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POWERTRAIN SIZING, POWER AND ENERGY MANAGEMENT OF 18 METERS SERIES HYBRID ELECTRIC BRT FOR METROBUS İSTANBUL

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ABSTRACT

The increasing demand for fuel economy and recent approaches for sustainable metropolitan cities has encouraged the introduction of innovative green propulsion systems in public transportation. The BRT's (Bus Rapid Transit) constitutes a great portion of the urban transportation in megacities like Istanbul. In this paper, a tailored approach to environmental friendly 18 meters series hybrid BRT for Metrobus. Istanbul is investigated from the driving cycle characterization, powertrain sizing, and power & energy management development perspectives. These studies were funded by Tubitak.

Keywords: Electrification of Transportation, Hybrid Electric BRT, Sustainable Mobility on Metropolitan Cities, Vehicle and Driveline System Analysis

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ÖZET

Metropol şehirlerde sürdürülebilirliğe yönelik yeni yaklaşımlar ve yakıt ekonomisine yönelik artan isterler, toplu taşımada inovatif, çevreye duyarlı araç teknolojilerinin kullanımını teşvik etmektedir. İstanbulun toplu taşımada en önemli paydaşlarından biri olan metrobüs de günlük sefer sıklığı ve araç filosunun büyüklüğü göz önünde bulundurulduğunda çevreci çözümlere yönelinmesi gereken bir alandır. Bu makalede metrobüs olarak kullanılacak olan çevreye duyarlı 18 m seri hibrit bir otobüs için yapılan çalışmalar yer almaktadır. Metrobüs hattının sürüş çevrimi karakterizasyonu, güç sistemlerinin boyutlandırılması, ön seviye güç ve enerji yönetimi geliştirilmesi detaylarıyla incelenmiştir. Bu çalışmalar Tubitak tarafından desteklenmiştir.

Anahtar kelimeler: Ulaşım için Elekrifikasyon, Hibrir Elektrik BRT, Metropol Şehirlerde Sürdürülebilir Değişkenlik, Araç ve Aktarma Organları Sistem Analizi

1. INTRODUCTION

Population is growing rapidly in metropolitan cities. This growth enlarges city territory to combine with outskirts and nearby towns to form mega-cities like Istanbul. In these mega-cities fast and efficient transportation becomes an important demand to provide sufficient life standard for the citizens.. . The environmental concerns and rising fuel costs have added another challenge and this resulted in an increased interest for alternative propulsion system deployment in transportation.

Metrobus is a 60 km bus rapid transit route in İstanbul, Turkey with 44 stations which follows the city's ring-road via Avcılar, Zincirlikuyu and the Boshporus Bridge to Söğütlüçeşme using dedicated bus lanes for much of the route [1]. There are 535 articulated bus in this closed system carrying 800.000 people daily. [2]. As the vehicles are traveling totally more than 250.000 km in a day , system should be highly efficient from all the perspectives to lower the cost of ownership and reduce harmful emissions.

The development of innovative technologies is oriented towards electrification of vehicle propulsion and auxiliary systems with the expectations of reduction in fuel consumption , harmful emissions , noise and maintenance costs.[3] For the metrobus application , electrification can provide all these advantages if the electric propulsion system is correctly sized to meet the restricted service time between the stations.

In this study, a series hybrid articulated bus is designed for Metrobus İstanbul because of the conceptual benefits of no range anxiety, satisfying performance, smaller battery size and much more economic engine operation compared to the conventional automatic vehicles. The brief content is; drive cycle characterization, identification of customer expectations, powertrain sizing and initial power/energy strategy development.

