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EXAMINATION OF THE BRAKING ENERGY RECOVERY POTENTIALS OF A CITY BUS UNDER URBAN DRIVING CONDITIONS

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Abstract: While operating under urban driving conditions, a city bus must have high enough traction power to overcome the rolling, aerodynamic, acceleration and positive road grade resistances. But, the bus must also have high enough braking power to decelerate the bus for a stop and to keep its speed at the required level when the road grade is negative. The rolling and aerodynamic losses are inevitable losses, but the braking energy losses are recoverable. At the present work, the operating characteristics affecting the braking energy of a 12 m long and 15 tons loaded weight city bus were analysed under real world urban driving conditions. Since the city bus driving under urban driving conditions involves frequent stop-and-go operations, recovery of the braking energy losses can provide a great potential to improve the fuel economy. The characteristics examined mainly include the speed and altitude profiles of the routes, micro-trip traction energies, and the cumulative traction and braking energies for the routes. Results of the analysis indicated that frequent stop-and-go operations of the urban routes increase the braking energy demands of the bus dramatically. Over the Campus route, which is a 22 km route with 88 micro-trips and an average speed of 19 km/h, the cumulative braking energy is 26 kW-h. It is accounted for 80% of the traction energy, and 14% of the micro-trips have the braking energies greater than 0.5 kW-h. But, over the route Karaman, which is a 41.5 km route with 58 micro-trips and an average speed of 26 km/h, the cumulative braking energy is 38 kW-h. It is accounted for 65% of the traction energy, and 50% of the micro-trips have the braking energies greater than 0.5 kW-h. If 50% of the braking energies are recovered, percentages of the energy savings for the Campus and Karaman routes will be approximately 40% and 30%, respectively.

Keywords: braking energy, energy recovery, city busses, urban driving, real world driving

BİR BELEDİYE OTOBÜSÜNÜN ŞEHIR İÇİ SÜRÜŞ ŞARTLARINDA FRENLEME ENERJİSİ GERİ DÖNÜŞÜM POTANSİYELİNİN İNCELENMESİ

Özet: Şehiriçi sürüş şartlarında çalışan bir otobüs yuvarlanma, aerodinamik, ivmelenme ve tırmanma dirençlerini yenebilecek kadar bir güce sahip olması gerekir. Fakat, aynı zamanda seyir halindeki otobüsü durdurabilmek ve yokuş aşağı inişlerde otobüsün hızını sabit tutabilmek için yeterli frenleme gücününde ihtiyaç vardır. Yuvarlanma ve aerodinamik direçler kaçınılmaz kayıplar oluşturur fakat frenleme kayıpları geri kazanılabilir. Bu çalışmada, 12 m uzunluğunda ve 15 ton ağırlığında şehir içinde çalışan bir otobüsün frenleme enerjisini etkileyen faktörler incelenmiştir. Şehi içi operasyonlar çok sık dur kalk içerdiği için otobüsün frenleme enerjisinin geri kazanımı otobüsün yakıt ekonomisini iyiyleştirecek önemli bir potansiyel sunmaktadır. İncelenen karakteristikler temel olarak hız, yolun yükseklik değişim profile (eğimi), mikro-yolculuk çekiş enerjisi, ve rotaların kümülatif çekiş ve frenleme enerjileri. Analiz sonuçları göstermiştir ki şehir içi yollarda çok sık dur kalk yapılması frenleme enerjisini ciddi olarak artırmaktadır. 22 km lik kampüs rotasında ortalama 19 km/h hızda 88 mikro-yolculuk oluşmuştur ve bu yolculuğun kümülatif frenleme enerjisi 26 kW-h olmuştur. Frenleme enerjisi bu yolculuğun kümülatif çekiş enerjisinin %80’ini oluşturmaktadır ve mikro-yolculukların %14’ü 0.5 kW-h’den daha fazla frenleme enerjisine sahiptir. Fakat, 41.5 km lik Karaman rotası’nda ortalama 26 km/h’lik bir hızda 58 mikro-yolculuk vardır ve bu yolculukta kümülatif frenleme enerjisi 38 kW-h olmuştur. Frenleme enerjisi bu yolculuğun kümülatif çekiş enerjisinin %65’idini oluşturmaktadır ve mikro-yolculukların %50’si 0.5 kW-h’den daha fazla frenleme enerjisine sahiptir. Eğer frenleme enerjisinin %50’si geri kazanılabilirse Kampus ve Karaman rotalarındaki enerji tasarrufu sırasıyla %40 ve %30 olacaktır.

Anahtar kelimeler: frenleme enerjisi, enerji geri kazanımı, şehir otobüsü, şehir içi sürüş, gerçek dünya koşulları

INTRODUCTION

City busses are the most commonly used vehicles for public transportation where urban population is very dense. Since energy needs of the busses are generally provided with diesel engines, which use fossil fuel for the energy conversion, both the local emissions such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC) and the global emission carbon dioxide (CO_2) are released in densely populated urban areas as combustion products.

