A comparative analysis of energy usage and emissions of transport systems

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Abstract

This study compares transport systems with respect to their energy consumption and airborne emissions. Both of these characteristics have been quantified with respect to the distance travelled by users at current occupancy rates. The study concludes that the petrol fuelled car equipped with a three-way catalytic converter currently offers the least overall impact upon the urban environment when compared with the diesel car, train and possibly bus. However, should these vehicles adopt the use of certain emissions reduction technologies this situation is likely to change. Electric forms of transport offer improved characteristics in the urban area and incur lower quantities of ‘greenhouse’ gases. Nevertheless, the problem of high sulphur dioxide emissions will remain for the foreseeable future. The Personal Rapid Transit option offers the possibility of mitigating many of the problems created by personal mobility.

1 Introduction

Major concerns have been expressed over both the energy usage and emissions output of current transport systems and there are now international efforts to reduce the negative impact of transport due to these environmental factors. Many of the suggestions for improving the environment relate to the transfer of trips from one mode to another. Thus it is important to have a clear understanding of the energy and emissions output of various transport modes.

Comparison of the environmental effects of various transport systems is not a straightforward task. The use of statistics based upon basic design figures for each vehicle would exclude the critical effects of operating parameters. In particular, no form of transport operates at its peak capacity for more than a short period of the day, so that useful comparisons of different transport systems must take into account the anticipated loading.
The objective of the present paper is to present a comparative analysis of the energy and emissions characteristics of various transport systems on a uniform basis. The paper is divided into two main sections dealing with energy and emissions issues respectively, together with a discussion. A brief discussion is also presented of a Personal Rapid Transit (PRT) approach which appears to offer significant benefits for both energy and emissions output.

2 Energy consumption of various modes of transport

The most useful overall measure of a transport system’s efficiency, is the energy consumption per passenger kilometre. The first step in deriving this relationship is to ascertain the average passenger load of the vehicles on each particular system.

The occupancy for each transport mode, as illustrated in Figure 1, was calculated using data detailing both the vehicular and passenger distances travelled, DoT\textsuperscript{2,3}. In cases where the operators used a variety of vehicles of different sizes, the average was derived by finding the configuration of vehicle stock and weighting the seating capacity of each vehicle type with respect to the relative distance travelled.

There are several features on Figure 1 which should be noted:

- The loading factors for trams/LR are overestimates because vehicles of this type are designed with minimal seating to allow greater ‘crush’ capacity and therefore the number of seats is not an accurate estimate of their maximum capacity. Low passenger loads may be expected on these systems under current demand rates because of the quality of their service. Such systems operate extremely frequent timetables; the Manchester Metro, for example, provides a service every 6 minutes throughout the day and the London Underground offered an average waiting time of only 3.2 minutes in 1993, LUT\textsuperscript{7}.

- The loading factor for trains was derived from statistics detailing the Network Southeast and Regional Railways operations, DoT\textsuperscript{2} . The average passenger loads of trains operating purely in the urban area was unobtainable due to the limited available data.

- The average loading factors for electric and petrol cars differ. This is because although the same mean occupancy has been assumed for each type of vehicle, the passenger capacities are different; the average petrol car has around 5 seats, whilst the average electric car only offers 3.

It is interesting to find that the average load factor for most collective transport is the same, or in some cases worse, than the car. However, these average figures hide very high peak loadings for mass transport systems when they are
far more capable than passenger cars. The overall effectiveness of collective transport is severely degraded by inefficiencies off peak.

The average loading factors have been combined with the mean energy consumption of the respective vehicles to obtain the energy consumption per passenger kilometre, as shown in Figure 2. This characteristic has also been illustrated with respect to seat kilometres and passenger kilometres at ‘crush’ capacity to demonstrate the theoretical efficiency of each transport mode.

![Figure 1. Average passenger loads for various modes of transport in the UK with respect to seating capacity, (1993).](image)

![Figure 2. Primary energy consumption per kilometre travelled by various modes of transport in the urban area, (1993).](image)
The data used to calculate Figure 2 was obtained from the following sources:

1,2 Based on the fuel consumption of the average size TWC petrol and diesel car, calculated from data compiled by the TRL. This data represents the whole UK car fleet operating over an urban cycle and includes cold starts, [Gover, et al, 1994].

3 Based upon the average energy consumption of 20 different EVs travelling over urban cycles.

4 Based upon the average urban fuel consumption calculated from data compiled by the TRL for buses of different sizes, [Gover, 1994].

5,6 Energy consumption figures acquired from the operators.

7,8 The urban energy consumption of trains, was obtained from the British Rail Train Performance Team for several different EMUs and DMUs travelling on Birmingham’s cross city line from Reddich to Lichfield.