2. DRIVING CYCLE

Preliminary examination shows that “34: Zincirlikuyu - Avcılar” is the most difficult line in terms of passenger capacity, topography and service time as shown below;

a. Vehicles: Karsan , Mercedes Conecto - Citaro - Capacity , Phileas 18 meters articulated buses
b. Length of Cycle: 58.5 km
c. Commercial Speed: 39 kph
d. Service time: 90 minutes
e. Number of Stops: 27
f. Peak Hours: 07.00 – 09.30 , 16.00 – 19.00
g. Passenger Capacities: 155 -160 in peak , ~ 80 others
h. Topograpyh Profile: max slope:8%
i. Service Period: 16–18 hours in service , 1 hour from/to garage , 5–7 hours maintenance/rest
j. Max Speed between Stations: 70 kph
k. Min Speed between Stations: 55 kph
l. Braking Distance before Stations: 320 – 340m
m. Maximum Acceleration Rate: 1.4 - 2 m/s^2
n. Maximum Deceleration Rate: 1.4 - 2 m/s^2
o. Duration between Stations: 215s (max) / 50s (min)
p. Distance between Stations: 3400m (max) / 540m (min)
q. Idle at stations: 12-30sec

Regarding all these parameters, driving cycle is designated as shown in **Figure 1** to use in simulations. The reason behind of simplifying the cycle is easier repeatability and applicability of driving cycle for different vehicle, propulsion parameters, also it is suitable to semi-automated driving for future

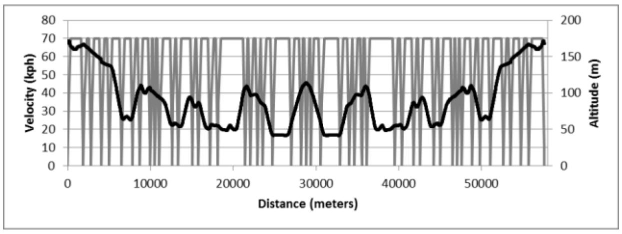

Figure 1. Driving Cycle (Distance- Velocity – Altitude)

3. SIZING OF ELECTRIC PROPULSION

3.1. Market Research

Table 1 shows the key specifications of the diesel buses operating in Metrobus line and also some hybrid and pure electric articulated buses. According to research, 200–260 kW propulsion power meets the general performance requirements of a bus with gross vehicle weight of 24-29 tones.

Table 1. Buses in Metrobus and Market Research [4]

Bus	KARSAN DIESEL	MERCEDES DIESEL	IVECO CITELIS HYBRID	VOLVO 7900 HYBRID	CITARO G HYBRID	SOLARIS URBINO HYBRID	SOLARIS URBINO ELECTRIC
Length (m)	18	18	18	18	18	18	18
GVW (kg)	28000	28000-29000	30000	29000	28000	24000	24000
Engine	10.5L MAN	12L MERCEDES	5.9L IVECO	5.1L VOLVO	4.8L MERCEDES	6.7L CUMMINS	NA
Emission Level	Euro V - VI	Euro V - VI	Euro V	Euro VI	Euro VI	Euro V	NA
Powertrain	Diesel	Diesel	Series Hybrid	Paralel Hybrid	Series Hybrid	Series Hybrid	Electric
Engine Power (kW)	235 to 265 Kw	220 to 260 Kw	210 kW	177 kW	160 kW	165 to 230 kW	NA
Engine Torque (Nm)	1600 to 1800 Nm	1250 to 1600 Nm	-	-	810 Nm	850 to 1100 Nm	NA
Electric Motor Power (Kw)	NA	NA	200 kW	120 kW	320 kW	264 kW	240 kW
Electric Motor Torque (Nm)	NA	NA	-	800 Nm	-	1424 Nm	-
EES Capacity (kWh)	NA	NA	Li-Ion 11 kWh	Li-Ion 4.8 kWh	Li-Ion 19 to 26 kWh	Li-Ion 11.4 kWh	Li-Ion 90 to 210 kWh

In order to compare net power on wheel for a conventional diesel and an electric powertrain, Figure 2 describes the power flow from motor/engine to wheel at maximum power and full auxiliary load. On-demand electric auxiliaries and single (only rear axle, no transmission) driveline reduces the load on the traction motor.

