Energy Efficiency of Personal Rapid Transit

Eva Gustavsson
Swedish Road and Transport Research Institute (VTI)

1 SYNOPSIS

Personal Rapid Transit (PRT) does not yet exist, but according to these calculations it can be an energy efficient mode of city transport for the future.

2 ABSTRACT

Personal rapid transit (PRT) could contribute to solving the crowding and pollution problems in our cities, as well as saving energy. The concept of the PRT system, which provides individual journeys in public systems, is about a quarter of a century old. However, when implemented, it will be a completely new element in urban transportation.

The result of our calculations is that the propulsion and heating of PRT vehicles may require less than a fourth of the energy used by passenger cars and less than half of the energy required by buses, all comparisons being based on energy use per passenger-kilometer. The energy required for construction of the guideway could also be quite low compared to road construction.

By introducing PRT, the modal split and probably also the total amount of travel will change. If travel increases strongly, less energy will be saved, if any. On the other hand, questionnaire studies and experience from existing transport systems indicate that the proportion of car drivers who could be attracted to PRT is so large that the energy used for construction may be saved in 4-5 years, even if the existing road capacity would have been sufficient without PRT.

The conclusion is that low energy use and moderate energy investments are typical characteristics of the projected PRT system. The type of system we have studied is very energy efficient in operation, and in a future with ever increasing traffic, PRT will be extremely profitable with regard to energy.

3 INTRODUCTION

In most cities throughout the world, traffic causes a great deal of problems, such as pollution, congestion and accidents. In answer to this, Personal Rapid Transit (PRT) was invented about a quarter of a century ago. After some years of little activity, the situation is now that PRT is again the subject of more intense development.

PRT consists of guideways, stations and vehicles. The guideway is built exclusively for PRT vehicles and is usually elevated about 4 meters above the ground. The stations are off-line to permit vehicles to pass the station without stopping. The vehicles are small, with 3-4 seats, and are used individually. The intention is that there should always be vehicles waiting for passengers at the stations, so that the passengers can depart without waiting. The vehicles are automatic, and will go directly to the desired destination without stops and changes (Anderson 1988 a; Alvehag 1992).

The development of PRT systems is taking place in the U.S.A. and in Sweden. The National Board for Industrial and Technical Development (NUTEK) has commissioned the Swedish Road and Transport Research Institute to calculate the probable energy expenditures for PRT in comparison with passenger cars and buses (Gustavsson, Kåberger 1994). These calculations will be reported in the following.

Please note that all calculations and discussions refer to energy, and none to economy.

4 METHOD

4.1 Factors considered

In analysing how much energy may be required for PRT compared to passenger cars and buses, we have considered

* construction of guideway and roads
* construction of vehicles
* propulsion
* heating of vehicles
* "cold start addition" for passenger cars
* distribution of electrical energy for PRT
* maintenance, including winter operation.

The energy calculations for operation carry most precision, while the corresponding calculations for winter maintenance and construction are rough estimates.

We have also analysed a number of scenarios, such as:

* insufficient versus sufficient road capacity
* changes in the modal split when implementing PRT.

4.2 Comparison of different energy sources

A general problem in energy analysis is to compare energy efficiency of transport modes using different energy sources. In Sweden during most of the year, electricity is produced both mainly and marginally using hydroelectric power and nuclear power. There is so much overcapacity in the electric power plants that electricity is used for heating purposes all the year round rather than fuel. As long as this is the case, it is possible to use the simplifying principle that the energy content in electricity and fuel can be considered equivalent (Koncessionsnämnden 1993).

In the future when the nuclear reactors are shut off, electric power may have to be multiplied by a factor of two (maximum) to compare with fossil fuels. However, fossil fuels should by then be replaced by fuels based on biomass or other renewable energy sources. Production of these renewable fuels and of electricity will probably be of similar efficiency.

4.3 DATA ON PRT VEHICLES AND GUIDEWAY

The dimensions of vehicles and guideway and the weight, acceleration and speeds of vehicles are specified for the projected PRT systems. Some data have been extracted from figures in publications, while others have been communicated orally by PRT project managers. Where information on PRT is missing, we have used data on existing techniques with assumptions about possible changes due to the application or current evolution. We have calculated energy use mainly for asynchronous motors, but also for linear motors. The driving cycles were taken from the PRT simulation for Gävle, a Swedish city with approximately 90 000 inhabitants. None of the high speed links in the outskirts of the city is included in the driving cycle.

