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Energy Consumption and Environmental Impacts of Bus Rapid Transit (BRT) Systems

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ABSTRACT

Urban transport in most cities around the world is developing in an unsustainable fashion. This study examines if Bus Rapid Transit (BRT) is a promising transit option for cities looking to reduce their transportation-related emissions. The twenty case studies investigated in this research are from fifteen cities in Europe. The energy consumption and Carbon Dioxide (CO_2) emissions produced by these operating transit systems are calculated. The BRT trips are converted into equivalent passenger car trips and their corresponding emissions are estimated using data collected over ten years. Finally, the two emission results are compared to highlight the environmental benefits of adopting the bus transit system over the use of private cars. The research concluded that the use of BRT systems resulted in significant reductions in CO_2 emissions in all cities.

KEYWORDS: Bus Rapid Transit (BRT), Energy consumption, Transport emissions, Air pollution, Fuel consumption.

INTRODUCTION

Urban transport in most cities around the world is developing in an unsustainable fashion. This is reflected by rapid growth in traffic congestion and air pollution driven by individual motorization (Schipper and Fulton, 2002). With the financial constraints present in most economies, Bus Rapid Transit (BRT) system is emerging as a viable alternative to rail-based public transport systems. Strengthened bus systems, built on rapid bus corridors, and improved bus technologies could play an important role in putting cities on a more sustainable path.

Air pollution is a major environmental problem in many urban areas. Automotive emissions play a major role in global warming, air pollution and urban air quality. Greenhouse-gas emissions contribute to the global greenhouse effect. The air pollution problem intensifies with increasing urbanization and growing levels of motorization. Moran and Gonzalez (2007) stated that transport is the second largest source of greenhouse gas (GHG) emissions in the European Union (EU); accounting for 26% of the total carbon dioxide (CO_2) emissions. According to the European Commission (2005), road transport is the largest source of emissions in the EU (84% in 2005), followed by air transport (13%), inland navigation (1.7%) and rail (0.8%). Vincent and Jerram (2006) stated that the BRT can provide significantly greater CO_2 reductions than Light Rail Transit (LRT) for most US cities. The main reason appears to be the generation mix of electricity used to power LRT. Additionally, the per passenger mile CO_2 emissions for a BRT system were found to be significantly lower than those of an LRT system.

The purpose of this research is to demonstrate how

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such bus transit systems contribute to the reduction of pollutant emissions and energy required for mobility. The outcome of this assessment can be employed to encourage decision makers in Jordan to adopt the BRT system as a transportation alternative in congested cities, such as Amman. Additionally, the findings of this study can assist transport planners in estimating the savings and benefits of their proposed BRT corridors by adapting the approach of this study to their own communities. Eventually, this study could support and encourage the choice of BRT as a viable transit alternative.

Data employed in this study are collected from twenty BRT systems operating in Europe. The essential seven features of BRT systems are: busways, frequent service, fast boarding, off-board fare collection, modern stations, high-capacity vehicles and a system image that is uniquely identifiable (Jazrab et al., 2002). These components make up the backbone of the whole system and determine the potential capacity, reliability and speed of the system. Although many assumptions are necessary to estimate the emission benefits and energy savings from the BRT implementation, the modified methodology from the research might be useful in communicating BRT benefits in any metropolitan area.

Table 1. Comparison of BRT Systems

BRT System	Country	City	Population of City (000)	Daily Ridership (trips/day)
Triskell	France	Lorient	190	10,000
TVM	France	Paris	11,000	66,000
TEOR	France	Rouen	495	49,000
Line 5	Germany	Hamburg	1,800	60,000
Malahide Line	Ireland	Dublin	1,100	20,000
Red Line	Italy	Prato	180	9,000
Blue Line	Italy	Prato	180	5,500
Green Line	Italy	Prato	180	8,500
Line 2	Italy	Brescia	190	12,000
Red Line	Italy	Pisa	90	8,000
Green Line	Italy	Pisa	90	4,000
Blue Line	Italy	Pisa	90	3,000
Line 11	Netherlands	Utrecht	300	20,000
Line 12	Netherlands	Utrecht	300	25,000
Zuidtangent	Netherlands	Amsterdam	1,450	60,000
Junqueira	Portugal	Lisbon	550	27,000
Line 4	Sweden	Stockholm	1,900	160,000
Line 16	Sweden	Goteborg	530	45,000
Line 31	Switzerland	Zurich	400	15,000
A6 Corridor	UK	Manchester	2,600	21,000

The twenty case studies investigated in this research are from fifteen cities, in both Northern and Southern Europe, who have adopted BRT as a transport mode. Table (1) presents the population data about each city and the user demand for the selected systems. Table (2) summarizes the operational data collected about the same transit systems analyzed in this research.