9 The fuel economy of motorcycles was obtained from the manufacturers.

10 The fuel economy of aeroplanes was acquired from Janes’ All the World Aircraft, 1989/90.

Figure 2 represents transport systems operating in the urban environment. The analysis not only considers the vehicular inefficiencies but also the losses incurred during fuel extraction, transport and processing, Gover⁶, and in the case of electrically powered vehicles the losses suffered during electricity generation and transmission, ETSU⁴.

Table 1, lists the present results for MJ/pax km and gives the results of other similar studies which highlights several disparities. The most significant is that of the urban bus which has previously been calculated to consume less energy per passenger kilometre. This variance may be attributed to several factors. The bus industry has recently been through considerable upheaval with the deregulation of buses in 1986. As operators battle for particular routes this has generated increased mileage whilst the number of journeys taken by bus has been reducing. Since 1983 the annual distance travelled has increased by over 20 % as the number of passenger trips has fallen by 21 %, DoT².

Table 1. Results of previous studies on energy use.

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<tbody>
<tr>
<td>Train MU</td>
<td>1.35</td>
<td>1.7</td>
<td>1.9</td>
<td>1.3</td>
<td>1.2-1.4</td>
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<tr>
<td>Urban bus</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>0.3-0.9</td>
<td>1.2</td>
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<tr>
<td>Tram / LR</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>2.4-2.5</td>
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<tr>
<td>Urban car</td>
<td>3.1</td>
<td>-</td>
<td>3.2</td>
<td>2.2</td>
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<td>1.9-2.0</td>
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<tr>
<td>Electric car</td>
<td>-</td>
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<td>1.7</td>
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<tr>
<td>Plane</td>
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<td>-</td>
<td>3.3</td>
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<tr>
<td>Motorcycle</td>
<td>1.7</td>
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Previous studies indicate that the modern car consumes less energy per unit distance travelled. This may be explained by the recent efficiency improvements which have been made, particularly under urban conditions, with new engine and fuel technology.

It is interesting to note that the energy consumption per passenger kilometre travelled by mass transport systems relates to the quality of the service as well as vehicle efficiency. Shorter waiting times result with lower average passenger loads and correspondingly greater energy consumption. The difference between personal and mass transport modes is fairly mixed, with trams/LR consuming more energy per passenger kilometre than cars.

3 Emissions generated by various modes of transport

The energy consumption figures derived in Section 2 have been used as a starting point, to project the emissions generated by different transport systems for the year 2000. Projected figures were considered to be more useful when reviewing urban transport, especially as the increasingly tightening emissions legislation is generating rapid technological change in vehicle emissions control.

![Figure 3. Projected life cycle emissions for various modes of transport in the year 2000.](image-url)
Data used to calculate Figure 3 was obtained from the following sources:

1, 6, 7 These figures are based upon the average emissions produced by the projected electricity generating configuration for the year 2000, ETSU\(^4\), DoE\(^5\).  
2, 3 These figures were calculated from results gathered by the TRL which represents the most up to date and comprehensive set of data currently available for the UK vehicle fleet, Gover\(^6\). This data defines both hot and cold emission levels which were weighted to emulate the typical fraction of urban mileage travelled under cold conditions. It has been assumed that by the year 2000 the petrol car will be equipped with a rapid heat-up Three-Way Catalytic converter, reducing the HC and CO emissions expelled before the catalyst has attained operating temperature. The advanced diesel car is expected to adopt the oxidation catalytic converter which will be permitted by the reduced sulphur levels in diesel fuel. Both vehicles are of average engine size.  
4, 5 The diesel and CNG buses have used figures projected by Gover\(^5, 6\), for new buses that will meet the Stage II emissions levels expected towards the end of 1996. The CNG bus is assumed to be equipped with a TWC.  
8 The emissions produced by the DMU were assumed to be similar per unit energy consumption to those of a Heavy Goods Vehicle, (HGV), greater than 17 tonnes in weight. The emissions of these vehicles has been derived by the TRL, Gover\(^6\).

Figure 3 illustrates the emissions produced over the average passenger kilometre by each mode of transport in the urban area. Each figure represents the whole life cycle and therefore includes not only the vehicle emissions but also the pollution generated during every stage of fuel production. The analysis has been limited to emissions of regulated air pollutants: hydrocarbons, nitrogen oxides, carbon monoxides, sulphur dioxides and particulates. The environmental and health risks of nuclear power have not been included in the analysis. Furthermore, the emissions generated during vehicle and infrastructure manufacture have not been considered.