Energy use for construction of the guideway consists mainly of production of the steel and concrete. Energy use for transports of material and the mounting of the guideway are insignificant. Construction of roads consumes very different amounts of energy depending on the type of road and the location. Levinson et al (1984) have given figures of between 3 and 7 MWh/meter for different types of roads.

The most important data on PRT vehicles used in VETO model calculations are

Wheel width; radius	130 mm; 303 mm
Empty weight	900 kg
Average speed	34-35 km/h
Acceleration	2,5 m/s^2
Front area of cabin; bogie	2,3 m^2; 0,42 m^2
Air resistance coefficient (c_w) of cabin; bogie	0,42; 1,0
Texture depth of tracks	0,25 mm
Rolling resistance of fender wheels	0,25*rolling resistance of wheels
Efficiency of gears; rear gears	94%; 96%
Efficiency of motor	68 – 92% (depending on load and rpm)

Maximum engine speed	12 000 rpm
Inertia of motor	0,1 kgm^2.

4.4 Passenger cars and buses

We have calculated the energy use of passenger cars and buses using well-known data on vehicles, pavements and street networks. In calculating propulsion energy, we have used VTI's VETO model (Hammarström 1987), both for PRT and for passenger cars and buses. VETO is a vehicle simulation program which calculates energy use, costs and emissions for vehicles, taking into account forces, torques, friction etc on a very detailed level. Driving cycles are representative for passenger cars and buses in a typical Swedish city, though only in central areas of the city where the speed is restricted to 50 km/h (Ragnarsson 1987).

Passenger cars and buses produce enough heat in the engine to cover the heating need inside the car or bus. The possible extra energy use for fans and ventilation is not included in our figures.

4.5 Number of passengers

The average number of passengers in PRT is assumed to be 1,2 according to the simulation for Gävle. This includes empty vehicles being sent from surplus areas to deficit areas. It will, however, require organized "ride sharing" (Andréasson 1993).

We have set the average number of passengers in cars to 1,5, an approximation of the value used in the simulation of PRT for Gävle (Andréasson 1991). An additional fuel consumption of 0,106 liter per start is added to passenger car fuel consumption according to new and still unpublished results by Henrik Jónsson at the VTI, and the average journey length is 6,2 km within cities according to Swedish statistics (SOS 19870).

According to statistics from the Swedish Local Traffic Association, buses have 12 passengers on average (SLTF 1991). The calculations are made for 12 m buses.

4.6 Climate in PRT vehicles

Air conditioning is not included in the calculations as it is not considered to be necessary for Swedish conditions. Heating, on the contrary, is very essential. Half level heating is assumed for 15 September to 31 October and for 1 April to 15 May. Full heating power, 1 600 W, will probably be necessary between 1 November and 31 March.

During the heating season all vehicles must be heated during peak hours. Our calculations are made under the assumption that around noon, in the evenings and on Saturdays and Sundays 40-60 % of the vehicles must be kept warm and at night only 10 %.

4.7 Winter operation and electric losses in the PRT system

Snow and ice can be a substantial problem in the winter in Sweden. It may be possible to construct the guideway so that heating is unnecessary. There is, however, some scope for heating the tracks and still achieving reasonable total energy use.

Losses in energy distribution within the system are considered to be 10% (Göte 1993).

5 RESULTS

The energy used for constructing the guideway will be approximately 1,7 MWh/m. This figure can be compared with 3 to 7 MWh/m for different kinds of roads. The production of materials consumes the major part of the energy, while construction and transports require more or less negligible amounts. However, approximately half the amount of energy can be recovered by recycling the steel when the guideway is worn out in the future, provided that the steel is easy to separate from the other materials. Production of PRT vehicles will use about a tenth of the energy for the guideway system. PRT vehicles are fairly similar to passenger cars in size and construction and will require more or less the same amount of energy in production, but they will probably be used more intensively, and consequently consume less energy per passenger-kilometer for construction.

Figure 1 and Table 1 show the result of the calculations for operation. Small amounts of energy are sufficient for propulsion of PRT vehicles and the amount of energy required for construction is also small.