Economic history suggests that as people get richer, they increase their use of private transportation. Car ownership and the number of households and individuals with access to a car have been increasing more-or-less continually over the past decades in all European countries (Dargay et al., 2007). Figure (1) illustrates the car ownership levels (defined as the number of cars per 1000 inhabitants) in the European countries and cities studied and other countries in Asia, North America, South America and Australia. Apart from the United States, Australia and New Zealand, the European nations have the highest car ownership levels compared to the rest of the world. This trend in these high-income countries is expected to continue, associated with worsened traffic conditions and environmental concerns.

Table 2. Operational Data of BRT Systems

BRT System	**Length of Corridor (km)**	**Average Commercial Speed (km/h)**	**Daily Operation Span (h)**	**Peak Headway (min)**	**Off- Peak Headway (min)**
	L	V	H	h_{peak}	$h_{off\text{-}peak}$
Triskell	4.6	17	14	3	3
TVM	20	21	21	3.5	7.5
TEOR	29.8	17.5	17.2	4	10
Line 5	14.8	15.9	20	4	10
Malahide Line	6.1	16.5	17	2.5	3
Red Line	28	18	15.3	15	15
Blue Line	8.3	19	15	7	7
Green Line	5.5	16	15.3	7	7
Line 2	13.1	16	16	7	12
Red Line	16.79	16.6	14.4	9	10
Green Line	8.16	14.3	14.4	9	10
Blue Line	7.8	19.5	14.4	9	10
Line 11	6.7	20	19	5	5
Line 12	5.9	21	19	2.5	2.5
Zuidtangent	56	35	12	5	10
Junqueira	4.8	15	24	3	3
Line 4	11.7	15	16	5	10
Line 16	16.5	21	16	4	10
Line 31	11.1	14.8	19	7.5	10
A6 Corridor	15.5	18.4	24	5	10

Methodology

The study covers 20 BRT case studies from around Europe. Figures on energy consumption are calculated from the data provided by the different transport agencies responsible for the case studies covered. After determining the energy consumption for each system, the emissions produced by the existing European BRT systems are computed. In order to quantify the environmental benefit of these transit systems, the BRT trips are converted into equivalent passenger car trips and their corresponding emissions are estimated. Finally, the results are compared to highlight the environmental benefits of the bus transit system over the use of private cars.

The methodology adopted for the analysis of data considered: (a) the specific fuel consumption units/100 km/vehicle for methane in cubic meters (m^3) under normal conditions of 15°C and 1 bar pressure (100 kPa), liters for liquid form fuels (Diesel, Bio-diesel) and kWh for electrical vehicles; (b) the occupancy level (defined as the average number of passengers in the vehicle) in Europe was 2 passengers/car (EEA, 2011); and (c) the energy contents of fuels as summarized in Table (3).