This projection includes several new technologies which are likely to be introduced and therefore does not examine the average emissions generated by the UK vehicle stock, but the levels produced by the latest models. All of the vehicles with the exception of the trams and trains, which are not likely to change over the 7 year period examined here, have received a fuel economy improvement of 1 % per year up to the year 2000, a typical increment for passenger cars, Sorrell\(^8\). The loading factors of each type of vehicle were assumed to remain the same over this period.

4 Discussion

It is difficult to evaluate the damage potential of the combinations of pollutants generated by each vehicle, especially between those which are electrically powered and those running on oil-based fuels, as the constituents and relative
effects are diverse. Nevertheless, some preferable modes of transport have emerged from the analysis.

The introduction of the TWC has enabled the modern petrol car to obtain emissions levels far lower than those of its predecessors. However, the petrol engine does still discharge relatively large quantities of CO$_2$, CO and HC into the urban environment.

The diesel engine produces far lower emissions in terms of weight, although the nature of the pollutants changes with significantly more particulate matter and NOx gases being formed. The implications for urban air quality are complex as both particulate matter and nitrogen oxides are both primary and secondary pollutants. However, a study by the Department of the Environment$^1$, examining the effect of increased diesel penetration at the expense of TWC car usage has indicated that on balance a shift towards the diesel car will incur a deleterious effect upon urban air quality.

The global effects of diesel car penetration into the UK car fleet should also be considered. Nitrogen oxides are an important precursor of both acid rain and ozone, while certain hydrocarbons play an important role in the formation of tropospheric ozone. Increasing diesel car use is likely to offset the imminent reduction in ambient NOx concentration resulting from the introduction of the TWC, but is not expected to have a large effect upon acid deposition, DoE$^1$. Furthermore, it will mitigate the quantities of HC generated. A recent study by the Earth Resources Research for the WWF has compared the global warming effect for the TWC petrol and diesel car. It reports that whilst the average diesel car emissions of carbon dioxide are around 10 % lower, the global warming potential is about 20 % lower because diesel engines emit lower quantities of other greenhouse gases such as reactive hydrocarbons.

It may be concluded that the petrol car is preferable in the urban environment, although the global effects of using the diesel car are favourable. However, it is probable that the diesel car will be forced to adopt new technologies at the beginning of the next century, such as the particulate trap and TWC designed for the lean burn conditions found in the diesel engine. Should this occur then the diesel car is likely to become the more attractive option.

The analysis shows that the average bus produces considerably more NOx and particulates per passenger kilometre when compared with the petrol car. However, by the year 2000 modern buses will expel considerably less particulates than the diesel car. It would therefore be erroneous to simply extrapolate the relationship between the diesel and petrol car and further investigation will be necessary to assess the relative impacts. The TWC CNG
bus, on the other hand, does appear to offer considerable advantages over the TWC petrol car, producing lower emissions in every respect.

It has been assumed that modern diesel trains will not be forced to adopt any emissions control technologies by the year 2000. This train will emit high quantities of NOx, and particulate matter and when compared with the TWC petrol car will undoubtedly have a deleterious effect upon urban air quality.

Comparing vehicles powered by electricity, the scheduled electric train offers the lowest emissions per passenger kilometre. The tram/LR systems incur over twice this level of emissions, a factor which may be justified by their frequent service and also the higher station density.

The electric car offers a promising future mode of transport. It incurs lower emissions and energy consumption than the tram/LR systems and generates lower levels of NOx, CO, CO\textsubscript{2} and HC than any other personal vehicle. However, at present it remains hampered by limited range and high development costs. In California the Battery Technology Assessment Panel which reports to California’s Air Resources Board (CARB), has proposed to drop the legislation which demands 2\% of car sales to be zero emission vehicles by the year 1998, due to the continuing poor battery performance despite considerable investment.

Shifting people from the petrol car onto electrically powered forms of transport will inevitably have a positive effect upon the urban air quality as no emissions are produced by these vehicles at the point of use. However, the global effects are unclear. The large quantities of SO\textsubscript{2} generated by UK power stations are precipitated as acid rain which is thought to result in the destruction of fauna and freshwater habitats. Whilst, in all cases the studied here, electric modes of transport result in lower CO, HC and CO\textsubscript{2} emissions all of which have ozone forming potential. Therefore, a shift towards electrically powered vehicles is likely to reduce the greenhouse gases emitted by the transport sector. The relative mass of SO\textsubscript{2} and other pollutants expelled into the atmosphere by UK power stations will continue to decrease well into the next century as the electricity generating configuration moves away from coal towards clean burning gas fired CCGT power stations and the remaining coal fired stations become equipped with Flu Gas Desulphurisation plants and low NOx burners.