Adverse health effects of the local emissions have been known for many decades and in order to prevent these effects many strict legislations, which reduced the emissions limits more than 90% over three decades, have been implemented (DieselNet, 2013). These legislations have become the driving force for the development of advanced combustion and exhaust after-treatment systems. CO_2, on the other hand, is the main greenhouse gas (GHG) emission from city busses. Nowadays, European Commissions (EC) is taking actions to drastically reduce CO_2 emissions with the goal of keeping climate change below 2 ^{0}C. It is suggested by the EC that in order to reach the goal, transport sector needs to reduce their GHG emissions at least 60% by 2050 with respect to that of 1990 (White Paper, 2011).

Similarly, Department of Energy of the United States (USDOE) is taking actions with its Vehicle Technology Program (VTP) with partnership of the industry leaders, the national laboratories, and universities (Davis, PB., 2012; VTP, 2013). The main goals of the VTP are to enable the US to significantly reduce fossil fuel consumption, GHGs, and the local emissions. In order to reach the goals, improving thermal efficiency of internal combustion engines (ICEs) and enabling their introduction in hybrid electric vehicles is chosen to be one of the most promising and cost effective approaches. When coupled with hybrid electric powertrains more than 30% fuel economy and near zero levels NOx and PM emissions are expected from commercial vehicles (Singh, G., 2011).

Fuel economy and emissions of a city bus operating under urban driving conditions are strongly dependent on its operating conditions (Erlandsson et al., 2008; Cocker et al., 2004; Johnson et al., 2009; Durbin et al., 2007; Zhihua et al., 2011). If operated at cruising conditions on a flat route, a bus would be needed enough power only for the rolling and aerodynamic losses, but real world operation of the bus is far from such an idealized condition. Depending on traffic and road conditions which may involve many micro-trips with accelerations, decelerations, and various road grades, braking energy losses of the bus increase dramatically and worsen the fuel economy.

Recovery of the braking energy, on the other hand, can be remedy for the excessive fuel consumptions of the busses under urban driving conditions. When compared to conventional busses, hybrid busses can easily save fuel and minimize emissions because of their braking energy recovery (regenerative braking) system. Kinetic energy of a conventional vehicle, which is normally wasted during braking, can be converted and stored in the form of electricity by the regenerative braking system. However, energy conversion in the regenerative braking system cannot be realized with 100% efficiency. Significant losses can be observed in components of the regenerative braking system, which are mainly motor/generator, power electronics and battery or ultra-capacitor. Moreover, efficiencies of the components are dependent on the operating conditions. It is given in the literature that combination of the motor/generator and its power electronics have approximately 80% efficiency and the ultra-capacitor efficiency is around 90% for both charge and discharge while operating under frequent stop-and-go operating conditions (Baisden et al., 2004; Grbovic et al., 2012; Miller, JM., 2003; Mi et al., 2008; O'Keefe et al., 2002; Williamson et al., 2006; Williamson et al., 2007). This means that round trip energy conversion efficiency in the regenerative braking systems is approximately 50%, which is a significant potential to minimize both fuel consumptions and emissions of the vehicles.

Several research works have been carried out to determine fuel economy and emission advantages of hybrid electric vehicles, which were published in the literature also:

Barrero et al. 2009, simulated and compared several power flow management strategies for hybrid city busses by using a quasi-static 'backwards/forward looking' simulation program. The simulation results indicated that energy savings can be achieved in a range from 32.6 % when using the kinetic strategy with 0.3 kW-h of energy storage system to 40 % when using the ICE on-off strategy and an energy storage system of 0.65 kW-h.

Xiong et al. 2009, developed an energy management strategy for a series-parallel hybrid city bus by using a forward-facing simulation program based on the software Matlab/Simulink. The simulation results indicated that the engine operation can be kept in a high-efficiency region and the fuel economy can be improved theoretically by 30.3% to that of the conventional bus under transit bus driving cycle.

Ahn et al. 2009, carried out the performance simulation for the regenerative braking system of a hybrid electric vehicle at various driving conditions by using MATLAB/ Simulink. It was observed that hybrid electric vehicles can improve fuel economy in a range from 20 to 50%.

All these research works indicate that recovery of the braking energy provide various degrees of benefits in terms of fuel economy and emissions. In order to quantify the benefits of the recovery under real world urban driving conditions, a research project entitled "Measurement and Modeling of Hybrid City Bus Emissions under Real World Operating Conditions" was introduced by Sakarya University with support of Turkish Ministry of Science Technology and Industry, and TEMSA R&D. Initial tests and reports of the project indicated that fuel economy of a conventional city bus is strongly dependent on the characteristics of the bus route and driving conditions (Soylu et. al., 2010; Bal et al., 2010; Semercioğlu et al., 2010). In the present work this dependency was further clarified by examining the braking energy of the bus under real world urban driving conditions, which involves frequent changes in the accelerations, speeds and the road grades. It is expected with this analysis that the benefits of the regenerative braking system can better be estimated.