Figure 1. *Engergy use for PRT, bus and passenger car per passenger-kilometer in city traffic*

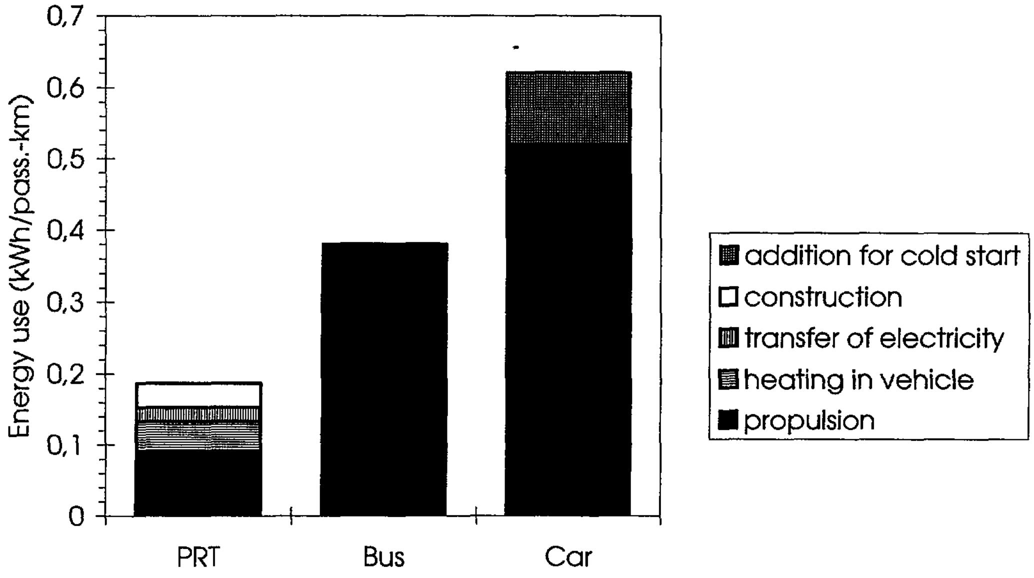

Table 1. *Energy use of PRT, passenger car and bus in city traffic, expressed as kWh/veicle-kilometer and kWh/passenger-kilometer respectively.*

Energy (kWh)	PRT		Passenger car		Bus	
	Vehicle-km	Pass.-km[1]	Vehicle-km [1]	Pass.-km[1]	Vehicle-km	Pass.-km[1]
Propulsion	0,11	0,092	0,78	0,52	4,53	0,38
Cold start	-	-	0,15	0,10	-	-
Heating	0,052	0,043	-	-	-	-
Losses in electric transfer	0,02	0,02	-	-	-	-
Total	0,18	0,15	0,93	0,62	4,53	0,38

[1] *Average number of passengers: PRT - 1,2 passenger car - 1,5, bus -12*

The linear motor will use slightly more energy, 0,17 kWh/passenger-kilometer instead of 0,15 kWh for the asynchronous motor. The linear motor could, however, be advantageous if it proves impossible to avoid snow and ice accumulation on the tracks as this motor can brake the vehicle electrically, without using the friction between wheels and guideway.

6 DISCUSSION

6.1 Effects of changes in the modal split

The amount of travel and changes in the modal split are important parameters for the energy savings that can be obtained by introducing PRT. In the case where road capacity is insufficient, it is very energy effective to build PRT systems instead of new roads. But PRT is advantageous also when roads have sufficient capacity. The most important energy savings are obtained when people leave their car at home and travel by public transport. Even if PRT requires as much energy as the bus, energy could be saved since PRT will probably attract more car drivers because of its far better service. It is likely that at least 20% of car drivers will switch to PRT according to questionnaire studies and results from the Morgantown People Mover, a PRT-like system in West Virginia, USA (Andréasson 1993; Elias, Neumann, Iskander 1982). Figure 2 shows how many years it will take to recover the energy investment in the guideway on the assumption that all bus passengers, 10 % of the pedestrians and cyclists and varying proportions of car drivers switch to PRT. Note that economic issues are not discussed, but only energy use.

