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Emissions of demand responsive services as an alternative to conventional transit systems

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Abstract

The environmental performance of public transport plays a key role in improving air quality in urban areas. An important way of improving existing transit services is to use innovative propulsive systems; however, this needs considerable financial resources that are not always available. Here we assess how the organizational form of the transit system may impact the environment relying on a new methodology that permits comparisons in terms of distance traveled between a traditional fixed-route and a demand responsive transit service. We apply an emission model to find the least polluting transit system under a broad range of scenarios with different road networks, service quality levels and demand densities. Results indicate that demand responsive transit services minimize emissions for high quality service level and low demand density scenarios. Furthermore, the possibility of employing smaller vans with lower emission factors guarantees additional substantial benefits in terms of atmospheric pollution for demand responsive transit services, thereby giving them a competitive advantage in virtually every case.

Keywords: Public transport; Demand responsive services; Emissions; Atmospheric pollution

1. Introduction

The development of public transport services is usually considered one of the key elements of any policy aimed at a more efficient use of energy resources and in reducing emissions of pollutants. As a consequence, the environmental performances of public transport systems are being examined much more than before. A good indication of this priority is the sharp increase in investments aimed at making public transport systems less polluting. Those investments are often technology oriented, the outcome being, for example, to have fleets of methane-powered or hybrid buses or even to build new facilities such as tramways or metro lines. However, there is a risk of moving emissions from exhaust pipes to other sources of pollution; in many cases alternative energy sources, such as electricity or hydrogen, are obtained from fossil fuels. Moreover, a technology-driven

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approach is normally expensive, and many local authorities (small and medium-sized cities, and even larger metropolis in developing countries) do not have sufficient financial resources to pursue it.

Here we assess the alternative possibility of lowering pollutant emissions through a change of the organizational form of the public transport mode itself, while keeping constant vehicle technology and the level of service provided to customers. In particular, we examine how a demand responsive transit (DRT) service would compare with traditional fixed-route (FIX) services in terms of emitting pollutants. We consider different urban contexts, different service qualities and demand levels.

DRT systems offer 'many-to-many' types of services without predefined paths or schedules that can serve requests between any origin/destination pair without vehicle changes, while allowing ride sharing. Customers have to book their ride specifying the origin, the destination, the number of passengers and the preferred pickup time. The operator then collects the reservations and schedules vehicle paths to serve the requests. In the US, beyond the flourishing market niche of airport feeders, these systems are mainly used to provide a mobility service to those that can not use traditional public transport lines, such as the physically disabled. It is however of interest to assess the environmental performance of these systems when using them in place of traditional fixed-route systems. A competitive environmental advantage of DRT systems is that their vehicles may be considerably smaller than the regular fixed-route buses and, therefore, with much lower pollutant emissions per distance traveled. This is because capacity constraints are not as important as time constraints when performing the scheduling and smaller vans would perform just as well as larger ones on most occasions.

2. Previous research in the field

The scarcity of published research on this topic has been another stimulus for our analysis. Diana (2003) developed a framework to understand how public transport emission levels would be affected if the evening bus service in the city of Turin, Italy, were to be partially substituted by a demand responsive transit service. However, the results cannot be easily generalized because they refer to the specific situation of that city; its service organization and the demand patterns. Over the years there have been other papers that, broadly speaking, have drawn comparisons between fixed and flexible route services, although their focus is usually more on the economic aspects (Daganzo, 1984; Aldaihani et al., 2004; Chang and Yu, 1996).[1]

The earlier studies offer useful insight but they do not offer a straightforward methodology to systematically compare emission levels. An introductory framework concerning the evaluation of the environmental performances of different forms of road transit systems is provided by Diana and Pronello (2004), who develop an experimental plan to determine the best system in terms of vehicle runs and emissions in a large set of scenarios. A new and more rigorous methodology for tackling the problem of comparing distance traveled of performance-equivalent fixed-route and DRT services is described in Diana et al. (2006). We build on those results and evaluate the environmental performance of the competing transit systems, thus determining which system minimizes exhaust gas emissions in each considered scenario, depending also on the type of vehicle employed.

3. Methodological steps

We consider three urban structures, each with its road network and demand distribution, to cover various plausible operational contexts and to measure their influences. The details of the simulation framework is reported in Diana et al. (2006) and here only the main elements are laid out. Case G assumes an evenly spaced grid covering a square area; in case R the road network consists in evenly spaced radial roads over a circular area, and in case RR circular lines are added to the R network. All these areas are of 25 km^2. Stops are located at every crossing in the road network for cases G and RR, whereas they are evenly distributed along the radial roads for case R.

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[1] A paper by Dessouky et al. (2003) is also of relevant interest; it shows how it is possible to consider environmental impact in the decision-making processes concerning fleet systems.

Concerning the demand, its temporal distribution is modeled as a Poisson process and it is assumed that all the demand is known in advance. Hence we only consider demand responsive static services, that allow for an efficient scheduling process, thus representing a benchmark for the more realistic dynamic systems (Diana, 2006). For case G, the demand is uniformly distributed across the whole service area. For cases R and RR, the demand distribution is linearly decreasing from a maximum in the centre to 0 on the outer edge.