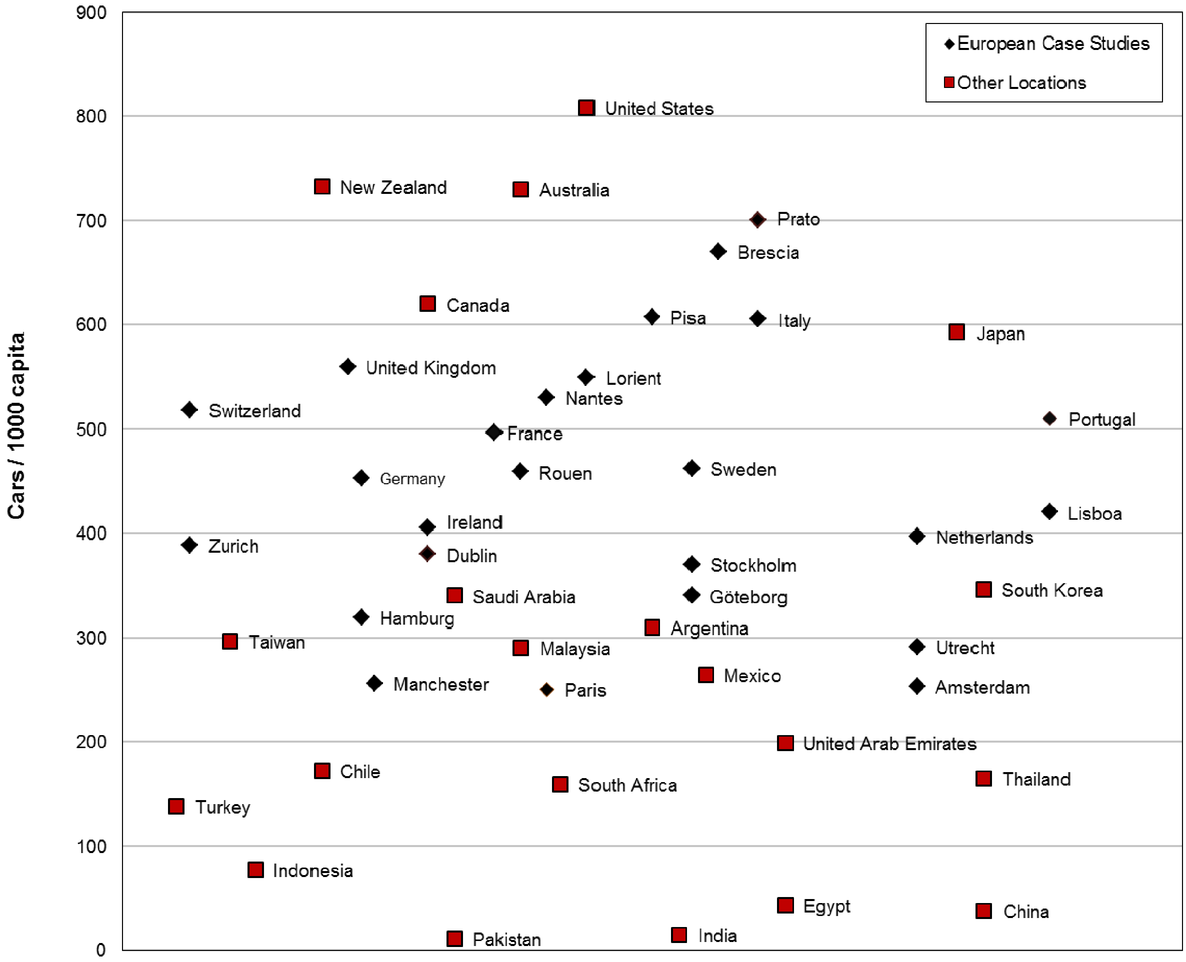

Figure 1: Car Ownership per 1000 Inhabitants (European Commission, 2011; World Bank Data, 2011; Nation Master, 2011)

Table 3. Energy Contents of Fuels (Schipper and Fulton, 2002)

Hydrogen	11 MJ/m^3
Ethanol	21 MJ/liter
Liquefied Petroleum Gas	24 MJ/liter
Petrol	32 MJ/liter
Bio-diesel	33 MJ/liter
Natural Gas	33-38 MJ/m^3
Diesel	36 MJ/liter

RESULTS AND DISCUSSION

In order to estimate the energy consumption of each BRT system, two values have to be calculated. The first is the total distance in revenue service (K), whereas the second is the number of buses operating daily (n) in the network.

Traveled Kilometers in Revenue Service (K)

The kilometers covered by a line in one day (K) are calculated by Equation 1 as follows:

$$K = v \times H \times n \qquad (1)$$

where:

K = kilometers run in one day;
v = average speed in km/h;
H = daily operating hours (service span);
n = number of buses in the line.

Number of Buses (n)

The number of buses needed to ensure the weighed headway (n_w) is found by Equation 2:

$$n_w = \frac{2 \times L}{h_w \times v} \qquad (2)$$

where

n_w = number of buses in the line;
L = length of the corridor in m. If “corridor” is replaced by “line”, then 2 is omitted.
h_w= weighed headway in min;
v = average speed in m/min.

For each BRT system, two headways in minutes have been collected: peak and off-peak headways. The weighed headway (h_w) is calculated using Equation 3 below:

$$h_w = \frac{H}{\frac{H_{peak}}{h_{peak}} \times \frac{H_{off-peak}}{h_{off-peak}}} \qquad (3)$$

Fuel Consumption (F)

The daily fuel consumption (F) can be calculated by Equation 4 as follows:

$$F = K \times f = v \times H \times n_w \times f \qquad (4)$$

where:

F = overall daily fuel consumption in volume units;
K = kilometers run in one day;
F = specific fuel consumption per bus in volume units/ km;
v = average speed in km/h;
H = daily operating hours;
n_w = number of buses (weighed).