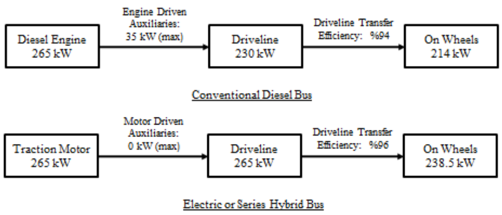

Figure 2. Power Flow through Powertrain

3.2 Powertrain Sizing through the requirements

IETT defines the vehicle level performance requirements for buses in terms of maximum speed , rolling gradeability and acceleration times on tender documents. These parameters are the primary input in sizing of electric powertrain. On the other hand, some other performance targets are deducted through the velocity, acceleration, inclination data based on GPS measurements of a bus while operating in line.

Table 2. Vehicle Performance Requirements

Requirements @ Gross Vehicle Weight	Reference
Maintain 18 kph on a 12% slope	IETT Tender
Maximum velocity 90 kph	IETT Tender
0-20 kph acceleration in 3.5s	IETT Tender
0-50 kph acceleration in 25.0s	IETT Tender
Maintain 60 kph on a 3% upward slope	Actual vehicle data

Maintain 30 kph on a 6% downward slope	From actual runs
Maintain 40 kph on a 8% upward slope	From actual runs
Average 1.5 m/s2 acceleration in 0-10 kph	From actual runs

Table 3. Reference Vehicle Parameters

Curb Weight	18.5 tonnes
Gross Vehicle Weight	29 tonnes
Wind Resistance (Cd x A)	0.725 x 8 m2
Driveline Efficiency	0.96 (for single drive)
Tire Dimension	275/70 R22.5
Rolling Resistance	0.007 x 28.000 x 9.81
Total Rotational Mass	645 kg (for e-drive + tires)
Traction	Center and Rear Wheel Drive

Vehicle level performance analysis are ran for off-the-shelf electric powertrain components (Table 4) of well-known suppliers to have an easily applicable solutions

.

Table 4. Electric powertrain alternatives

	E-Axle	Electric Motor #2	Electric Motor #1
Supplier	ZF	Siemens	Siemens
Product	AVE 130	1DB2016 – 1NB06	1DB2022 – 1NA06
Drive type	Hub Motor (e-axle)	Motor with axle	Motor with axle
Position	Center or Rear	Rear	Rear
Gear Ratio	1	6.2 or 7.38	6.2 or 7.38
Maximum output Power (kW)	2 x 120	160	240
Maximum output Torque (Nm)	2 x 10500	15500 (6.2) 18450 (7.38)	23560 (6.2) 28045 (7.38)
Maximum output Speed (rpm)	485	564 (6.2) 474 (7.38)	564 (6.2) 474 (7.38)

Table 5. Electric powertrain and requirement health chart

#	Description	Peak or Nominal Power	Center Axle: E-Axle Rear Axle: E-Axle FDR: -	Center Axle: E-Axle Rear Axle: Electric Motor 1 FDR: 6.2	Center Axle: E-Axle Rear Axle: Electric Motor 1 FDR: 7.38	Center Axle: No Traction Rear Axle: Electric Motor 2 FDR: 6.2	Center Axle: No Traction Rear Axle: Electric Motor 2 FDR: 7.38
1	Maintain 18 kph on a 12% slope	Nominal	G	G	G	R	R
2	Capable to reach 90 kph	Nominal	G	G	G	G	G
3	Limited Maximum Speed 80 kph	Nominal	Y	G	Y	G	Y
4	0 - 20 kph in 3.5 seconds	Peak	G	G	G	G	G
5	0 - 50 kph in 25 seconds	Peak	G	G	G	G	G
6	Maintain 60 kph on a 3% slope	Nominal	G	G	G	Y	Y
7	Maintain 30 kph on a 6% slope (retarder function)	Nominal	G	G	G	G	G
8	Maintain 40 kph on a 8% slope (for 10 seconds)	Peak	G	G	G	G	R
9	Maintain 1.5 m/s2 Acc/Dec rate between 0 - 10 kph	Nominal	G	G	G	G	G

The results clearly show that the combination of e-axle on center and e-axle or electric motor #1 on rear axle delivers a satisfying performance. Regarding the packaging, modularity and complexity perspectives; configuration #1 "e-axle on both axle" will be considered in further analysis.

