from this analysis. The first is the impact of fuel prices. While fuel prices are not expected to double soon, any increases in fuel prices make the argument for more fuel-efficient vehicles more relevant.

Economic reasons are not the only reasons for adopting hybrid vehicles. If we compare this particular hybrid powertrain model to existing commercial passenger hybrids, the difference in tag price would also outweigh the fuel savings that a hybrid car owner can accumulate in the life of his car. Instead, the other biggest selling point for hybrid vehicles is its impact on the environment. It is a bit difficult to quantify the exact value of reductions in tailpipe emissions. However, if 49% less fuel is burned every day by the public transportation sector, that much less carbon dioxide is released to the atmosphere every day.

Aside from trying to justify adopting this discouraging economic model, analysis should be done on finding how to make this hybrid drivetrain feasible. It was mentioned earlier that other transport routes that consume more fuel would be potential targets for hybridization. However, care must be taken to apply this hybrid scheme only for similar driving patterns. Highway driving would require more power due to the high speeds, but would not reap the benefits of hybrid drivetrains. This is because hybrid vehicles power their motor from the excess engine capacity which is typically wasting during bad traffic.

A better application of this hybrid drivetrain would be for inner-city buses. Metro Manila buses spend a lot of fuel stuck in traffic, while running their air-conditioners and driving slowly. While the motors and engines would cost proportionally more because of the greater vehicle weight, the fuel savings would also be a lot bigger. In addition, buses are typically operated 24 hours a day, 7 days a week, with just changeovers of drivers. For bigger motors and engines needed by heavier buses, the useful life is also expected to be longer due to their heavier duty construction. Amortization can be spread thru longer periods of time.

As of June 2016, a hybrid bus using this drivetrain design was recently developed in the University of the Philippines and is currently being evaluated for public transportation. Initial results show a hybrid bus mileage of 1.9 km/L versus 0.38~0.81 km/L of conventional buses in Metro Manila, according to a 2014 JICA study [8].

Another good way to make hybrid drivetrains like this economically feasible is to use cheaper locally-made mass-produced components. All of the components used in this model were imported, including the batteries. Economies of scale were not considered here. In contrast, the Philippines has a strong electronics industry, both in manufacturing and design and development. Recall that the controllers comprise over a third of the drivetrain. If the motor controllers were made locally, hybrid costs would be much lower.

8. CONCLUSIONS

The economic and technical feasibility of adopting a hybrid drivetrain were investigated. Despite achieving substantial fuel savings, the cost of acquiring and maintaining a hybrid powered jeepney would currently be too high. However, the environmental aspects of this hybrid upgrade are promising. While this has yet to be verified, the arguments presented here warrant continued research into adoption of fuel-efficient vehicles for public transportation.

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