POTENTIAL CONTRIBUTIONS OF DEMAND RESPONSIVE TRANSIT SERVICES IN REDUCING PUBLIC TRANSIT POLLUTANTS EMISSIONS IN METROPOLITAN AREAS: AN EXAMPLE FOR THE CITY OF TURIN

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SUMMARY

We assess the potential that Demand Responsive Transport Services can have in reducing the emissions of pollutants of urban public transit systems. A comparison between the “normalized” emissions of the existing evening transit service in the city of Turin (Italy) and those of several hypothetical dial-a-ride systems serving the same transport demand is drawn. It is shown that the utilization of smaller vehicles, made possible by the low levels of demand during off-peak hours, can induce substantial emission savings in the monitored pollutants.

OVERVIEW AND PURPOSE OF THE RESEARCH

This paper is concerned with the potential that Demand Responsive Transport Services (DRTS) can have in reducing the emissions of pollutants globally caused by the operation of the public transit system in a metropolitan area. DRTS are a particular form of public transport characterised by the fact that the vehicles (cars, taxicabs, vans, minibus) operate in response to calls from passengers or their agents to the transit operator, who then dispatches a vehicle to collect the clients and transport them to their destinations. A demand responsive operation is characterised by the fact that the vehicles do not operate over a fixed route or on a fixed schedule, and that they may be dispatched to pick up and deliver several passengers at different points: unlike the conventional taxi, one vehicle can serve more than one request at a time, and so the passenger is not necessarily transported directly towards its destination.

Among the “paratransit options” initially made possible by the development and availability of computers, DRTS were in the past regarded as a promising way of developing a public transport service. One of the leading forces that pushed towards the implementation of these systems in the 70s was the oil crisis (Kirby et al., 1974). The basic idea was to substitute traditional buses with smaller vehicles, with a more flexible schedule, in order to reduce fuel consumption. However the performances of the systems that were widely implemented from the 70s onwards were generally disappointing, mostly for economic and financial reasons.

Nowadays DRTS are experiencing a renaissance (Cervero, 1997), for reasons which can be summed up as follows:
1) *Technically*, the implementation of efficient and cost-effective ITS, the increasing performances of computers, the advances in the development of optimisation algorithms are all aspects that contribute to removing one of the historical flaws of these systems: their economical inefficiency, even compared to traditional transit services. In fact, it has been widely recognized that the only way of developing efficient DRTS is to implement them on a technologically advanced basis.

2) *Economically*, the increasing attention paid to issues related to the maintenance of the environment and the sustainable economic development, together with uncertainties on the supplies of non-renewable energy sources, are progressively seeking improvements in the efficiency of transportation systems.

3) *Socially*, welfare policies in many countries of the western world are increasingly aiming at the fuller integration of people who for various reasons cannot owe or use a car, nor take advantage of a conventional transit service. Nowadays, hundreds of systems exist, but only a few of these transport more than a few dozen people daily or have been designed for use by the general population (Casey et al. 2000).

The focus of our research is to verify if the operation of a DRTS can help reducing the contribution of the transit system to air pollution in cities. Efforts are being made in several cities in the world to improve this aspect, mostly by substituting obsolete vehicles with newer ones. These latter can substantially reduce emission levels, since several technological improvements have been achieved in recent years. However it seems that in order to radically solve the problem the only way is to abandon diesel engines. For this, several transit agencies also introduced vehicles that make use of more innovative fuels such as methane. Also more innovative vehicles, such as hybrid or hydrogen-powered, are currently being tried.

It is however well known that the renewal of the fleet with such innovating vehicles is still very expensive. Our proposal may constitute an alternative way to achieve similar results, with much smaller costs. Of course the implementation of a DRTS has several consequences in a broad range of different ambits, among which those related to pollutants emissions could often be considered negligible. However we believe that it is still worth exploring this issue, given the importance that the theme of the sustainability of transport systems has in current research.

**CURRENT TRANSIT SERVICE AND ITS PARTIAL SUBSTITUTION**

In the following we will assume that a DRTS is implemented in a metropolitan area in order to substitute a traditional network of bus lines. We will assume that the behaviour of the customers does not change, i.e. the travel patterns will be the same also with the new system. This of course is not realistic, but here the focus is not on fully modelling a DRTS. On the contrary, we are interested in a direct comparison between the two competing systems from the point of view of the emissions, and assuming that the travel demand is constant in the two cases allows us to exactly evaluate the gap.