EXPERIMENTAL SETUP

Figures 1 indicates schematic of the conventional drivetrain and instrumentation. Test vehicle was TEMSA brand city buses. The length and loaded weight of the buses were 12 m and 15 tons, respectively. The bus was powered with a 6.7 liter Euro 4 CUMMINS diesel engine which has 250 HP of rated power at 2500 rpm. The tests were carried out on the Campus and Karaman routes of Sakarya Municipality during summer time and it is assumed that wind speed is negligible. The route were chosen as representatives of Sakarya Municipality bus routes by looking their average speeds, number of stop-and-go events and altitude characteristics. The routes were divided in two parts as “Go” and “Return” for better analysis of the altitude effects. During the tests, data for the vehicle speed and location, the engine operation, the exhaust emissions and environmental conditions were sampled second by second by using SEMTECH DS from Sensor Inc. Semtech DS is a portable emission measurement system (PEMS) that is capable of monitoring real time gaseous emissions and environmental data such as ambient pressure, temperature and humidity. It also has a vehicle interface module (SAE-J1708) to collect engine and vehicle operation data.

The main specifications of SEMTECH DS are given as follows:

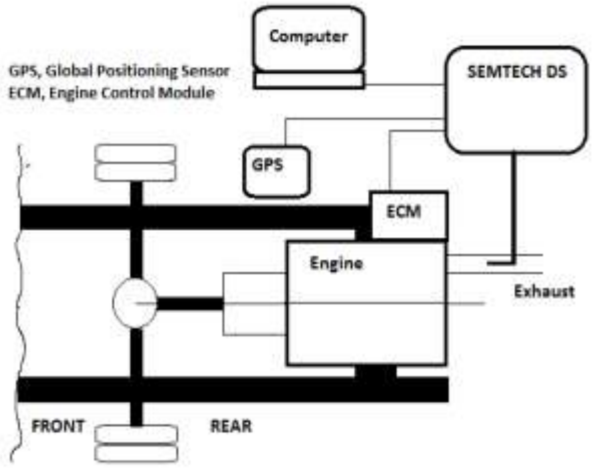

Figure 1. Schematic of the Drivetrain and Instrumentation.

- Ambient operating temperature: 0°C to 45°C
- Storage temperature: -40°C to 60°C
- Sample flow rate: 10 SLPM (including bypass)
- Sample rate: 1 Hz
- Power requirement: 12VDC, 70A during warm up, 30A at steady state
- Dimensions: 36cm x 43cm x 55cm (HxWxD)
- Weight: 41.7 kg (92 lbs)
- Communications: 802.3 (10BaseT) and 802.3u (100BaseTX) wired, and 802.11b or 802.11g (DSSS) wireless Ethernet

EXAMINATIONS OF THE CITY BUS OPERATING CHARACTERISTICS

Because of the characteristics such as traffic conditions, frequency of the bus stops and the road grades, the speed and altitude profiles of city busses over urban routes are very specific. Figure 2 and 3 indicate the speed and altitude profiles along with the acceleration histograms for Campus and Karaman routes. Note that the road grade is percent change in altitude per unit horizontal distance, and it is calculated by using the altitude data. As can be seen from the figures, the routes involve many micro-trips with changing speeds and altitudes. It should be noted here that the altitude in Figure 2 divided by 5 for better presentation of the figure. The analyses were carried out based on the micro-trips of the routes.

Table 1 summarizes the basic characteristics of Campus and Karaman routes which are typical routes of Sakarya Municipality. As can be seen from the table, Karaman route has higher mean and maximum speeds and less stop-and-go events per km travel. The altitude change of Karaman route is almost half of that of the Campus route. It is clear that driving over Karaman route is smoother when compared to that of the Campus route which involves highly frequent stop-and-go events with dramatic altitude changes. However, the acceleration range of Karaman route is slightly wider.

MODELING OF THE CITY BUS TRACTION POWER

If operated with a constant speed over a flat road, power source of the bus would run at its most efficient operating conditions and provide traction energy for rolling and aerodynamic (R&A) losses, only. But, as shown in the Figures 2 and 3, typical operations in urban areas involve frequent changes in the speed, which is a measure of changes in the kinetic energy (KE), and the altitude, which is a measure of changes in the potential energy (PE). While operating at these conditions, power source of the bus must operate in a wide range of the engine map and provide enough traction energy for changing the KE and PE, also.