The transit systems under investigation are a traditional FIX and a DRT with both services serving the same stops. FIX services are organized in several lines, each line running back and forth along one street of the networks. Each FIX service is characterized by a headway h; the longer the headway, the worse the quality of service, but less vehicles would circulate and emissions would be lower, at least until the capacity limit of the buses is reached. DRT services operate in the same area and serve the same demand. The trip origin and destination can be any stop on the road network. Parameters MT and MW represent the maximum ride and wait times at the pick-up point. They are embedded in a scheduling algorithm (Diana and Dessouky, 2004) and control the quality of the service: tightening them ensures a higher quality of services to the customers, but decreases the probabilities of sharing a ride, thus increasing both the number of vehicles, the kilometers driven, and, ultimately, emissions.

To make a meaningful comparisons, the two systems provide an analogous service to customers, so that a potential improvement in air quality would not come at a cost in terms of the overall service quality level – the performance of the system – for which computation is analytically troublesome and depends on the headway h in the FIX case and on MT and MW for the DRT system. Diana et al. (2006) compute for every scenario the virtual ride time, a weighed multi-term sum that includes the actual in-vehicle ride time, the wait time at the pick-up stop, and possibly at the transfer stop, and the inconvenience of having to change vehicle, if necessary, for the FIX case. Weights are determined on the basis of two recent studies (Wardman, 2004; Guo and Wilson, 2004). The two competing systems are thus considered to have the same performance in terms of overall quality of the service offered to customers if their virtual ride time distributions across all the passengers are comparable.

The goal is to determine the least polluting transit service configuration among a fairly broad range of cases. Hence, beyond the three road network cases both the demand density and the service quality are varied. These factors are set to two different levels giving a total of 12 scenarios.

The demand density is expressed by the Poisson arrival rate λ of customers requesting the service. We consider $\lambda = 2$ requests/min for the low demand level and $\lambda = 50$ requests/min for the high demand level. The quality of the services is expressed in terms of mean headway h for FIX, with lower headways indicating better service quality. We consider an h of about 30 min for low quality service level and an h of about 5 min for the high quality service level. Once the service level is decided, the MT and MW parameters for the DRT system are adjusted until the distributions of the virtual ride time is comparable to the corresponding FIX case to ensure comparability of the systems.

The 12 scenarios are delineated using the following notation. The initial letters indicate the considered case (G, R or RR). Then, a "q" is added for low service quality scenarios and a "Q" is added for high service quality scenarios. Finally, the demand density of each scenario will be indicated with either a "L" for low or a "H" for high. Table 1 shows the factor level combinations for the scenarios.

Exhaust gas emissions can be estimated on the basis of the distances traveled and mean vehicle speed, assumed to be 20 km/h, by using one of the emission models that are widely available. Here we use the standard European Union method, as recommended by current regulations (European Commission, 1999) and which is essentially based on the COPERT (COmputer Programme for estimating Emissions from Road Transport) model. It seems unlikely that the results would dramatically change if another emission model were to be used, since we compare two competing systems rather than considering the absolute quantities of emitted pollutants.

The pollutants that we monitored are: carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), volatile organic compounds (VOC) and particulate matter (PM). For each of these, the first step is to compute the corresponding emission factor, i.e., the grams of pollutant emitted per kilometer of traveled distance, which is dependent upon the mean speed and the type of vehicle used. We observe that one of the advantages of DRT services is the possibility of using smaller vehicles, since it is seldom possible to share a ride among a large number of passengers; even more so if the time windows for visiting points are tight and

Table 1
Scenarios definition

Scenario	Road network (–)	h (min)	λ (req/min)
G_q_L	G	27.0	2
G_q_H	G	27.0	50
G_Q_L	G	6.7	2
G_Q_H	G	6.7	50
R_q_L	R	30.8	2
R_q_H	R	30.8	50
R_Q_L	R	6.1	2
R_Q_H	R	6.1	50
RR_q_L	RR	27.0	2
RR_q_H	RR	27.0	50
RR_Q_L	RR	6.5	2
RR_Q_H	RR	6.5	50

Table 2
EURO III emission factors for buses and eight-seat vans (g/km)

	CO_2	CO	NO_x	VOC	PM
Buses	1139.31	6.592	7.356	1.729	0.1682
Eight-seat vans	215.44	0.471	0.482	0.068	0.0379

the spatial and temporal demand density is not too high. In those cases there is an important benefit concerning fuel consumption and emissions, whereas distances covered are almost the same or slightly increase (Diana and Pronello, 2004).

It is assumed initially that the DRT service employs the same type of vehicle used by the FIX service to allow exclusively an analysis of the effect of the organizational form of the transit system, without any influence from other factors. We then assess the potential benefits of using smaller vehicles to operate the demand responsive service. Table 2 presents the emission factor values for larger buses and for smaller eight-seat vans. In both cases the EURO III emission class has been considered in computations.

The emissions of each pollutant can then be obtained by multiplying the total distance traveled by the emission factors. The computations of the total distance traveled by FIX services are straightforward and depend only on the geometry of the service area and on the headways seen in Table 1. On the other hand, the distances traveled for the DRT fleet are dependent upon the particular demand patterns and scheduling processes, and have been computed on the basis of the simulation results.