In order to better present our methodology, we will develop a real case. We will take as example the current transit service of the city of Turin (Italy). We consider the evening service, after 8:30pm. This service currently involves the operation of about 80 lines, carrying 14,000 passengers in a typical weekday evening. Headways between two consecutive buses are typically of 20-30 minutes. For this transit service, we know the characteristics of the offer (length of the line, schedules, speed etc.) and of the demand. This latter is expressed as an O/D matrix among 166 zones in which the territory of the city has been divided.
We imagine changing the offer, i.e. substituting about half of the lines with a DRT service that will be better described in the following paragraph. Of course we will substitute the lines with less ridership, since in those cases the actual system is less efficient, having heavy vehicles that travel with only a few people onboard. On the contrary, it is well known that a DRTS works better when the travel demand density is not too high (Daganzo, 1984). Substituting lines that have a high number of customers might not be a good idea, since an overloaded DRTS is very difficult to manage, the computational time of the scheduling algorithm becomes a problem and the distance travelled tends to increase very rapidly. Hence, we believe that a partial substitution of the actual system should lead to the best results.

The lines to be substituted currently carry each evening about 3,200 people out of the total of 14,000, distributed over a temporal range of about three hours (from 21 to 24). Of course the service demand is not constant within this interval (Fig. 1). Since we assumed that the demand is not affected by the new service, as a consequence we will have that these 3,200 people must be serviced with the DRTS, whereas the remainder will go on using the traditional transit lines that are not substituted, in exactly the same manner. Hence, we will not have to consider these latter lines, since their schedule is unchanged in absence or in presence of the DRT system.

![Fig. 1. Distribution of the desired pickup or delivery time](image)

**DEFINITION AND “ITS CONTENTS” OF THE ENVISIONED DRTS**

We have 3,200 people to be serviced with a DRTS. Our system specification will strictly follow what has been proposed for a previous research (Diana and Dessouky, 2002); here we will recall the main features. Some of these originally proceed from a former work by Jaw et al. (1986).

We assume to operate a many-to-many advance-request service, i.e. the service requests are known before the service starts. When making a reservation, the customer has to specify the origin and the destination of the trip (corresponding to the centroids of two of the above mentioned 166 zones). He can also specify either the pickup or the delivery time; on the other
hand, the operator computes the maximum ride time MRT as a linear function of the direct ride time DRT. He also fixes the maximum wait time WT at the pickup point (for customers that specify the pickup time) or the maximum advance time AT at the delivery point (for customers that specify the delivery time). We use the following definition for MRT, where a and b are two parameters that are specified by the scheduler:

$$MRT_k = \begin{cases} \max(a \cdot DRT_k + b, DRT_k + WT) & \text{for requests with specified pickup time} \\ \max(a \cdot DRT_k + b, DRT_k + AT) & \text{for requests with specified delivery time} \end{cases}$$

It is convenient to merge these constraints, related to the quality of the service to be provided, into the definition of the time windows for all the pickup and delivery nodes. Let EPT be the earliest pickup time requested by the customer. Then, let (EPT, LPT) and (EDT, LDT) be the time windows associated with the pickup and delivery times for customer k, respectively. When the user specifies EPT, the time windows are computed as follows.

- $LPT = EPT + WT$
- $EDT = EPT + DRT$
- $LDT = EPT + MRT$

When the customer specifies LDT, the time windows are computed in the following manner.

- $EPT = LDT - MRT$
- $LPT = LDT - DRT$
- $EDT = LDT - AT$

In addition, we associate with each request a service time both at the pickup and at the delivery node, and the vehicles are allowed to stop and idle at any pickup location, waiting to serve the following request, if only no passengers are onboard. Passengers must have a seat, so that each vehicle has a maximum capacity given by the number of seats.

As it has been pointed out in the introduction, ITS technologies play a vital role in the operation of a DRTS, since it is often impossible even to organize the service without making a wide use of them. Past experience has shown that the communications channels between the three most important entities that form the system (customers, fleet and operations centre) are a critical factor for the success of the service. It is important to allow several different ways in which customers can book a ride, since there is not one system that outperforms all the others. On one hand, there are customers that usually book the service with a short advance notice. They would like to use flexible technologies such as Internet, SMS or WAP with a highly automated procedure, in order to complete the task as quickly as possible. On the other hand, a more traditional and labour-intensive call centre is needed for those customers (elderly etc.) that can only use the telephone.

