Modeling Vehicle Performance for Sustainable Transport

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ABSTRACT

The paper deals with two main aspects of sustainable transportation systems (STS): modeling of the behavior of an electric vehicle (EV) and deployment of multi-modal transport systems.

A general simulation method is presented that can serve for modeling the behavior of (a) electric vehicle, (b) fleet of EVs, and (c) co-modal system. It can be used for comparison between energy consumption of mass and individual transport and for optimization of the energy management of transport systems.

Energy demands of several transportation modes and systems are compared. Environmental effects are assessed based on the energy consumption predictions. An example is given of using the simulation model for analysis and optimization of cybernetic transportation system. Optimized system operation by intelligent energy fleet management is also discussed.

Keywords: *Sustainable Transportation, Electric Vehicle; Cybernetic Transportation System; Energy impact; Environmental Effects.*

Introduction

There is a widespread consensus now that new transportation systems must be developed such that they will be sustainable. This means “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, Brundtland (1987). Sustainability includes vehicle and engine technology for reduced (or zero) emission of pollutants and greenhouse gases, and also introduction of transport systems that are operated in order not only for providing mobility but also with optimized energy management and minimal emissions. Here there is an important role of Intelligent Transportation Systems (ITS) and in particular, urban Cybernetic Transportation Systems (CTS). These mostly consist of Electric Vehicles (EV), which are indeed zero-emission in the city centre, but for being truly sustainable, the energy sources for the electricity should be renewable. It is noted that other solutions have also started to emerge, such as car sharing and providing bicycle systems for cities.

A viable approach for providing sustainable transportation to the cities is, indeed, based on co-modal systems. This means well-designed systems that will combine the use of the private (individual) car and the collective (public) systems. When these will be managed and controlled to operate efficiently, they would offer the advantages (e.g. comfort) of the former with those of providing sustainable overall mobility by the latter. A system that answers all of these requirements is the Cybernetic Transportation System, which is clearly an Intelligent Transportation System. Several CTS types have started to appear in the second half of the last decade of the 20th century. Some have been or are now under construction in various European locations, while others have been deployed in demonstrations, during R&D work in the field.

A CTS is a system of road vehicles with automated driving capabilities (either fully or partially). Its vehicle fleet is used for moving passengers or goods on a network of roads, and is under control of a computerized management system. The vehicles are used individually by the customers in a way similar to car sharing systems, and thus the CTS offers the link between the private car and the public transport modes. The CTS can be based on any type of vehicle, but usually EVs are used, so the systems are environmental friendly. They offer solutions that will drastically mitigate or solve the problems that we encounter in current urban transportation systems: congestion, noise, emissions of pollution and CO_2, better accessibility and safety. The result will be not only higher air quality, but higher quality of living at large, and advancement towards sustainability.

For proper design and operation of EVs and fleets of CTS, it is important to develop a simulation tool that will enable optimization of the energy consumption and also estimation of emissions. This paper describes results of two research programs that have included development of a simulation model for the calculation of the energy consumption of an EV. The vehicle propulsion configuration can be dual-battery, which allows achievement of high whole vehicle performance by combining benefits of different energy sources, in particular a main battery with high energy density and an auxiliary one with high power density. The input data include parameters of the vehicle and its loading, road profile and traffic characteristics (speed profile). Two operational modes are simulated: driving and regenerative braking. The algorithm is used for calculating the energy consumption, recoverable energy in the regenerative braking operation, etc.

The model was employed for simulating the behavior of an electric vehicle with a main battery of Zinc-Air and an auxiliary Ni-Cd battery. The ECE 101 cycle was chosen to represent standard urban driving conditions. It is often used for determination of EV energy consumption, according to Meier-Engel (1997).

The algorithm and model were then extended to enable simulation of a CTS fleet. The simulation results show that the model can be used for optimization of the energy impacts of both single electric vehicle and a whole CTS fleet. Furthermore, the simulation results obtained here were found to be in good agreement with the experimental data described and analyzed by Kottick et al (2000).

Finally, the energy needs of a CTS fleet were compared with those of a conventional diesel bus. This is important when considering alternative and new transportation systems.