Figure 2

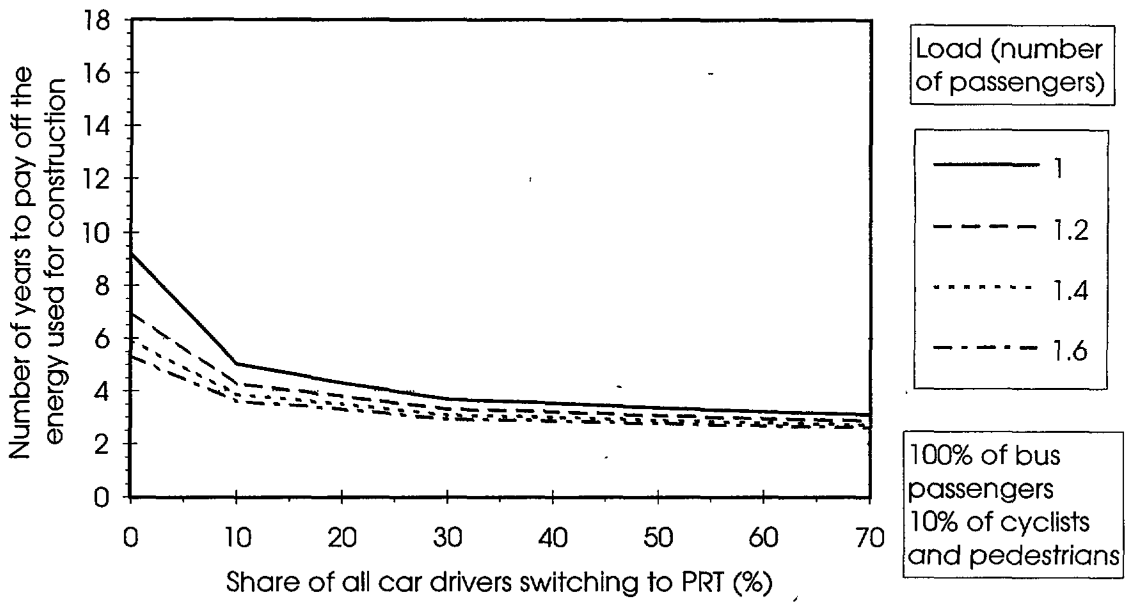

Figure 2. *This diagram shows how many years it will take to save the energy used for construction in the case where all bus passengers and 10% of all pedestrians and cyclists have switched to PRT. Recycling of steel is assumed when the guideway is scrapped. In spite of their increased energy use, this means a total saving of energy. The amount of energy saved will be greater for every additional car driver attracted by PRT.*

6.2 Empty running

Empty running is usually considered when calculating the energy for PRT and for buses it is included in the statistics on the average number of passengers. For passenger cars, however, there are no data on empty driving. This does not mean that it is non-existent. On the contrary, driving family members to their activities, returning home and going out once again to fetch them is a very frequent errand. In this case, returning home and going out once again is non-transport. It can be compared with taxis travelling empty to pick up passengers and later returning without passengers. Empty running is consequently included in the figures for PRT and bus, but not for passenger cars.

6.3 Comparison with previous calculations

Ed Anderson (1988 b) has calculated the energy use of PRT with a different method. Our result is 0,15 kWh/passenger-kilometer, whereas Anderson arrived at 0,09 kWh/passenger-kilometer. It is quite logical that his figure is lower as he assumed substantially lower weight and lower air resistance. Also, he seems to calculate heating only when vehicles are carrying passengers. We have assumed heating for a number of vehicles at each time of the day, since we believe that people prefer to step into a vehicle that is already comfortably warm. We have also assumed that more power is necessary for Swedish conditions. However, we do not consider air conditioning necessary in Sweden and we have used a somewhat higher number of passengers per vehicle.

6.2 Secondary effects

Changes in car ownership, land use and modal split could lead to energy savings on a secondary level by shortening journey lengths and modifying travel patterns. These are, however, effects that are very difficult to assess. Even after the changes have taken place, it may be difficult to obtain incontestable quantifications of such effects.

7 CONCLUSIONS

Low energy use for propulsion and moderate energy investments are typical advantages of the projected PRT system compared to passenger cars and buses. The type of system we have studied is very energy efficient in operation, and in a future with ever increasing traffic, PRT will be very profitable in terms of energy use.

But also when existing road capacity is sufficient for transport needs, the energy used for construction can be saved in four or five years. It is, however, necessary to construct both guideway and vehicles carefully in order to keep the energy use this low.