Table 4. Fuel Consumption Results of the BRT Systems Studied

BRT System	h_w	n_w	K	f	F
Lorient – Triskell	5.9	10.82	2,575	45	1,159
Paris – TVM	6.96	19.38	8,547	61	5,213
Rouen- TEOR	2.83	29.34	8,831	67.5	5,961
Hamburg-Line 5	7.27	15.36	4,884	60	2,931
Dublin – Malahide Line	3	15.66	4,393	55	2,416
Prato- Red Line	7.83	12.44	3,426	45	1,542
Prato- Blue Line	5	7.44	2,120	35	742
Prato- Green Line	2.5	5.89	1,442	35	505
Brescia LINE 2	7.62	10.01	2,563	65	1,666
Pisa - Red Line	6.81	12.6	3,012	47	1,416
Pisa- Green Line	9.19	7.2	1,483	47	697
Pisa- Blue Line	8.78	4.8	1,348	47	633
Utrecht- Line 11	9.63	8.83	3,355	62.5	2,097
Utrecht- Line 12	9.63	13.49	5,383	62.5	3,364
Amsterdam- Zuidtangent	15	24.53	10,303	55	5,666
Lisbon- Junquiera	7	12.8	4,608	56.5	2,604
Stockholm-Line 4	9.63	12.29	2,950	80	2,360
Goteborg-Line 16	7	13.85	4,654	80	3,723
Zurich- Line 31	9.81	9.79	2,753	42.5	117
Manchester – QBC	3	11.51	5,083	55	2,796

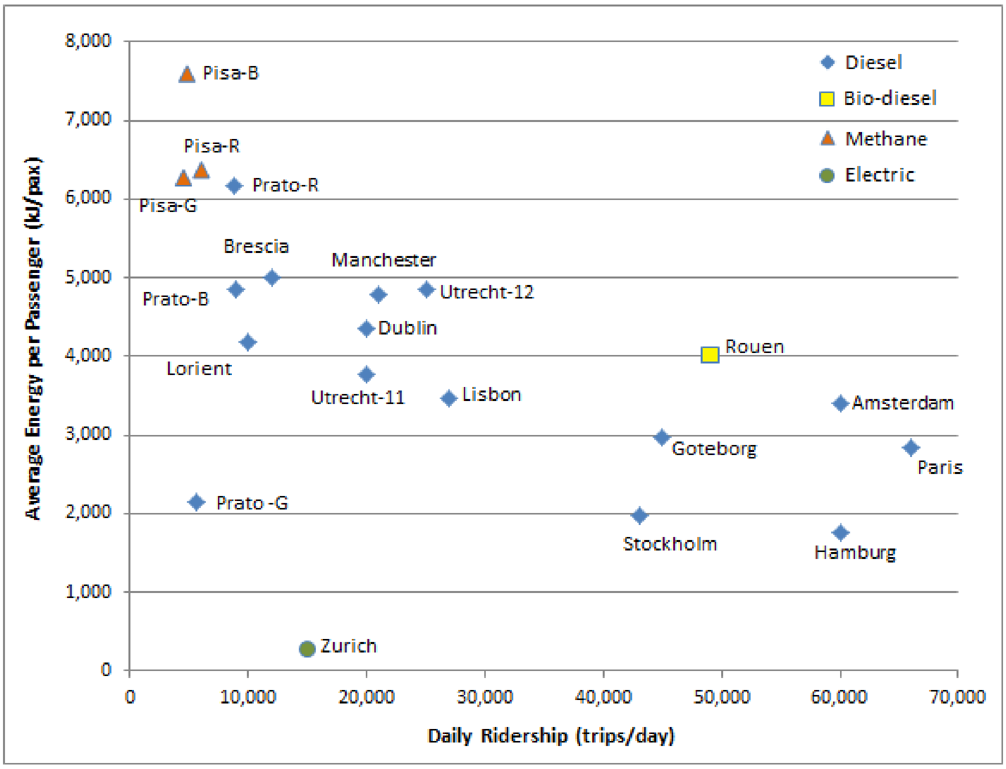

Figure 2: Average Energy per Passenger *vs.* Daily Ridership

The results of the fuel consumption calculations are summarized in Table (4) for each BRT system investigated in this research.

Dividing the overall daily energy consumption by the daily ridership provides the average energy consumption per passenger. Figure (2) is a plot of the average energy consumption per passenger (in kJ) *versus* the daily ridership for all the BRT systems investigated. The systems studied use four different energy sources: diesel, bio-diesel, methane and electric energy. The graph follows the general trend of a lower energy per passenger for the higher capacity systems (greater than 30,000 trips/day). Figure (3) is a plot of the energy consumption per passenger (MJ/pax) for all 20 transit systems examined in this paper.

As presented in Figure (3), the values for energy per passenger trip ranged between 1.7 and 7.6 MJ, with a strong concentration around 3 MJ per passenger trip for systems with daily ridership of around 30,000 passenger trips or less. This represents a major energy saving when compared to motorized trips which have an average value of 4.7 MJ/km in Europe (Kenworthy, 2003).