4. SIZING OF ENGINE AND ENERGY STORAGE SYSTEM

4.1. Electrical Energy Consumption in Drive Cycle

The energy consumption simulations are done by AVL Cruise to see the effect of each variable separately in **Error! Reference source not found.**.

Variables					Simulation Results		
Mtr / Gen Power Limit (kW)	Weight	Rolling Resistance	Drag Coefficient	Auxiliary Load	Service Time (sec)	Consumption per km (kWh/km)	Consumption per hour (kWh)
320/320	24000	0,7	0,725	Energy Saver	5230	1,53	60,6
320/320	24000	0,7	0,725	Normal	5230	1,60	63,5
320/320	24000	0,6	0,65	Energy Saver	5220	1,43	56,7
320/320	24000	0,7	0,725	ACOn	5230	1,90	75,2
320/320	29000	0,7	0,725	Energy Saver	5270	1,76	69,2
320/320	29000	0,7	0,725	Normal	5270	1,83	72,0
320/320	29000	0,6	0,65	Energy Saver	5258	1,65	65,3
320/320	29000	0,7	0,725	ACOn	5270	2,10	82,6
320/320	29000	0,6	0,725	Normal	5260	1,74	68,7
320/320	24000	0,6	0,725	Normal	5224	1,53	61,0
320/320	29000	0,7	0,65	Normal	5265	1,79	70,5
320/320	24000	0,7	0,65	Normal	5226	1,57	62,3
260/260	29000	0,7	0,725	Normal	5392	1,96	75,6
260/260	24000	0,7	0,725	Normal	5312	1,72	62,7
260/320	24000	0,7	0,725	Normal	5301	1,57	61,5
260/320	29000	0,7	0,725	Normal	5364	1,78	67,4
260/320	24000	0,6	0,65	Energy Saver	5292	1,40	55,3
260/320	29000	0,6	0,65	Energy Saver	5350	1,60	62,0
260/320	24000	0,7	0,725	ACon	5301	1,86	72,8
260/320	29000	0,7	0,725	ACon	5364	2,04	79,1

Figure 3. Energy consumption chart by variables

Findings:

- 260/320 kW power limitation is the most efficient combination because of higher regenerative braking capability than it is for 260kW , and it also has less motor & inverter loss due to lower load performance metrics.
- Lower rolling resistance tires reduce the overall consumption by 0.9 kWh/km Aerodynamic styling reduces the overall consumption by 2%.
- All of the cases meets< 54000 service time limitation.
- +1 ton of extra payload has +2.6% effect on energy consumption.
- Electrical Air Conditioner adds +0.21 kWh per km .

- Energy saving electrical auxiliaries consumes 3 kW less than normal auxiliary power of 9 kW with benefit of 0.07 kWh/km.
- Diesel engine has to provide minimum electrical energy of 67 kW to the system. For hot summer days , Air Conditioner requires an additional 12.3 kW from energy source

4.2. Initial Sizing of Electrical Energy Storage

Energy storage capacity should be optimized to travel maximum time without harmful emission while departing from station, recuperate maximum energy during deceleration and keep the EES size low to prevent high cost and weight penalty of the extra modules. Table 6 and 7 shows the analysis results.