1 - Theoretical Algorithm and Model

The theoretical model was developed for evaluating the performance of dual-battery electric vehicles: a high energy density battery (main) and an auxiliary one with high power density, and regeneration braking capability. The model includes the relations between the electrical motor efficiency and load factor, between the batteries efficiencies and depths of discharging (DOD) for driving and regenerative braking (RB) operation. Analytical forms for these relations were derived based on measurements performed by Kottick et al (2000) and on available literature data. Known equations to simulate the dynamics and the heat losses in the electrical circuit have been used. The model does not pre-suppose using large data files for the efficiencies of the vehicle motor, transmission, inverter, battery, and for driving and RB operational conditions of the engine. All the details related to the various efficiencies are given in the work of Zvirin et al (2004).

The mechanical equations that describe the dynamics of the motion of the vehicle include expressions for the forces exerted on it: climbing and rolling resistances, F_{cl}, F_{rol}, acceleration and aerodynamic drag forces, F_{acc}, F_{drag}. The corresponding empirical coefficients are taken from Bosch Handbook (2007) and SIMPLEV (2002):

$$F_{cl} = m * g * \sin\alpha \qquad (1)$$

where m is the vehicle mass; g is the acceleration of gravity; and α is the road gradient.

$$F_{rol} = C_1 * (1 + C_2 * v) * m * g * \cos\alpha \qquad (2)$$

where C1 = 0.01; C2 = 0.00447 s/m and v is the vehicle speed.

$$F_{acc} = \kappa_r * m * a \qquad (3)$$

where a is the vehicle acceleration and $k_r = 1.03$ is the rotation coefficient.

$$F_{drag} = \pm 0.5 C_d * C_{cor} * \rho * A * v_{rel}^2 \qquad (4)$$

where ρ is the air density; A is the maximal vehicle cross sectional area; C_d is the drag coefficient (for a van, simulated in this work, it can be taken equal to 0.6); v_{rel} is the wind speed relative to the vehicle in the driving direction; C_{cor} is a correction factor, accounting for the lateral component of the wind speed relative to the vehicle: $\vec{v}_{w.rel} = \vec{v}_w - \vec{v}$. C_{cor} is determined as:

$$C_{cor} = 1 + \beta |\gamma|^b \qquad \text{for } |\gamma| < 17.5$$

$$C_{cor} = 1 + \beta * 17.5^b = 1.223 \qquad \text{for } |\gamma| > 17.5 \qquad (5)$$

where γ is the angle between the directions of $\vec{v}$ and $\vec{v}_{w.rel}$, β = 0.00194 and b = 1.657. The sign of F_{drag} in eq. (4) is determined by the sign of the longitudinal component (in the driving direction) of the relative speed between the vehicle and the wind $v_{rel} = v - |\vec{v}_w| \cos\gamma$. The acceleration time, t_{acc}, is calculated according to the known formula, e.g. as suggested by Meier-Engel (2000):

$$t_{acc} = \int_0^{v_a} \frac{k_r m v * dv}{P_{dr.\max} - F_{st} v - C_{rol} v^2 - C_{aer} v^3} \qquad (6)$$

where v_a is the prescribed speed (km/h), attained by the vehicle for the acceleration time t_{acc} from the start, at the maximal drive power. $P_{dr.max} = P_{bat.max} * \eta_{\text{tot.dr}}$; $P_{\text{bat.max}}$ is the battery power at relatively small DOD; $F_{st} = C_1 * m * g * \cos\alpha$ is the first term in eq. (2); C_{rol} is the second term; and $C_{aer} = F_{drag} / v_{rel.l}^2$, with F_{drag} from eq. (4).

The forces given by equations (1-5) are needed for the computation of the driving and regenerative braking power and energy consumed and recuperated, which are inversely and directly proportional, respectively, to the corresponding total efficiencies of the electric vehicle propulsion system. These are products of the batteries, motor, inverter and traction efficiencies – see Kottick et al (2000) and Zvirin et al (2004).