Calculation of Emissions

In this section, carbon dioxide emissions produced by the existing European BRT systems are calculated based on the energy consumption values estimated in Table (2) and Figure (3). The BRT trips were then converted into equivalent passenger car trips to calculate their corresponding emissions. Finally, the two emission results are compared to highlight the environmental benefits of adopting the bus transit system over the use of private cars. The Carbon Dioxide (CO_2) emissions from the different fuel sources can be calculated as:

$$q_{CO_2} = \frac{c_f}{h_f} \times \frac{C_{CO_2}}{C_m} \qquad (5)$$

where:

q_{CO_2} = specific CO_2 emissions (CO_2/kWh);
C_f = specific carbon content in the fuel (kg_C/kg_{fuel});
h_f = specific energy content (kWh/kg_{fuel});
C_m = specific mass of carbon (kg/mol Carbon);
C_{CO_2} = specific mass of carbon dioxide (kg/mol CO_2).

Equation (5) was applied to compute emissions of carbon dioxide for diesel and methane (assuming no heat loss). The results are summarized in Table (5).

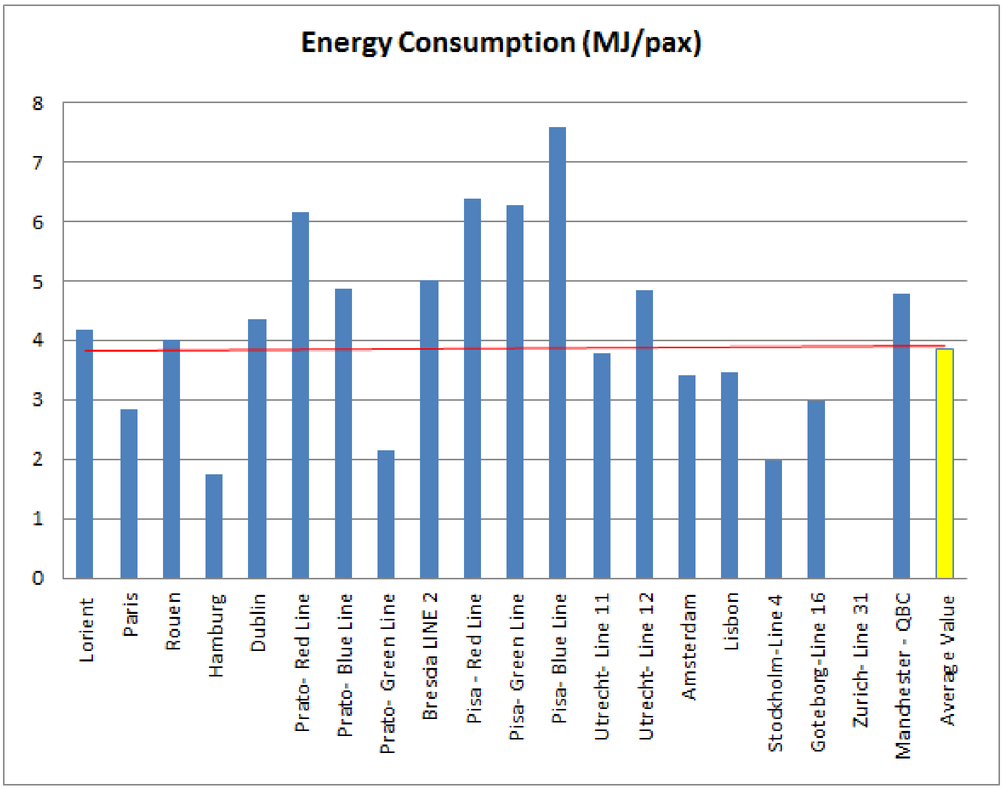

Figure 3: Energy Consumption per Passenger

Table 5. CO_2 Emissions of Diesel and Methane

Fuel	**Specific Carbon Content (kg_C/kg_{fuel})**	**Specific Energy Content (kWh/kg_{fuel})**	**Specific CO_2 Emission (kg_{CO2}/kg_{fuel})**	**Specific CO_2 Emission (kg_{CO2}/kWh)**
Diesel	0.86	11.8	3.2	0.24
Methane	0.75	12	2.8	0.23

As for bio-diesel, USEPA (2002) reported that the addition of bio-diesel to a clean base fuel causes a moderate increase in carbon dioxide emissions, while the use of animal-based bio-diesel with an average base fuel is predicted to produce a slight decrease. Based on this conclusion, this study assumed that carbon dioxide emissions from bio-diesel are similar to those from diesel. Lastly, the amount of carbon dioxide emissions resulting from electricity generation depends on the source of electricity. Some typical values in grams of CO_2 per kWh for various generation technologies are: coal = 950, oil = 900, natural gas = 600, gas (combined cycle) = 450, solar photovoltaic = 50, nuclear = 6, wind = 4.5 and hydro = 3. This study adopted an average value of 370 g of CO_2/kWh for electric energy, with no transmission and distribution losses.