Table 6. Energy Consumption during Acceleration

Duration (s)	Consumption (kWh)	Distance Traveled on a 6% Slope (m)
5	0,321	15
10	0,756	50
15	1,19	100
25	2,06	200

Table 7. Storage Capacity and Percentage of Recovered Energy

EES Capacity (kWh)	0,4	0,6	0,8	1,0	1,2	1,4	1,6	1,8	2,0
Percentege of Recovered Energy (%)	38,8	57,3	73,5	86,4	92,9	96,6	98,2	99,3	100,0

Note: Vehicle is fully loaded; both analysis is done in driving cycle. EES capacity is calculated without considering the efficiency of EES.

According to analysis results, a net usable energy of 1.2 kWh gives an optimum balance of efficiency benefit and system cost.

4.3. Initial Sizing of Generator Pack

Preliminary assumptions and targets are as follows:

- Engine type: Diesel Euro VI.
- Engine displacement should be lower than 7 L to eliminate the payload reduction of electrification weight. Maximum engine power rates are between 160-210kW for the determinated engine size.
- Energy transfer efficiency between combustion engine and EES is %90.
- Engine BSFC range is 194-200 g/kWh.
- Air compressor, power electronic cooling fans, steering pumps are electric driven. Only engine sub-systems (cooling fan, fuel pump etc.) driven by diesel engine.

Table 8. Percentage of Driving Conditions and Duty Cycle of Generator Pack

Vehicle Operation in Driving Cycle (% in a hour)									
	Accel.		**Decel.**		**Idle**		**Steady**		**Sum**
	%	On	%	On	%	On	%	On	On
24t	19	0,5	34	0	13	0	34	1	43.6
29t	21	0,6	36	0	13	0	30	1	42.5

Minimum power limit of the generator pack is calculated with regard to maximum duty cycle (**Table 8**) and average energy requirement per hour rates.

Table 9. Generator Pack Power Calculation

	Air Conditioner is Off - Continuous Power				Air Conditioner is Off - Peak Power			
Vehicle Weight	Energy Consumption per hour (kWh)	Duty Cycle %	REX Power (kW)	Engine Power (kW)	Energy Consumption per hour (kWh)	Duty Cycle %	REX Power (kW)	Engine Power (kW)
24000 kg	61,5	43,6	141,1	157	73	43,6	167	186
29000 kg	67,4	42,5	158,6	176	79	42,5	186	207

Note: Engine driven cooling fan are not considered in the calculations. Engine auxiliary has to be controlled to operate at idle and deceleration.

As a result of this study, diesel engine has to be capable of producing 210kW and recommended to select a generator with nominal / peak power of 170/210 kW.

4.4. Re-Sizing of Electrical Energy Storage

Final part of third section evaluates the preliminary sized energy storage system through the drive cycle with generator pack for different auxiliary loads at half and full loaded conditions.
Max. Discharge Power of EES: 304kW (peak) , 163 kW (nominal)
Max. Charge Power of EES: 245 kW
Min. Energy Storage Capacity of EES: 6,5 kWh

Even if the preliminary sizing study gives a lower energy storage capacity ~ 1.2 kWh, Avcılar to Zincirlikuyu direction has an inclining profile and some sections draws maximum power more than a minute. Nevertheless it is not possible to cover + 90 kW excess power at peak from 1.2 kWh ESS for a minute. There are two ways to overcome this problem;

1. Maintain the EES capacity at 2kWh with ultra-capacitor technology (1.2kWh at 60% DOD) , replace 210kW generator pack by a 320kW unit with weight and cost penalty.
2. Replace the 2kWh ultra-capacitor by a 30kWh power type Li-ion battery (Max Charge/Discharge at

10C.) Do not increase the generator pack power further.

Ultra-capacitor and battery units will have same weight, whereas 320kW generator pack will weigh minimum 250kg over a 210kW system. Hence, Li-ion battery replaces the ultra-capacitor in next steps.

5. INITIAL POWER AND ENERGY MANAGEMENT STRATEGY DEVELOPMENT

Initial power and energy management strategies are already developed in the previous sections according to demands. Here is an overall look and recommendations are given to manage the power and energy storage units with minimum stress / maximum efficiency.