To model the traction power requirement of the bus at urban driving conditions, well known Vehicle Specific Power (VSP) approach was used (Jimenez-Palacios, 1999; MOVES2010, 2010). As can be seen from Formula 1 and 2, the VSP is the power per unit mass of a vehicle to change the KE, PE and overcome the R&A losses.

$$VSP = \left(\frac{d}{dt}(KE + PE) + v\left(F_{rolling} + F_{aero}\right)\right)\frac{1}{m} \text{ .... (1)}$$

The terms of Formula 2 from the beginning to end stand for the KE, PE, rolling resistance and aerodynamic drag (R&A losses), respectively.

$$VSP = v\big(a(1+\varepsilon)\big) + v(g.grade) + v\big(g.C_{rolling}\big) + v(\tfrac{1}{2}.\rho.\frac{C_D.A}{m}(v+v_w)^2) \quad (2)$$

where, VSP = vehicle specific power (kW/ton); v = vehicle speed (m/s); v_w = wind speed (m/s), a = vehicle acceleration (m/s^2); ε= Mass factor for rotating components; g = 9.81 m/s^2; $grade$ = road grade (dimensionless); $C_{rolling}$= rolling resistance term coefficient; and C_D= drag coefficient. Traction power ($P_{traction}$) for the bus was defined as:

$$P_{traction} = VSP.m \quad (3)$$

The coefficients of the Formula 2 were slightly modified for fine tuning of the model with the experimental data of the bus.

In order to tune the rolling and drag coefficients the traction and engine powers were compared at various speeds. During the comparison the third power dependency of aerodynamic resistance to vehicle speed is especially observed. The rolling resistance linearly increases with speed.

Final values of these coefficients were as follows:
$\varepsilon = 0.1$, $C_{rolling} = 0.07$

$\frac{1}{2}.\rho.\frac{C_D.A}{m} = 0.00026$, this term has a unit of 1/m

EXAMINATION OF EFFECTS OF SPEED AND ALTITUDE PROFILES ON THE TRACTION POWER AND ENERGY OF THE BUS

Figures 4 and 5 indicate the micro-trip traction energies for Campus and Karaman routes. As was given in Table 2, the Campus and Karaman routes have 88 and 58 micro-trips, respectively. While the positive traction (PT) energy accelerates the bus, the negative traction (NT) energy, which is actually the braking energy, decelerates the bus for a stop or to keep the speed at a desired level for roads with negative road grade. It is clearly seen from both of the figures that the micro-trip traction energies are not homogenous. They are directly related to the changes in the micro-trip speed and altitude. As can be seen from Figure 5, the fifth micro-trip of Karaman route has the PT of 6.0 kW-h and the NT of 5.5 kW-h which are the maximums of the route. If the speed profile of the fifth micro-trip, which corresponds to the time duration from 500 to 1000 seconds, is checked in Figure 3, it can be seen that it is the longest micro-trip with the higher speeds. The changes in micro-trip altitudes have strong impacts on the micro-trip traction energies, also.

As can be seen from Figure 4, the micro-trips from 12 to 15 have significantly higher NT energies when compared to that of the others. If the altitude profile for the corresponding micro-trips, which correspond to the time duration from 600 to 900 seconds in Figure 2, is checked, it can be seen that the altitude is decreasing significantly. But, in the return route, the bus must be climbing for the same altitude. The PT energies for the micro-trips from 79 to 83 in Figure 4 correspond to the climbing. At this condition the PT energies are significantly higher than that of the other micro-trips. If the road grade is not changing significantly, the PT and NT energies of the micro-trips are comparable, and the difference between the positive and negative traction energies are equals to the R&A losses and these losses are increasing with the speed.