The data from Figure (4) along with the assumptions regarding the fuel types are used to compute the daily emissions (in kg of CO_2) resulting from the operation of the BRT systems. The calculations are presented in Table (6).

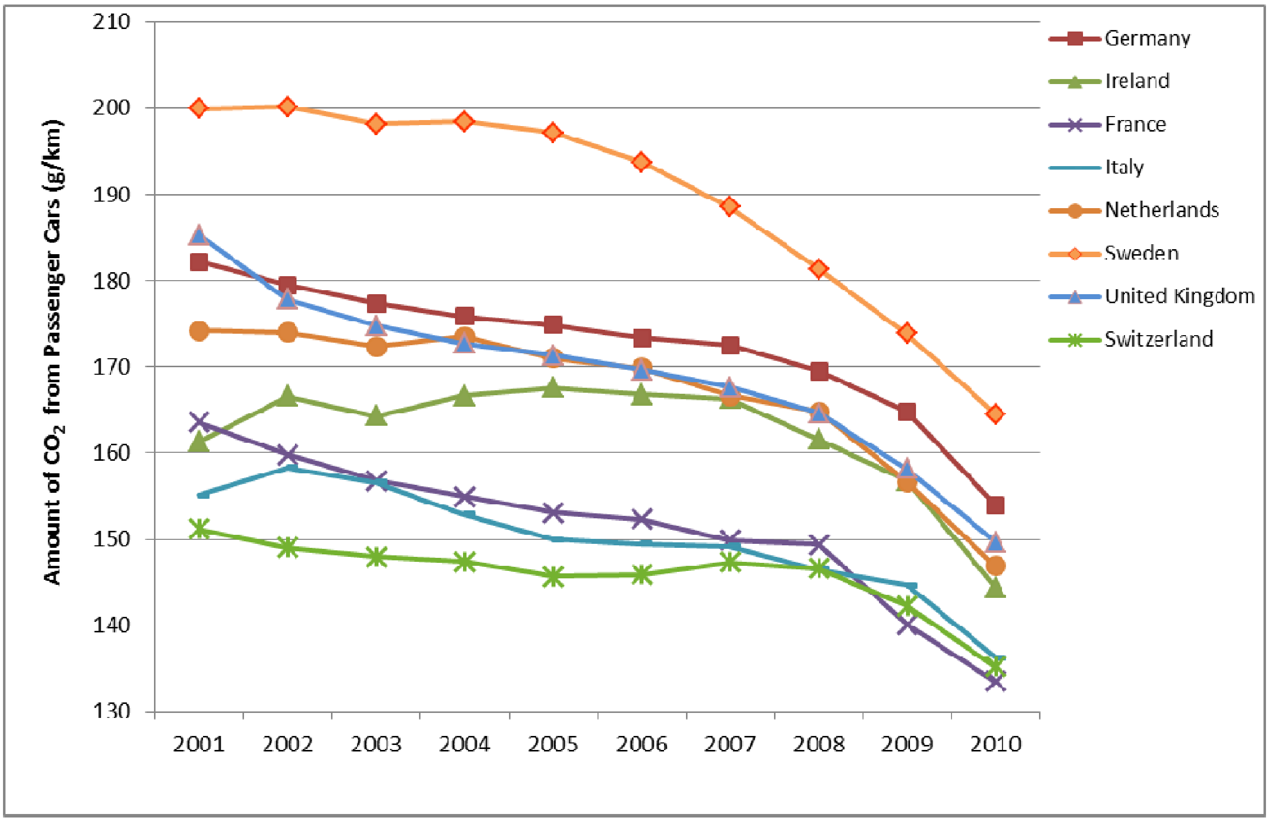

Figure 4: CO_2 Emissions (g/km) from Passenger Cars in the European Countries

In order to complete the calculations, an estimate of the emissions of the equivalent passenger car trips should be obtained. To perform this calculation, two more variables are required: the average car occupancy and the CO_2 emissions per km from passenger cars. An average car occupancy value of 2 passengers was assumed, while the CO_2 emissions per km from passenger cars (in g/km) were collected for all the BRT locations for the years from 2001 to 2010, as shown in Figure (4).

Figure (4) shows that the average CO_2 emissions per km from passenger cars in all the European countries have considerably decreased with time due to the more fuel-efficient engines, the new hybrid technology and the greener cars introduced across Europe. Despite these improvements, the magnitude of the emissions resulting from individual motorization remains considerably high.