Of course the problem of urban transport is not this simple even in terms of energy consumption and air quality. By shifting the modal split from cars to collective transport systems the density of traffic may be reduced, improving flow throughout the urban area and allowing vehicles to operate more effectively, resulting with lower fuel use and emissions. Furthermore, collective transport will lead to a drop in the number of vehicles required to
service the population. Such a reduction will provide a useful decrease in the energy usage as around 24% of the energy consumed by a car over its life time, is employed during the manufacturing process.

There are many other considerations which have been overlooked by this report. Examples include the social and economic benefits of reduced congestion, community severance and passenger safety. Mass transport systems have a considerably better safety record than personal transport. In terms of fatalities per unit time exposure, travel by train and bus yield 3 and 15 times fewer deaths, respectively, than the passenger car.

Ultimately, we are attempting to improve the quality of life in the urban area, and this involves many different factors. Determining the preferable means of transport is a complex process as each mode presents an array of benefits and disadvantages which are not easily compared. The characteristics revealed by this study, has questioned the effectiveness of current mass transport systems in terms of emissions and have indicated that measures should be taken to mitigate their pollution levels. It may be argued that if public transport services were more attractive then people would be inclined to leave their cars at home and the relative energy consumption and emissions of the mass transit systems would increase. However, the reality is that 87% of travel in the UK is performed by cars and vans, indicating that people are attracted to the convenience and security of personal transport, which offers an infinite coverage, no waiting times and usually much shorter travelling times. The ability of any mass transport system currently available to match the quality of service presented by the passenger car is very unlikely.

However, there is one option which offers the possibility of reducing if not eliminating congestion in urban areas together with huge benefits in terms of energy consumption and emissions, whilst maintaining many of the benefits offered by the car. This mode of transport is known as Personal Rapid Transit (PRT) and was first described in a paper by LR Blake in 1966. More recently this idea has received renewed interest around the world as recent technological developments may now permit the concept to become a feasible means of transporting people.

The PRT system is based on the use of segregated guideways, to support many automated, guided, personal vehicles which act as ‘taxis’, being continually recirculated after delivering each customer to their destination. It is envisaged that the density of stations will be sufficient to allow users in the urban area to walk no further than 250m and stations will be off-line so stopping vehicles do not hinder the passage of others. This mass transport system is extremely appealing as it is not limited to corridor routes, offering direct rapid travel throughout the urban area which is available within minutes. In addition, this
system could easily be extended to offer inter-urban travel and would, for many journeys, provide an effective substitute for the car.

It is envisaged that the vehicles will run at a constant speed for the whole length of their journey as braking for junctions, roundabouts or traffic lights will not be necessary. The constant operating conditions will allow the power plant to be optimised for maximum efficiency and such a vehicle has been shown to yield at least a factor of three reduction in the energy used per passenger kilometre than the conventional electric car in urban traffic conditions, Coffey\(^{10}\). This translates to a factor of ten reduction in HC and CO emissions when compared with the petrol car and over a factor of three for NO\(_x\). SO\(_2\) and particulate components will be similar, but as power stations are usually found outside sensitive urban areas the overall damaging effects of this proposed system in terms of airborne emissions will be far less than any other mode of transport.

The computer controlled system will avoid driver delay and permit very short headways, increasing the capacity of the network and allowing it to carry more vehicles than a conventional road. Passengers will be taken by the quickest route to their destination, avoiding busy areas and thus evading congestion. It is expected that during peak hour traffic this system will reduce journey times by a factor of 2-3 when compared to the passenger car.

The construction of an extensive network of guideways throughout the urban area with a high density of off-line stations would require huge investment and real commitment for change. Nevertheless, this option provides the best solution presently available to the problem of personal mobility as it mitigates many of the difficulties associated with transport; pollution, energy consumption, congestion, safety and oil dependency. Furthermore, the system...
provides an opportunity to reinvent the city centre improving access and allowing it to thrive as an economic and social centre.

The main conclusions which may be drawn from this paper have been listed below:

• The energy consumption of mass transport is highly dependent upon the quality of service offered. Trams/LR, for instance, offer short waiting times, but their energy usage is significantly greater than the car.
• The vehicle with least environmental impact in the urban environment is the TWC CNG bus which generates very low emissions.
• The TWC petrol car offers a lower urban environmental impact, in terms of emissions, than the diesel car, train and possibly the diesel bus, but further investigations will be required to assess the relative impacts. However, should emission reduction technologies be adopted by the diesel fuelled vehicle this situation is likely to change.
• The electric car offers good energy and emissions characteristics for urban use, although it still requires future development.
• Personal Rapid Transit offers the potential to mitigate many of the problems associated with transporting people.

5 Bibliography