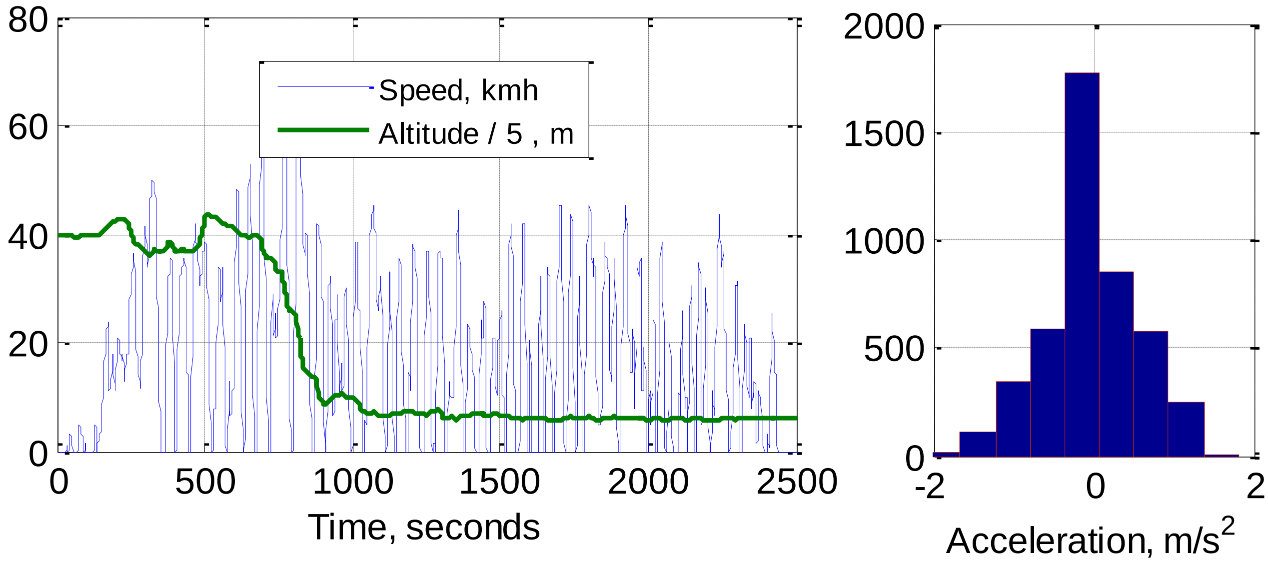

Figure 2. Speed and altitude profiles and accelerations histogram for the Campus Return Route (17.06.2009).

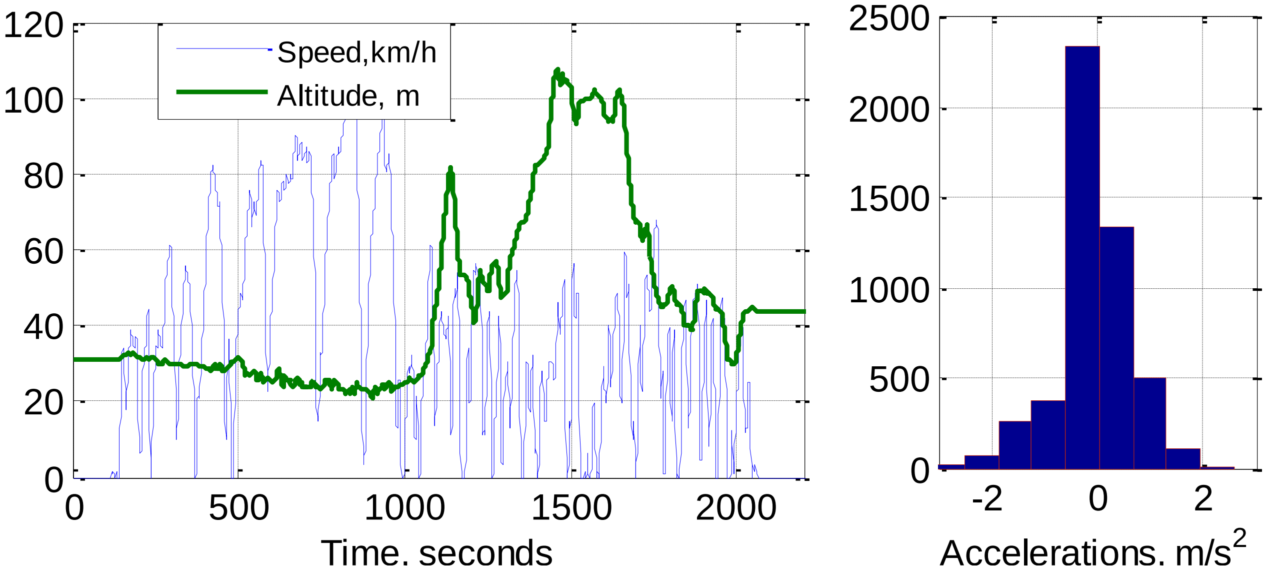

Figure 3. Speed and altitude profiles and accelerations histogram for Karaman Go Route (12/06/2009).

Table 1. Main characteristics of the routes

	Campus (17.06.2009)	**Karaman (12.06.2009)**
Travel distance (km)	22.2	41.5
Travel time (seconds)	4521	5022
# of stop-and-go events	88	58
# of stop-and-go events/km	4	1.4
Altitude range (m)	27-221	21-108
Average of mean speeds of the micro-trips	19	26
Average of maximum speeds of the micro-trips	32	44

Figure 6 indicates histograms for the positive and negative micro-trip traction energies for the Campus routes. As can be seen from the histogram, 86% of the micro-trips have the NT energies less than 0.5 kW-h. The magnitude of the PT energies are little higher than that of the NT energies, and as mentioned earlier the differences correspond to the R&A losses.

Similarly, Figure 7 indicates the histograms for positive and negative traction energies for Karaman route. As can be seen from the histograms, the traction energies are much higher than that of Campus route. 50% of the micro-trips have NT energies less than 0.5 kW-h, only. Beside the magnitudes of the PT energies are significantly higher than that of the NT energies. The reason for the higher traction energies is the higher speed travels of the micro-trips for Karaman route. Moreover the longer travel distances make significant contribution to the PT energies of the micro-trips and make the PT energies much higher than the NT energies. As was given in Table 2, the number of stop-and-go events per km travel for Karaman route, which is 1.4, is significantly less than that of the Campus route, which is 4.