We have assumed that the guideway does not need heating in the wintertime. Whether it is possible to construct such a guideway can only be proved by building a test track.

Heating of the vehicles may require half as much energy as propulsion, so the vehicles should be designed carefully in order to keep heating power down. However, it is not advisable to try to save energy by accepting less comfortable vehicles, as the energy savings are especially great when car drivers and passengers switch to PRT. PRT must accordingly be at least as comfortable as a passenger car. Even when only 10-20 % of car drivers switch to PRT, the savings will be considerable. An estimate that 20 % of car drivers will be attracted by PRT is rather modest, according to questionnaire studies and measurements of changes in the modal split when opening automatic transport systems with good service.

Some of the most essential parameters for the energy use of propulsion are the weight of the vehicle, the air resistance of the bogie and the efficiency of the motor at low torque. The motor will mostly work with a low load, as the vehicle is fairly light and has a low rolling resistance. It is also important that the guideway design permits the steel to be easily removed when the guideway is worn out in the future.

The development of passenger cars is another point that is difficult to assess. But even if the fuel consumption of passenger cars is reduced by 50% in the 21st century, they cannot compete with PRT. The modest land requirements of PRT might also indirectly save energy by shortening distances in the city and promoting non-motorised transport modes.

8 ACKNOWLEDGEMENTS

This paper is based on a project conducted in cooperation with Tomas Kåberger the Institute of Physical Resource Theory, Chalmers University of Technology (CTH) in Gothenburg (Gustavsson, Kåberger 1994).

In particular, I wish to thank Eie Herlitz, who provided contacts with some of the many experts in different areas and with some of the PRT project managers.

9 REFERENCES

Alvehag, Ann-Charlotte; Malmén, Per; Sundberg, Jonas 1992. *Spårtaxi - för persontransporter*, en analys av Personal Rapid Transit, Transportforskningskommissionen rapport, 1992:7, Sweden, 1992

Anderson, J Edward: "The TAXI 2000 Personal Rapid Transit System", *Journal of Advanced Transportation*, vol 22, s 1 - 15, spring 1988 a

Anderson, J Edward: "What Determines Transit Energy Use?", *Journal of Advanced Transportation*, vol 22, no 2, s 108 - 133, 1988 b

Andréasson, Ingmar: *Simulering av spårtaxi i Gävle*, Etapp 1, TFB-rapport 1991:25, Göteborg, Sweden, 1991

Andréasson, Ingmar: *Simulering av spårtaxi i Gävle*, redovisning av projekt SIMSPÅRT, Logistikcentrum, Göteborg, Sweden 1993

Elias, Samy E G; Neumann, Edward S; Iskander, Wafik H: "Impact of People Movers on Travel: Morgantown - A Case Study", *Transportation Research Record* 882, U.S.A., 1982

Gustavsson, Eva; Kåberger, Tomas: *Energiförbrukning för spårtaxi - en jämförelse med bil och buss*, VTI meddelande nr 737, Statens väg- och transportforskningsinstitut, Linköping, Sweden, 1994

Göte, Sune, Göteborgs spårvägar, the tram company in Gothenburg, 1993

Hammarström, Ulf; Karlsson, Bo: *VETO - ett datorprogram för beräkning av transportkostnader som funktion av vägstandard*, VTI meddelande 501, Linköping, Sweden, 1987

Koncessionsnämnden, Beslut i ärendet 'Tillstånd till verksamheten vid Arlanda flygplats i Sigtuna kommun' Stockholms län, 1993-04-06. Dnr 171-597-90, Sweden, 1993

Levinson, Herbert S; Strate, Harry E; Edwards, Syd R; Dickson, William: "Indirect Transportation Energy", ur *Journal of Transportation Engineering*, vol 100, nr 2, March 1984

Ragnarsson, Gunilla: *Korsningsinventering i tätort*, VTI notat T25, Statens väg- och trafikinstitut, Linköping, Sweden, 1987

SLTFs branschstatistik 1990, Länstrafikstatistik, Svenska Lokaltrafikföreningen, K-Konsult, Sweden, 1991

SOS, *Sveriges officiella statistik*, Statistiska Meddelanden, serie T, "Resvaneundersökningen 1984/85", T 11 SM 8701, Stockholm, Sweden, 1987