It should be noted that the old paradigm of electric-powered buses being greener than diesel buses is still valid. Despite the dramatic improvements in auto emissions observed in Europe over the past decade, further reductions entail changes in a combination of factors such as the adoption of renewable or non-fossil based fuels, significant declines in energy intensity, shift to less energy intensive modes or reductions in travel. The decline in energy intensity refers to increases in load factors (i.e., car occupancy). The alternative technologies mentioned include fuel cells and gasoline-electric hybrid engines which have proven their potential in reducing CO_2 emissions in the road transport sector. Nevertheless, a reduction in travel could be expected through appropriate pricing policies that reflect the environmental costs of travel.

The results of both emission calculations for all the case studies explored are summarized in Figure (5). The bar chart depicts two values per system; one is the daily emissions of the BRT system in operation, while the second is the daily emissions from its equivalent passenger cars.

Table 6. CO_2 Emissions of the BRT Systems Investigated

BRT System	Type of Fuel	Units of Volume	Capacity of Buses	*F*	Fuel Density	Specific CO_2 Emissions	CO_2 Emissions (kg/day)
Lorient	diesel	liters	85	1,159	0.85	3.2	3152
Paris	diesel	liters	85	5,213	0.85	3.2	14179
Rouen	bio-diesel	liters	85	5,961	0.89	3.2	16977
Hamburg	diesel	liters	120	2,931	0.85	3.2	7972
Dublin	diesel	liters	85	2,416	0.85	3.2	6572
Prato- Red	diesel	liters	85	1,542	0.85	3.2	4194
Prato- Blue	diesel	liters	85	742	0.85	3.2	2018
Prato- Green	diesel	liters	85	505	0.85	3.2	1374
Brescia	methane	m^3	85	1,666	0.68	2.8	3172
Pisa - Red	diesel	liters	85	1,416	0.85	3.2	3852
Pisa- Green	diesel	liters	85	697	0.85	3.2	1896
Pisa- Blue	diesel	liters	85	633	0.85	3.2	1722
Utrecht- 11	diesel	liters	85	2,097	0.85	3.2	5704
Utrecht- 12	diesel	liters	85	3,364	0.85	3.2	9150
Amsterdam	diesel	liters	120	5,666	0.85	3.2	15412
Lisbon	diesel	liters	85	2,604	0.85	3.2	7083
Stockholm	diesel	liters	85	2,360	0.85	3.2	6419
Goteborg	diesel	liters	85	3,723	0.85	3.2	10127
Zurich	electric	kWh	120	117	-	0.37	43
Manchester	diesel	liters	85	2,796	0.85	3.2	7605

The emission calculations highlight the huge savings achieved when using the BRT, as opposed to individual motorized transport in the form of passenger cars. Figure (5) emphasizes the gap between the two emission values estimated. Overall, the BRT emissions ranged between 11% and 85% of the passenger car emissions.

The three case studies from Pisa using methane had an average reduction of 35% in CO_2 emissions. The Rouen BRT using bio-diesel achieved a significant 83% saving in CO_2 emissions. Finally, the diesel case studies achieved an average fall of 60% in CO_2 emissions. The Zurich example is the only case with 100% drop in emissions due to the BRT adopting the electric trolley buses that produce no tailpipe emissions. Overall, the environmental benefits of this type of transit system are substantial.

The performance of a BRT system is usually measured by travel time, reliability, identity and safety. BRT systems face the challenge of being related to conventional bus services, which studies suggest are unattractive to choice users. However, with their encouraging fuel consumption values, transport agencies could use these findings to help overcome this image problem. When environmental benefits are considered (as outlined by the investigated European

BRT examples), cities like Amman, planning their own bus-based transit system, could support their project's benefit-cost analysis and system appraisal by including emission reduction calculations plus its associated benefits. The benefits of controlling vehicular pollution may be realized in several ways, including reductions in population mortality and morbidity; improvements in visibility; reduced damages to crops, vegetation, ecosystems, buildings and materials; and reduction in pollutants contributing to climate change. The results of many studies indicate that population health improvements often comprise the most substantial fraction of monetized benefits (Evans et al., 2002). Of these health improvements, the majority of the monetized benefits are usually related to the reductions in airborne fine particulate matter ($PM_{2.5}$).