The other key element is the communication between vehicles and operation centre, moreover when the service is real-time. The information flow is quite relevant, since the vehicle knows only the following stop of its route, and whenever it reaches a service point new information must be sent in order to let it know where to go next. It is also a good norm to send back to the centre a confirmation message whenever a user is successfully served.

ITS are also essentials in managing all the unexpected events that could occur during the service operation (no show, vehicle breakdown, variability of the service and of the travel times etc.). These are usually detected by the centre through an AVL (Automatic Vehicle Location) system, so that the algorithm can accordingly modify the schedules. It is finally important to notice that the reliability of ITS technologies is not only necessary in order to
have a good level of service, like in many other transportation systems. The point is that a DRTS completely relies on ITS technology, and a fault might be critical even for continuing the service operation. For example, it is vital that the communication channel between vehicles and centre is never interrupted, and the centre itself must never stop working. In order to achieve this, a redundancy in all the devices is needed (e.g. more than one computer for scheduling the requests, vehicles equipped both with GPRS and radio communication).

**SCENARIOS DEFINITION AND SERVICE SCHEDULING**

In order to schedule the aforementioned service, we use a parallel insertion heuristics that has been described in Diana and Dessouky (2002), where it has been named “Algorithm 2”. Our objective function is to minimize the total travel length of all the vehicles. The inputs of the algorithm are the list of the requests, the travel times and distances between all the pairs of centroids, the number of vehicles to be used and their capacity (number of seats). The algorithm provides the schedule of the service, and a separate list of the requests that have been rejected, i.e. that cannot be serviced within the given time windows. We determined the minimum number of vehicles needed to serve all the 3200 requests by running several times the algorithm, each time lowering the number of vehicles until some requests were rejected.

In order to perform more meaningful and complete comparisons, we have simulated several different kinds of service. We set the quality constraints at three different levels, so that a low, a medium and a high quality scenario can be envisaged. Given the current characteristics of the evening bus service in Turin, we could say that it should have a quality more or less comparable to that of the first scenario in terms of waiting time at the stops and travel time. The settings of the above-introduced parameters for these quality levels are reported in the following table.

**Table 1. Parameters settings for the considered DRTS quality levels**

<table>
<thead>
<tr>
<th>Service quality</th>
<th>a (-)</th>
<th>b (min)</th>
<th>WT (min)</th>
<th>AT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>2</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Medium</td>
<td>1,5</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>High</td>
<td>1,2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Furthermore, we also considered vehicles of different capacity. Using smaller vehicles of course leads to benefits in terms of emissions, but on the other hand if the capacity limit is reached it might be necessary to do longer tours or to use more vehicles in order to serve all the requests. Here we consider two somewhat extreme cases:

a) homogeneous fleet of vehicles with 8 seats;

b) homogeneous fleet of vehicles with 20 seats.

Crossing this variable with the preceding quality levels originates six different scenarios, that will be indicated as follows: L8, M8 and H8 are respectively the low, medium and high quality scenarios using vehicles with 8 seats, and L20, M20 and H20 are the corresponding ones that use vehicles with 20 seats.
EMISSIONS EVALUATION AND COMPARISONS

We evaluated the emission for both the systems (bus lines being substituted and DRTS) using the standard methodology recommended in the MEET report (EC, 1999). The pollutants that we quantified are the following five: carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen (NOₓ), volatile organic compounds (VOC) and particulate matter (PM). In the following we will consider only hot emissions.

For each of these, the first step is to compute the emission factors, i.e. the grams of pollutant emitted per kilometre of travelled distance. This is a function of the mean speed and of the kind of vehicle. For the purposes of the MEET report, the vehicles are classified on the basis of their use (cars, commercial vehicles etc.), as well of their fuel and of their emission class. Since as we said we are not interested in exactly modelling the Turin case, but rather we want to assess the potentialities of the DRTS system, we will not consider the bus fleet actually in operation in the city, but we will assume a homogeneous fleet of vehicles satisfying the EURO III emission class. For the DRTS scenarios, we have two kinds of vehicles, with 8 and with 20 seats, which we will also consider complying with the EURO III class. This way, a comparison is to be drawn among vehicles of the same class, so that the different emissions will have to be imputed to the service operation.