For the evaluation of the energy impacts and energy management optimization of CTS, the vehicle productivity was defined as follows in Zvirin et al (2004):

$$VP = PC * R_{dr} \qquad (7)$$

where PC is the passenger capacity of the vehicle and R_{dr} is the driving range between battery recharging (km).

The number of passengers moved (NPM), for full capacity, is defined as:

$$NPM = VP / L \qquad (8)$$

where L is the route length (km).

These definitions apply for a single vehicle on the route, as well as for the whole CTS fleet.

2 - Electrical Vehicle and the Cybernetic Transportation System

The model described above was applied for the simulation of the behavior of a single EV and of CTS. These were two different research programs; the former described in Kottick et al (2000) within a national program in Israel and the latter, Zvirin et al (2004), within a European program. The simulation model was calibrated and verified in the former that also included experimental performance evaluation of the vehicle – a van, which was converted to EV operation and powered by Zinc-Air batteries, under various traffic situations and with different driving styles. .

It is noted that the vehicles considered in the CTS simulations were different. The simulation model was used for a parametric study of a preliminary CTS design for the campus of the Technion – Israel Institute of Technology and for the INRIA testing site (description of these routes can be found in Zvirin et al (2004)), in order to investigate the effects of the battery weight, the electric motor power and the average speed on the vehicle and system performance: driving range, energy consumption, number of passengers moved and number of vehicles required. The simulations were performed for the vehicle with main parameters similar to those of the Yamaha-Europe cyber-car (see Table 1) with the possibility of changing the passengers' capacity. This was applied for optimization purposes.

The length of the simulated Technion driving route was 1600 m; the absolute averaged value of the road gradients is 7.5%, and the basic average speed 12.0 km/h. The same parameters for the INRIA testing site were: length – 555 m; average road gradient – 2.5%; basic average speed – 8.7 km/h.

To obtain an estimate of the demand for the proposed CTS line, an estimated LOGIT model was used, based on a Stated Preference study performed in the campus and described by Bekhor (2004). The simulation was performed separately for the downhill and uphill parts of the road. The simulation code was used also for comparison between the performance of the CTS fleet against a ‘hypothetical’ electric bus, whose parameters appear also in Table 1.

3 – Results and Discussion

The theoretical model was calibrated by using the detailed experimental data for the EV described above. Efficiency parameters that are used in the simulation model were selected, in order to ensure the best possible correlation.

EV performance

Detailed presentation and analysis of the experimental and theoretical results for the EV with zinc-air batteries appear in Kottick et al. (2000) and Zvirin et al (2004). Here we show some additional results that pertain to 'Eco Driving'. Fig. 1 shows experimental data of the instantaneous current drawn from the battery in real driving. An obvious result is the immense effect of the driving style. The impact of this on the energy consumption is seen in Fig. 2. The large difference between 'calm' and 'aggressive' driving styles indicates that by adopting the former, much energy can be saved. For the EV it also means an increased driving range. It is emphasized, indeed, that there is a strong need for education of drivers towards Eco Driving. This is important in particular for drivers of vehicles fleets, but also for the public in general, e.g. Shaheen (2008). The driving style is obviously more pronounced in city centre low-velocity traffic, when the aggressive driver is over-accelerating.

The simulation model was used for demonstrating the capability of weights optimization of the main (Zinc-Air) and the auxiliary (Ni-Cd) batteries of the dual-battery EV for various driving styles. This was done for the vehicle described in Kottick et al. (2000).The total weight of the two batteries was kept the same as in the tested vehicle – 850 kg. The total vehicle and the propulsion system weights were also kept unchanged.

The simulation was performed for the vehicle on a modified standard urban driving cycle. This cycle, Meier-Engel (2000), was modified by 2 times increase of every cycle section length. This was done, in order to allow cycle fulfilment at low values of vehicle accelerations. The normal driving style acceleration values are as in the cycle description in Meier-Engel (2000). For the calm driving style acceleration values of 0.5 and 0.8 of those for normal driving style were applied (acceleration factor AF = 0.5 and 0.8, respectively). For the aggressive driving style AF values of 1.25 and 1.5 were used. The results are shown in Table 2.