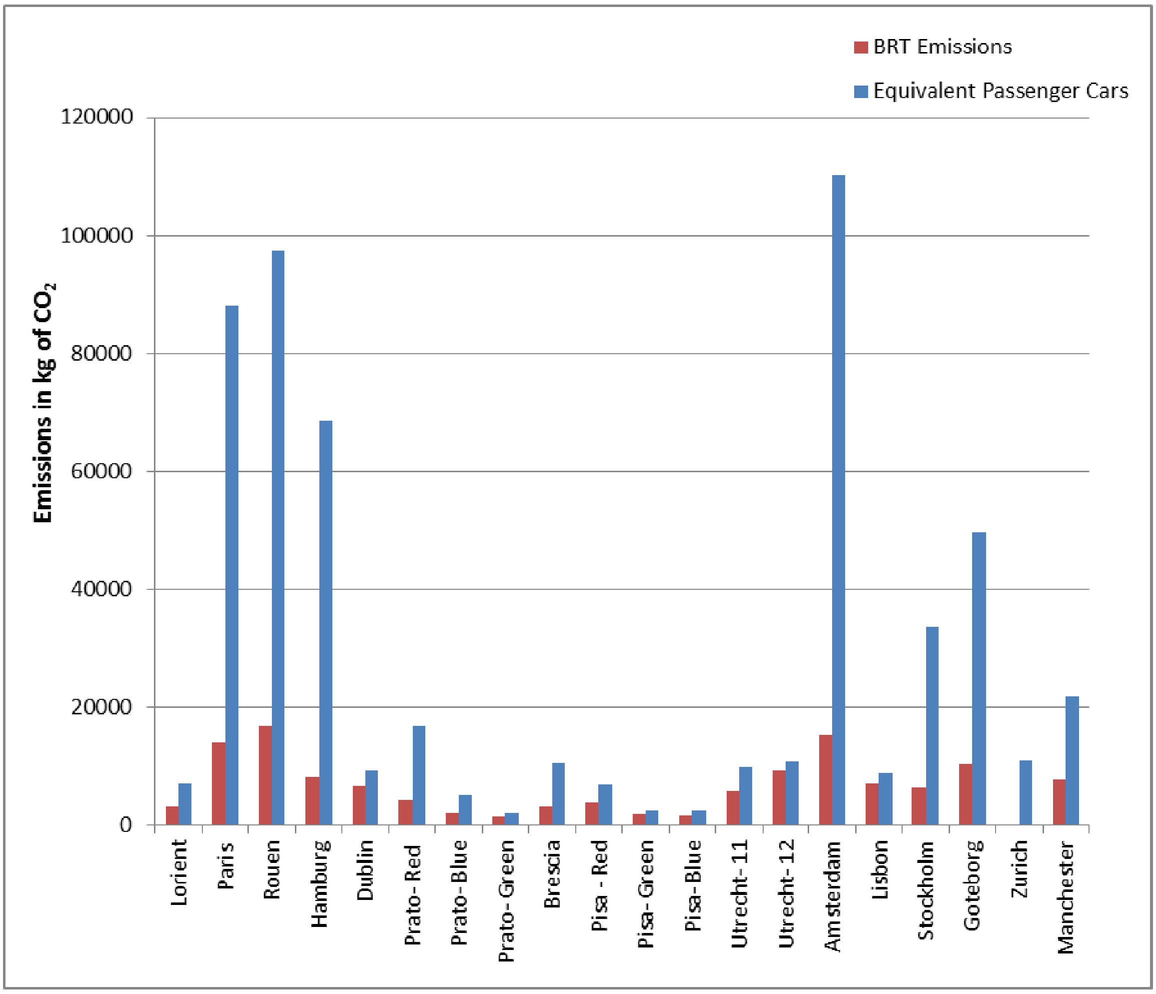

Figure 5: Daily Emissions (kg of CO_2) of the BRT and the Equivalent Passenger Cars

CONCLUSIONS

This work examined and analyzed various existing BRT systems. The work focused on the energy consumption and CO_2 emissions of the BRT systems. The study concluded that the values for energy per passenger trip ranged between 1.7 MJ and 7.6 MJ, with a strong concentration around 3 MJ per passenger trip for systems with daily ridership of around 30,000 passenger trips or less. This represents a major energy saving when compared to motorized trips which have an average value of 4.7 MJ/km in Europe.

The emission calculations highlight the huge savings achieved when using the BRT, as opposed to individual motorized transport in the form of passenger cars. Overall, the BRT emissions of the systems considered ranged from 11% to 85% of their corresponding equivalent passenger car emissions.

In conclusion, with the continuing rise in traffic congestion levels, a backlog of infrastructure needs and renewed environmental concerns, more and more focus is given to public transportation and new technologies that enhance the performance of transit systems. BRT is considered one of the promising high-performance, cost effective solutions that provide high quality services to the users.

RECOMMENDATIONS

Other possible areas for further analysis would be to calculate non-CO_2 emissions which are main contributors to climate change; like nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter. An area for further research would be to add an exposure model that includes not only the absolute amounts of emissions but also the exposure of these emissions to the population. Measurements of gaseous pollutants and particulate matter could be taken at different distances from the BRT corridors for development of exposure models for these emissions.

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