It is well known from the first law of thermodynamics that energy cannot be destroyed but converted to the other forms. In this sense, the braking energy can be converted to a useful form of energy with the regenerative braking system and stored in an energy storage system. If the braking energy was recovered with 100% efficiency and converted to mechanical energy, the bus would be needed energy to overcome R&A losses, only. Such an operation of a bus would be highly fuel efficient. Figures 6 and 7 are very useful for sizing the capacity of energy storage systems. Because of cost considerations, sizing of the energy storage system is quite important. A battery or a bank of ultra-capacitors (Ucap) can be used as an energy storage system to store the recovered braking energy in the form of electricity. But, Ucaps are generally preferred for city busses because of their higher specific powers, which can provide large burst of power within a few seconds. Since cost of a Ucap is still very high, capacity of the Ucap must be optimized based on the operating conditions of the city bus for a favourable cost/benefit ratio.

As can be seen from Figures 6 and 7, magnitude of the NT energy, which is the energy to be recovered, is strongly dependent on the bus route. If a Ucap with 0.5 kW-h of capacity was chosen, 86% of the NT energies of the Campus route would be recovered with the regenerative braking system and the rest would be lost with the mechanical braking.

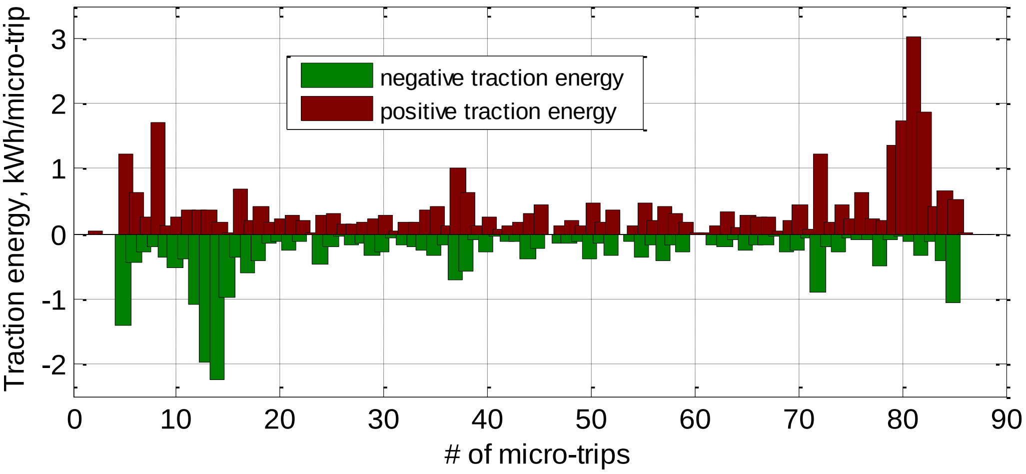

Figure 4. Micro-trip traction energies for the Campus route.

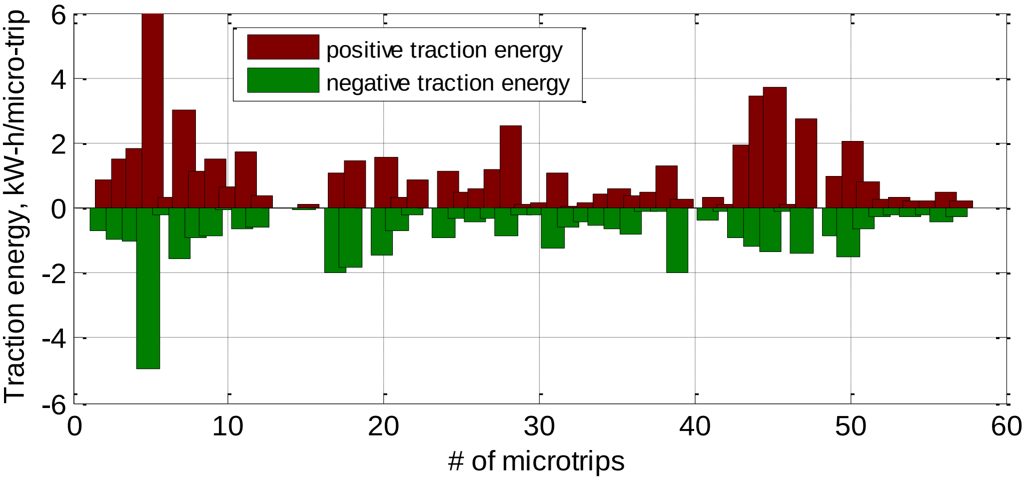

Figure 5. Micro-trip traction energies for Karaman route.