The non-proportional reduction of the driving range, in the "aggressive" style case compared to the related change in energy consumption, follows from the reduction of the main battery weight and appropriate increase in the weight of the auxiliary one, in order to ensure power output required by the "aggressive" style accelerations.

As can be seen from Table 2, the simulatio**n** results clearly show that the EV driving range can be increased significantly (by more than 50%) by appropriate selection of the vehicle driving style and utilization of a dual-battery energy source for optimal energy and power density performance. It is noted that for the case of 'very calm' driving style (last row in Table 2), the main battery with large energy density is sufficient, and there is no need of the auxiliary with the high power density. Obviously, however, there is no guarantee, in general, that the vehicle will always be driven by such a driver. In addition, the auxiliary battery could be needed in other road and traffic conditions. The model developed here can be used for the optimization, as mentioned above.

CTS performance and comparison with electric bus

Experiments and demonstrations of CTS with electric cybercars have been planned and performed within the CyberMove, Zvirin et al (2004), and CityMobil, Stam et al. (2008) Projects. For some of them, simulations were done, in particular regarding energy performance, Zvirin et al (2004). This reference includes all the details of the systems, vehicles, roads vehicle loading and driving patterns, etc. Here we show examples of simulation results, in order to demonstrate the capability of the simulation tool for optimization of system design and operation, in terms of productivity, driving range, energy consumption, etc.

Figure 3 shows the effect of battery weight (BW) on the productivity (VP – defined as passengers*km) of the cybercar tested at the INRIA (FR) site. It is clearly seen, that the curve of the VP vs. BW depicts a maximum, here – at about 320 kg, for the specific vehicle, speed and route data. The location of this maximum is almost independent of the average speed (Vav) in the range of these experiments.

The simulation model was applied also for the Technion campus CTS, mentioned in Section 2 above, Zvirin et al (2004) and Bekhor (2004). Table 3 presents results of battery weight optimization attempt, for the average vehicle speed of 12 km/h. A "hypothetical" vehicle was simulated, with various possible passengers' capacity. The results show that a battery of 355 kg allows transporting the required number of passengers (3,229 in the considered example) by use of the minimal quantity of cars in the system. The total energy consumption of the CTS is inversely proportional to the passenger capacity of the vehicle. Therefore it is possible to achieve minimal energy consumption of the whole CTS by using cars with maximal passenger capacity and minimal battery/ies weight, which will enable running within the required driving cycle.

Figure 4 and Table 4 show results for an electric bus (EB) providing the same service as the CTS, in a format similar to that of Fig. 3 and Table 3. The results in Table 4 are provided for the same average bus speed of 12 km/h and number of passengers to be transported – 3229. As can be seen, here again the productivity reaches a maximum, meaning that optimization of battery weight can be achieved. The minimal total energy consumption of the bus is obtained, as previously, at the minimal battery weight and maximal passenger capacity.

It is clear from the results shown in Table 4 that use of EB with an advanced battery technology, such as Li-Ion, for example, can significantly improve the driving range of the bus and reduce the total number of buses required for transportation of the given number of passengers. The total energy consumption of the CTS fleet (167 kWh) is much lower than that of the EB's (307 kWh), which is an obvious advantage of the former.

Energy consumption values of the simulated EB were compared with the fuel consumption data of a similar conventional diesel bus shuttle serving today the Technion Campus. The average fuel consumption value that has been received from the bus operator is 4.5 km/l. Assuming fuel density 0.84 kg/l and lower heating value of diesel fuel 42 MJ/kg, an energy consumption of 2.1 kWh/km is obtained. Comparison of this value with the predicted energy consumption of the simulated electric bus shows clear benefit of the latter with reduction of energy consumption by more than 35%. Assessment based on the assumptions of fuel tank capacity of the diesel shuttle – 75 l and passengers' capacity of the bus – 12 seats shows that the required number of passengers on the Technion Campus (3229) can be transported by 2 diesel buses with a total energy consumption of 941 kWh.