4. Results

Table 3 shows total emissions when both systems use the same kind of vehicle, namely a standard EURO III bus. The last column shows the variations in percentages of the DRT service compared to the FIX one.

For each scenario identified by a geometry and a quality level and regardless of the demand level (i.e., G_Q scenarios) the emissions of the FIX fleets are between those of the DRT services in the same scenario for low (i.e., G_Q_L) and high (i.e., G_Q_H) demand density levels, except for the RR_Q scenarios, where the DRT service is always less polluting.[2] Therefore, a DRT service would be justified in terms of pollutant emissions for low demand scenarios (L), especially for high quality service level (Q) and particularly for the RR case.

The high service quality (Q) scenarios allow for a better performance of the DRT service. For example, the improvement of the DRT service compared to the corresponding FIX in the R_Q_L scenario (−79%) is much more significant than in R_q_L (−18%). The same pattern can be noted for the other scenarios.

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[2] This is consistent with the results in Diana and Pronello (2004), where DRT services were found to be relatively more effective compared to FIX services in monocentric road networks.

Table 3
Emission When using the same vehicle kind in both transit services

Scenario		CO_2 (kg)	CO (g)	NO_x (g)	VOC (g)	PM (g)	Δ%
G_q_L	FIX	911	5274	5885	1383	135	−43
	DRT	523	3026	3376	793	77	
G_q_H	FIX	911	5274	5885	1383	135	+311
	DRT	3748	21688	24201	5687	553	
G_Q_L	FIX	3646	21094	23539	5532	538	−79
	DRT	759	4390	4899	1151	112	
G_Q_H	FIX	3646	21094	23539	5532	538	+62
	DRT	5907	34180	38141	8963	872	
R_q_L	FIX	729	4219	4708	1106	108	−18
	DRT	602	3481	3884	913	89	
R_q_H	FIX	729	4219	4708	1106	108	+650
	DRT	5469	31642	35309	8298	807	
R_Q_L	FIX	3646	21094	23539	5532	538	−79
	DRT	760	4399	4909	1154	112	
R_Q_H	FIX	3646	21094	23539	5532	538	+135
	DRT	8550	49471	55204	12973	1262	
RR_q_L	FIX	1185	6856	7650	1798	175	−73
	DRT	318	1842	2055	483	47	
RR_q_H	FIX	1185	6856	7650	1798	175	+140
	DRT	2850	16490	18401	4324	421	
RR_Q_L	FIX	5013	29005	32366	7606	740	−91
	DRT	86	189	193	25	15	
RR_Q_H	FIX	5013	29005	32366	7606	740	−18
	DRT	4089	23662	26404	6205	604	

In more general terms, the findings are in line with the well known observation that DRT services perform best in terms of distances traveled, and hence in terms of emissions, when the demand density is low and good service quality is sought.

Examining existing DRT services, one notices that most of them use small vehicles for their operations – often eight-seat van – because vehicle capacity constraints are much less tight compared to time constraints and it is very improbable that a DRT vehicle would be able to carry more than eight people at any time during a journey. Basically the extra capacity is unnecessary. In fact, as shown in Diana and Pronello (2004), using

Table 4
Emission reductions compared to FIX when using eight-seat vans for DRT services

Scenario	CO_2 (%)	CO (%)	NO_x (%)	VOC (%)	PM (%)
G_q_L	−89	−96	−96	−98	−87
G_q_H	−22	−71	−73	−85	−7
G_Q_L	−96	−99	−99	−99	−95
G_Q_H	−69	−88	−89	−94	−63
R_q_L	−84	−94	−95	−97	−81
R_q_H	*+42*	−46	−51	−73	*+69*
R_Q_L	−96	−99	−99	−99	−95
R_Q_H	−56	−83	−85	−91	−47
RR_q_L	−95	−98	−98	−99	−94
RR_q_H	−55	−83	−84	−91	−46
RR_Q_L	−98	−99	−99	−100	−98
RR_Q_H	−85	−94	−95	−97	−82

eight-seat vans instead of the conventional larger buses does not change the results significantly in terms of distance traveled for the DRT system. However the effect in terms of pollutants emissions is substantial because of the much lower emission factors values for the eight-seat vans. In Table 4 the emissions percent variations is shown for a DRT service using eight-seat vans compared to the FIX service.

Comparing these figures with those in the last column of Table 3, one can see that further improvement in terms of pollutant emissions is expected and noticeable in almost every scenario. The DRT system performs better than FIX for every pollutant considered in every scenario, except the emissions of CO_2 and PM in R_q_H.

5. Conclusions

How the organizational form of a public transport service can affect pollutant emissions in different urban contexts and for different levels of service quality and demand has been examined. Demand responsive transit (DRT) services appear more effective than the fixed-route services in minimizing emissions when the demand density is not excessive and a good level of service is sought. In particular, demand responsive services perform better in a ring-radial network and the possibility of using smaller vehicles allows them to outperform fixed-route services in almost all the scenarios examined.

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