But if the same storage system was chosen for Karaman route, 50% of the NT energies would be recovered and the rest would be lost. For this reason sizing the capacity of the energy storage system is strongly dependent on the operating conditions of the bus. It is also important to mention it here again that the conversion of braking energy to electrical energy and storing it in a Ucap associate efficiencies. Figures 8 and 9 indicate cumulative energy lines for the Engine, PT and NT energies along with the speed and altitude profiles for the Campus and Karaman routes. As can be seen from the figures, both the PT and NT energies are very sensitive to the changes in the micro-trip altitude. The PT energy demands increase significantly with increasing altitudes (in the last 1000 seconds of Figure 8) while the NT energy demands increase significantly with decreasing altitudes (in the first 1000 seconds of Figure 8). The PT energies are approximately 25% less than the Engine energies. The difference between the Engine and PT energies correspond the powertrain losses from the engine to the wheels.

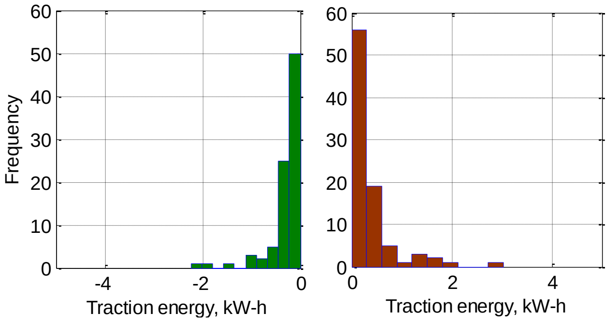

Figure 6. The negative and positive traction energy histograms for the Campus route.

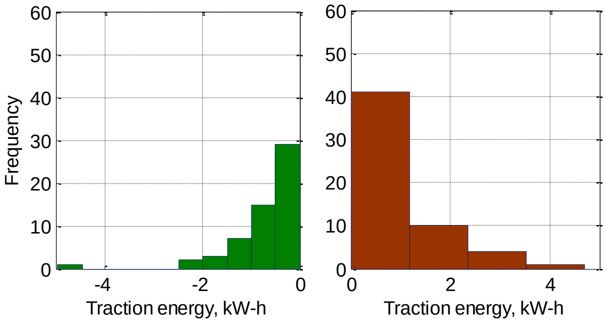

Figure 7. The negative and positive traction energy histograms for Karaman route

PT energies for the Campus and Karaman routes are 31.85 and 58.93 kW-h, respectively, and NT energies for the Campus and Karaman routes are -26.15 and -38.59 kW-h, respectively. The NT energies are about 82% and 65% of the PT energies for the Campus and Karaman routes, respectively. As mentioned earlier micro-trips of Karaman route have higher maximum speeds with longer distances and therefore the R&A losses are significantly higher than that of the Campus route. For this reason the NT energy of Karaman route corresponds to 65% of the PT while that of the Campus route is 82%. These NT energies are actually very significant and should not be wasted. Especially when considering the goals of the USDOE and EC to improve fuel economy of the vehicles for the next years, recovery of the braking energy provides a great opportunity.

For this reason, the hybrid electric city busses with regenerative braking system are taking serious attention for improving the fuel economy. As was given in the literature, assume that only 50% of the braking energies are recovered percentages of the energy savings for the Campus and Karaman routes will be approximately 40% and 30%, respectively.

CONCLUSIONS

Because of characteristics such as traffic conditions, frequency of bus stops and the road grades, the speed and altitude profiles of the Campus and Karaman routes of Sakarya Municipality are highly transient. Averages of the micro-trip maximum speeds are 36 and 44 km/h for the Campus and Karaman routes, respectively. The city bus accelerations for the Campus route have a range from -2 to 2 m/s^2 but, Karaman route has a slightly wider range.

The braking energy losses, which are normally wasted if it is not recovered, correspond to 82% and 65% of the PT energy for the Campus and Karaman routes, respectively. Actually, the braking energy losses correspond to the energy used to increase the KE after the bus stops and the PE due to positive road grades. The R&A losses of the bus are inevitable losses, but the braking energy losses can be recovered.

As was given in the literature, assume that only 50% of the braking energies are recovered, percentages of the energy savings for the Campus and Karaman routes will be approximately 40% and 30%, respectively.

Since the micro-trip traction energies are directly related to the changes in the micro-trip speed and altitude, the sizing of the energy storage system is very important. If a recovered energy storage system with 0.5 kW-h of capacity was chosen, 86% of the NT energies of the Campus route would be recovered with the regenerative braking system and the rest would be lost with the mechanical braking. But if the same storage system was chosen for Karaman route 50% of the NT energies would be recovered and the rest would be lost.