Total CO_2 emissions by the considered alternatives: CTS, EB and diesel bus were estimated based on available emission factors for diesel vehicles, Tartakovsky & Zvirin (1998), and for electricity production, Killip (2005). Two cases of electricity supply by using coal and natural gas (NG) fuels were considered with CO_2 emission factors of 0.95 and 0.44 kg CO_2/kWh, respectively. The results are summarized in Table 5. As can be seen from the Table, the CTS has a clear advantage over the EB and the diesel bus for both energy consumption and CO_2 emissions, even in the worst case of electricity production with coal. Use of CTS will allow reduction of energy consumption by a factor of 5.6 together with lowering CO_2 emissions by 30%. For the case of electricity supply with NG, reduction of CO_2 emissions by a factor of 3 can be achieved. In this work, an assessment of well-to-wheel CO_2 emissions was not performed, but, of course, it can be done using the suggested approach.

4 – Conclusions

A general simulation method is presented that can serve for modelling the behavior of single electric vehicle, fleet of EVs, and co-modal systems. It can be used for comparison between energy consumption of collective (public) and individual transport and for optimization the energy management of transport systems.

In this paper, energy demands of several transportation modes and systems are compared. CO_2 emissions are assessed based on the energy consumption predictions. An example is given of using the simulation model for analysis and optimization of CTS. It is shown that the number of vehicles required for the CTS or its energy consumption and CO_2 emissions can be minimized by careful design and selection of vehicle type and optimal parameters of both the vehicle and the driving pattern.

References

Bekhor S. & Y. Zvirin (2004): Estimating the Potential Use of Cybernetic Cars for a University Campus. Paper presented at the 10th World Conference in Transport Research, Istanbul, Turkey.

Bosch G. (2007): Automotive Handbook, 7-th edition, SAE Society of Automotive Engineers, Warrendale, PA USA.

Brundtland G. R. (1987): Our Common Future. Report of the World Commission on Environment and Development, Annex to General Assembly document A/42/427: Development and International Co-operation: Environment.

Killip G. (2005): Emission factors and the future of fuel. Background material M. 40% House project. http://www.eci.ox.ac.uk/research/energy/downloads/40house/background_doc_m.pdf

Kottick D., L. Tartakovsky, M. Gutman & Y. Zvirin (2000): Results of electric vehicle demonstration program. Proceedings of the 21st IEEE Convention of the Electrical and Electronic Engineers in Israel, p. 318 – 321.

Meier-Engel K. (1997): Automobile Technology Division, Bench–test for Electric Vehicles. Electric Engineering and Electronics.

Meier-Engel K. (2000): Failure Time and Energy Consumption of Vehicles. Final report, Matador Contract JOE3 - CT97 - 0081.

Shaheen S. (2008) Car Sharing and carbon dioxide emission reduction. Proceedings of the 15th World Congress on ITA, New York, NY, USA, paper 30085.

SIMPLEV (2002): Simulating Electric & Hybrid Vehicles, http://ev.inel.gov/simplev/pg2.html.

Stam D., Alessandrini A., Ruberti G., Marco S., Zvirin Y & Librino R. (2008): Field trial A ex-ante evaluation report. CityMobil EU Project, Deliverable 5.2.1a.

Tartakovsky L. & Y. Zvirin (1998): Contribution of transportation to emission of greenhouse gases in Israel and measures for its reduction. Report to the Israeli Ministry of the Environment, Technion Transportation Research Institute.

Zvirin Y., B. Aronov, A. Alessandrini, K. Malone, H. Raekers, M. Parent, T. Meisner, S. Bechor & L. Tartakovsky (2004): A tool to choose the Energy System and dimension the vehicle fleet of CTS systems. Final research report, deliverable CM D4.2, EC project: Cybernetic Transport Systems for the Cities of Tomorrow CYBERMOVE EESD EVK4-2001-00050, 38 p.

Table 1: Main parameters of the simulated cybercar and E-bus.