Unluckily, the MEET report embeds all the kind of buses in only one class. For this, it is not possible to distinguish among 20-seat vehicles and the larger buses commonly being used to provide traditional services. Hence, we are forced to consider only two kinds of vehicles: EURO III cars for the DRT with smaller vehicles and EURO III buses for the DRT with 20 vehicles and the fixed-line service.

Once the emission factors have been computed, we find the total quantities of pollutants emitted multiplying them for the distance travelled in the whole evening. The results of these computations, for both the fixed line service and the six DRTS scenarios, are reported in the following table, together with the percentages of variation of the emissions of the DRTS against the fixed line service.

Table 2. Emissions of pollutants in the considered scenarios

<table>
<thead>
<tr>
<th>Service</th>
<th>CO₂ (g)</th>
<th>CO (g)</th>
<th>NOₓ (g)</th>
<th>VOC (g)</th>
<th>PM (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix</td>
<td>4625152</td>
<td>28058</td>
<td>30175</td>
<td>7432</td>
<td>676</td>
</tr>
<tr>
<td>L20</td>
<td>7725088</td>
<td>39831</td>
<td>49370</td>
<td>9288</td>
<td>1000</td>
</tr>
<tr>
<td>H20</td>
<td>13793618</td>
<td>71120</td>
<td>88154</td>
<td>16584</td>
<td>1786</td>
</tr>
<tr>
<td>M20</td>
<td>9801631</td>
<td>50537</td>
<td>62641</td>
<td>11785</td>
<td>1269</td>
</tr>
<tr>
<td>H8</td>
<td>2861359</td>
<td>4683</td>
<td>5898</td>
<td>700</td>
<td>391</td>
</tr>
</tbody>
</table>

Once the emission factors have been computed, the quantities of pollutant are linearly dependent on the travel distances, according to the MEET methodology. In our simulation the
DRTS fleet has to run a number of kilometres that is twice (for low quality scenarios) or three times higher than the actual fixed line service in order to satisfy all the requests. This is mainly due to the fact that we serve all the customers without making them change vehicle, whatever is their origin and their destination. The distance being travelled and the number of needed vehicles are almost not dependent on the capacity, because the demand density is not so high. As a consequence, their greater capacity is under-utilized and using bigger vehicles has the only consequence of worsening the emissions.

This is clearly shown in the table. Since we did not distinguish between buses and 20-seats vehicles, the increase of the first three DRT scenarios is due to an increase in the total distance being travelled (and, marginally, in the variation of the mean speed). However it should be pointed out that the two kinds of vehicles are still quite different, so that using a different methodology that allowed keeping this into account would lead to percentages that are not so bad such as these. For the last three scenarios, the improvement is uniquely due to the change of the vehicle, since as we said the distances travelled are almost the same. It is interesting to point out that using small vehicles leads to substantial emission savings, even if the distances travelled increase.

Finally, there is a clear relationship between solution quality and emissions, again due to the increase in the distance travelled and in the number of vehicles needed to serve more quickly all the requests, lowering the rideshare probabilities.

**CONCLUSIONS**

We want primarily to stress on the fact that the results from the previous section can only partly be seen as a forecast of the change in emission levels in case the envisioned DRTS would be implemented in the city of Turin. This because we did not take into consideration any change in the behaviour of service users. The results of our investigation are more general and allow us to draw conclusions in form of guidelines that should be of help for planners interested in developing a DRTS and concerned with the related implications in terms of emissions.

The most important decision to be taken involves the kind of vehicle to be used. It is not a trivial task, since this must be done before the service starts operating, when the demand patterns are in many cases unknown. The level of demand must be carefully assessed and extensive simulations should be run, so that the optimal vehicle capacity can be detected. A naive approach to this problem usually leads to an optimistic overestimation of both ridership level and rideshare possibilities, thus generating serious economic problems. However the utilization of small vehicles (8 seats) seems to be able to guarantee substantial emissions decreases in any case.

The service quality level has also an influence on the emissions. If these are of concern, this element should be taken into account when the service provider has to set the quality constraints. Since the relationship between service quality and emissions can be explicated through the travelled distance, when performing an economic evaluation it is possible for example to introduce a correcting factor on the unit cost of a travel to keep this aspect into account.
ACKNOWLEDGEMENTS

We acknowledge Enrico Bernardis, from the Turin Transit Agency ATM (Azienda Torinese per la Mobilità), for having elaborated the data concerning the potential DRTS service demand in Turin.

REFERENCES