5.1. Power Management:

- Traction motors are limited to produce totally 260kW at motoring, 320kW at generating. This operation range is correctly matching with the continuous operation level of the selected electric propulsion components.
- Controllable electrical auxiliaries (A/C compressor, Steering Pump) turns off when the motoring power >100kW or stationary to reduce the peak discharge power. On the other hand, these auxiliaries operates at maximum load at deceleration , that leads to reduction of charge power.
- Generator pack turns off during electric powertrain is in generator mode or vehicle is standstill. (Note: If SOC goes below a specified threshold, generator pack activates.)
- Engine driven auxiliaries should be precisely controlled to activate when the engine is idle before shut-off or when engine peak power is not necessary.

5.2. Energy Management:

- Controllable electrical auxiliaries (A/C compressor, Steering Pump) turn off or runs at lower load by demand.
- On-board GPS system is used to warn the driver to release the throttle when arriving to station for maximum regenerative braking capability. Braking Distance: 320m
- Battery charge circulates between 36-66% SOC where the charge/discharge efficiency is highest. Besides, 30% of battery capacity is used to maximize the lifecycle of EES.
- Generator pack goes in action when the SOC lower than %60 with the following power output;
  Acceleration: Generator at peak + remaining energy from battery
  Steady Speed: Generator runs the vehicle and charges the battery at 1C or 2C.
  Deceleration & Idle: Generator turns off.
- Remaining %6 capacity over %60 is always maintained to recover 2kWh energy in braking.

6. FUEL ECONOMY and CO2 EMISSIONS

	Air Conditioner is Off				Air Conditioner is On			
Payload	Fuel Consumption (L/100km)	CO2 Emission (g/km)	Daily Usage (h)	Combined Daily Consumption (L/100km)	Fuel Consumption (L/100km)	CO2 Emission (g/km)	Daily Usage (h)	Combined Daily Consumption (L/100km)
Half	44,8	1107,0	11,0	46,7	51,1	1352,8	11,0	52,0
Full	50,5	1336,8	5,5		53,8	1425,8	5,5	

Table 10. Fuel Economy of Conventional Diesel and Series Hybrid Electric Buses in line

The diesel buses on Metrobus İstanbul consumes average ~ 55.6L/100km (January to May) , the series hybrid electric bus improves the fuel economy by **16%** without any infrastructure investment or negative impact on service time. (5360 sec)

7. CONCLUSION

As a conclusion, the advantage of energy recuperation power on-demand engine and auxiliary (electric) operation, high overall efficiency of powertrain leads to %16 reduction in fuel consumption and CO2 emissions. For a daily range of 600km and 300 days operation , series hybrid bus consumes approximately **16.000 L** less fuel than conventional bus annually . If it is extended through the Metrobus fleet, more than half million liters of fuel can be saved monthly. Beside of the benefit in metrics, hybrid electric bus will leave from and arrive to the stations without engine noise and harmful gasses, therefore makes the stations more passenger friendly.

Next steps would be thermal analysis of traction motor , generator , battery systems through the driving cycle data's for more detailed power management strategy. The cost of ownership should be also evaluated with maintenance costs of new electrical components and less usage of air/mechanical brake system.

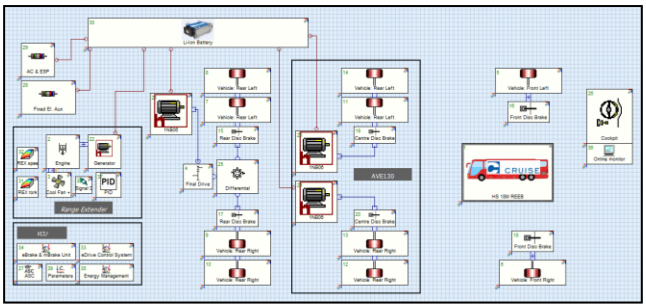

Figure 3. AVL Cruise Model of Series Hybrid Bus

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