Parameter	cybercar	E-bus
Gross vehicle weight, kg	1250	7,700
Frontal area, m^2	2.31	5,70
Battery type	Pb-Acid	Pb-Acid
Maximal depth of discharge (DOD)	0.8	0.8

Table 2: Optimized batteries weights, driving range and energy consumption of the dual-battery EV for different driving styles. Main battery: Zinc-Air, Energy Density (ED) = 215 Wh/kg, Power Density (PD) = 95 W/kg; Auxiliary battery: Ni-Cd, ED = 65 Wh/kg, PD = 95 W/kg.

Driving style	Acceleration factor	Main battery weight (kg)	Auxiliary battery weight (kg)	Maximal driving range (km)	Average energy consumption (kWh km-1)
Normal	1	780	70	380	0.415
Aggressive	1.25	750	100	350	0.444
Aggressive	1.5	700	150	310	0.460
Calm	0.8	800	50	400	0.404
Calm	0.5	850	0	470	0.353

Table 3: Effects of battery weight and passenger capacity on energy consumption of CTS.

Parameter	Simulation Experiment					
	1	2	3	4	5	6
Battery weight (kg)	205	280	355	430	505	580
Number of passengers in each car	7	6	5	4	3	2
Vehicle energy consumption (kWh/km)	0.231	0.224	0.221	0.218	0.217	0.214
Driving range (km)	30.1	43.0	56.0	68.8	81.6	95.5
Total cars needed to run the whole CTS	24	20	18	19	21	27
Total CTS energy consumption (kWh)	167	193	223	285	372	552

Table 4: Effects of battery weight and passenger capacity on energy consumption of E-bus.

Parameter	Simulation Experiment					
	1	2	3	4	5	6
Battery weight (kg)	600	825	1050	1200	1350	1500
Number of passengers in each bus	22	19	16	14	12	10
EB energy consumption (kWh/km)	1.30	1.32	1.32	1.31	1.33	1.33
Driving range (km)	13.9	22.4	28.6	32.8	36.8	40.9
Total EBs needed to run the whole system	17	12	11	11	12	13
Total EBs energy consumption (kWh)	307	355	415	473	587	707

Table 5: Energy consumption and CO2 emissions of various transport alternatives.

Transport Alternative	Total energy consumption (kWh)	Number of vehicles in the system	CO_2 emission (kg) Coal/NG
CTS	167	24	159/73
E-bus	307	17	292/135
Diesel bus	941	2	229

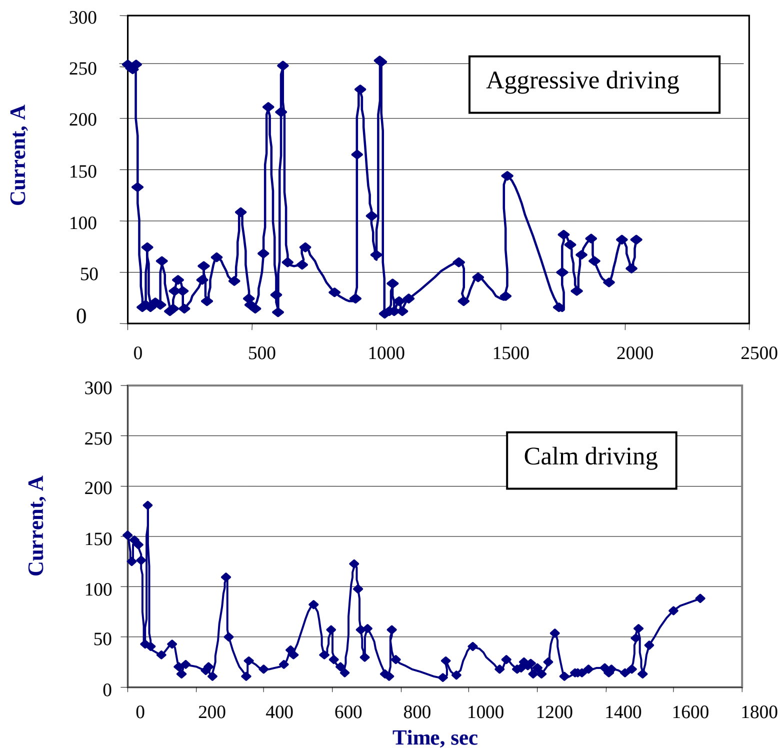

Figure 1: Real time EV current drawn from battery – effect of driving style.