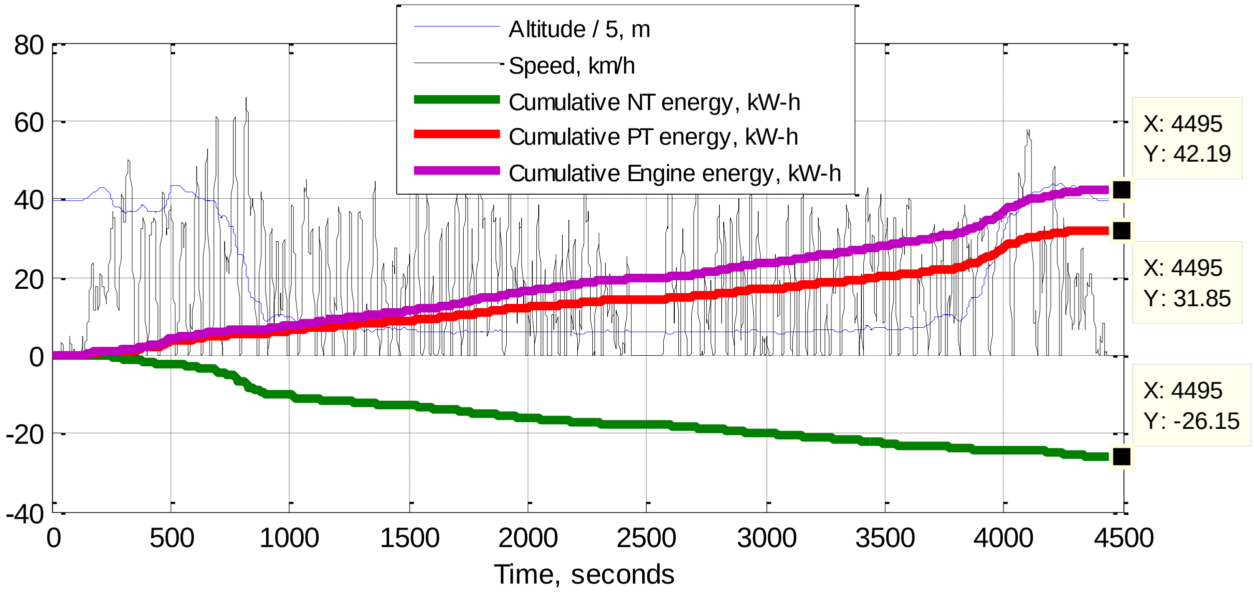

Figure 8. Positive and negative cumulative traction energies for the Campus route.

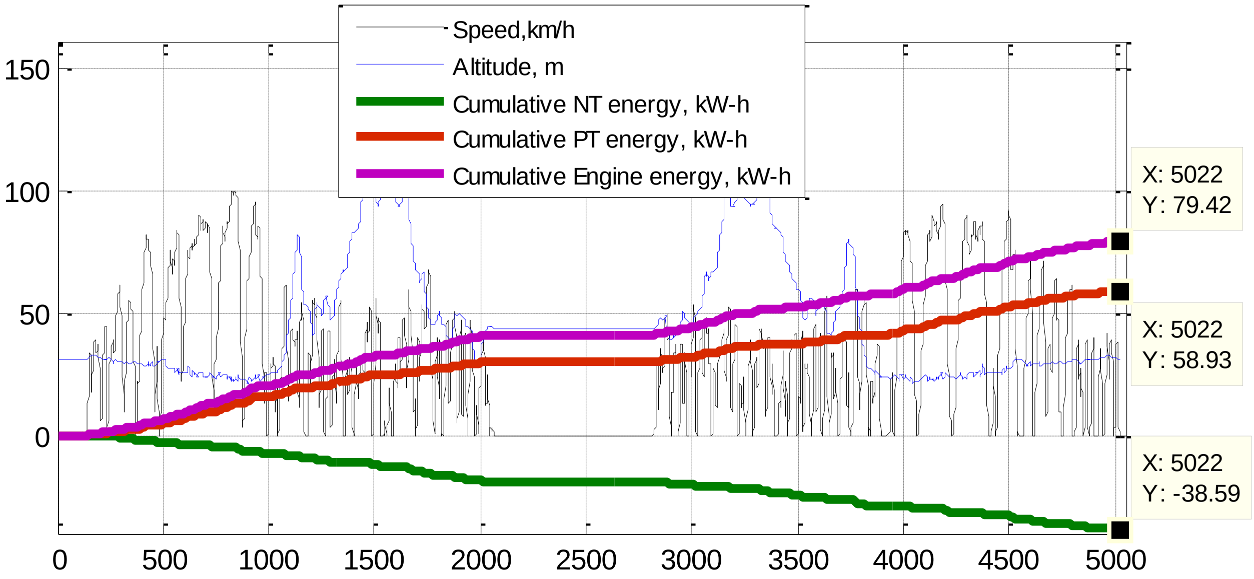

Figure 9. Positive and negative cumulative traction energies for the Karaman route.

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