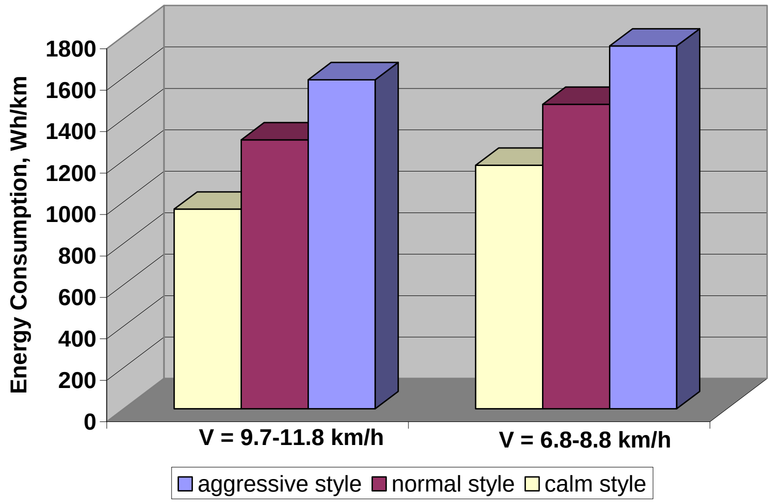

Figure 2: EV energy consumption – effects of speed and driving style.

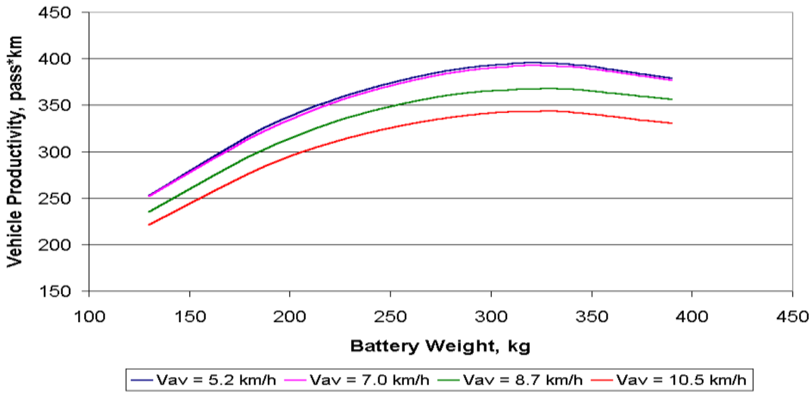

Figure 3: Effects of Battery Weight on Cybercar Productivity.

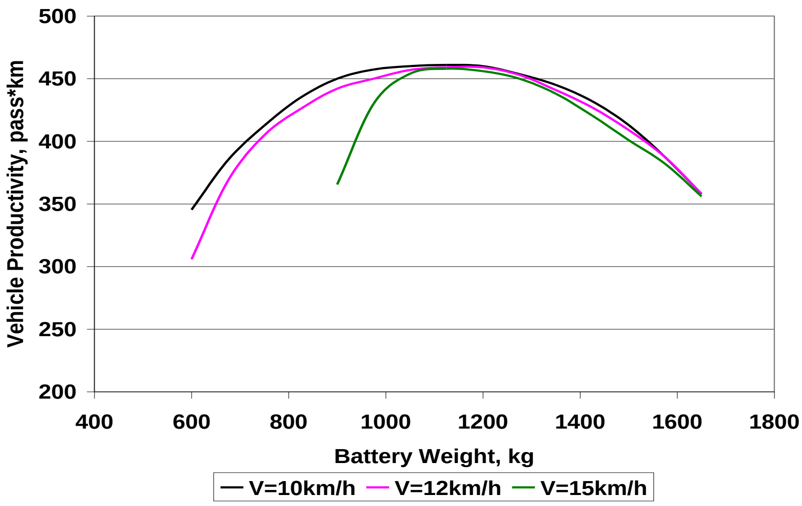

Figure 4: Effects of Battery Weight on Electric Bus Productivity.