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Analytical models for comparing Demand Responsive Transport with bus services in low demand interurban areas

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ABSTRACT
As new shared mobility services emerge there is an increasing need for better understanding of the role and potential markets of these services which would result in viable business models. The current research aims at exploring Demand Responsive Transport (DRT) services, as a case of efficient mobility service provision for low demand interurban areas. Analytical models are developed and applied in a real case identifying critical demand thresholds for the alternative modes. Finally, the analysis points out the trade-offs between costs and level of service a transport operator or mobility provider needs to consider to implement a successful service.

KEYWORDS
Demand Responsive Transport; analytical model; optimization; public transport network design

Introduction

Over the last years the Public Transport (PT) landscape is experiencing a growing transformation with new private mobility providers and operators offering services, competing with traditional public transport authorities (usually publicly owned and/or managed). Innovative shared mobility services offer, in general, additional options and increased flexibility to specific target groups, aiming at better meeting users' needs. One form of innovative shared mobility services is Demand Responsive Transport (DRT). DRT, also encountered as Flexible Transport Services (FTS) (Brake, Nelson, and Wright 2004), Dial-a-Ride (Daganzo and Ouyang 2019) or Paratransit (Charisis, Iliopoulou, and Kepaptsoglou 2018) constitutes a service positioned between taxi and conventional bus.

A number of methods have been employed to compare DRT with bus and other 'traditional' transport services, from agent-based simulation and algorithmic approaches (Charisis, Iliopoulou, and Kepaptsoglou 2018; Inturri et al. 2018) to economic and qualitative approaches (Daganzo and Ouyang 2019; Charisis, Iliopoulou, and Kepaptsoglou 2018) each one focusing on different aspects of the problem. A recent review of methods and approaches used in DRT literature can be found in (Nourbakhsh and Ouyang 2012). As opposed to simulation methods, which often only focus on optimizing trips, in favor of the operator (Quadrifoglio and Li 2009), extensive research has been also devoted using analytical methods. Analytical models have been developed for various network layouts to compare the performance of DRT with alternative modes (Charisis, Iliopoulou, and Kepaptsoglou 2018; Nguyen-Hoangab and Yeung 2010; (Papanikolaou et al. 2017). Research efforts using these methods typically model both operator and user sides, by developing cost functions which are minimized to find the optimal values of network design variables, balancing operator and user cost.

Although many network layouts and contexts have been studied, surprisingly, to our knowledge, no generic analytical models have been developed for the case of connecting low demand interurban areas with a neighbor city center, a context typically encountered in DRT services. Following this line of research, the current paper aims at developing generic analytical formulations for assessing DRT services in cases of low interurban demand. The following paragraph sets out the formulae describing the two alternative services, namely conventional bus and DRT, while paragraph 3 presents numerical results from a case study in the interurban area of Thessaloniki, Greece. Finally, the paper concludes with a note on the use and generalization of the findings as well as extensions of the research.

Analytical model

To compare the two alternative transport services (bus, DRT), analytical expressions of the cost functions for each service are developed. The analytical models consist of two parts, operator's and users' costs. The sum of these costs represents the total social cost of each service and does not include any transfer payments (e.g. ticket costs), thus reflecting the opportunity cost to the society. Total costs of the services are then minimized, to determine the optimal values of the operational characteristics of each PT service and identify the most efficient transport mode for each scenario and demand level. The network design optimization problem takes the form:

$$min\{TC_{Mode} = TC_{Operator\_Mode} + TC_{User\_Mode}\} \tag{1}$$

In Equation (1), $\mathrm{TC}_{\mathrm{Operator\_Mode}}$ corresponds to the total cost of the operator (either for bus or DRT) which is further broken down to its various components of operational, maintenance, and investment costs (Equation (2)): $TC_{OpM_{ode}} = C_{Oper_{/Mode}} + C_{Maint_{/Mode}} + C_{Inv_{/Mode}}$. On the other hand, the average total passenger cost consists of the sum $TC_{User\_Mode} = C_{Walk} + C_{Wait} + C_{Travel}$ (Equation (3)), which represents the different (time) components of user's journey cost, namely walking, waiting, and in-vehicle travel time.

The transport network and service area modeled corresponds to a setting frequently met in practice, namely the connection between a remote (interurban) area and a terminal station (e.g. city center, central bus station, etc.). The interurban area is modeled as a rectangular shape with length β and width α, located L kilometers

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from the terminal station and is depicted in Figure 1. The temporal distribution of passenger demand is assumed to be a Poisson process with an average rate of d passengers per hour for both directions while the spatial distribution of demand is considered homogeneous throughout the area. The average demand rate d takes values up to 100 passengers per hour and direction to represent cases of relatively 'low interurban demand.' Within the interurban area, in the case of bus, vehicles start at the top of the area (point A in Figure 1) and run across the bus line which is located in the middle of the area (at $\alpha/2$). The total length of a bus route (per direction) equals to $\beta + L$, with β representing the length inside the interurban area and L the distance between the area and the terminal. During a full cycle, each bus travels $2(\beta + L)$ kms and serves $2d^*H_{Bus}$ passengers (in both directions). The duration of a full cycle is given by:

$$CL_{Bus} = \frac{2L}{V_L} + \frac{2\beta}{V_\beta} + \tau_b * \left(\frac{2\beta}{s} + 1\right) + \tau_p * 2dH_{Bus} \tag{4}$$

In Equation (4), $2L/V_L$ and $2\beta/V_\beta$ represent the time for a bus to travel across L and β, while the coefficients τ_b, τ_p denote the additional time (delay) a bus spends at stops because of acceleration/deceleration and the boarding/alighting time per passenger at stops respectively. The number of bus stops in the interurban area is $\beta/\mathbf{s}$, where **s** is the spacing (average distance between stops). The headway (H_{Bus}) and the spacing (s) constitute the network design (decision) variables since they define the quantity and quality of the service the operator provides.

The total (bus) operator cost per cycle (TC_{Oper_Bus}) is the product of the number of vehicles/buses in operation with the total cost per bus and cycle. There are CL_{Bus}/H_{Bus} vehicles operating which serve a total demand of $2d^*CL_{Bus}$ passengers per cycle. Thus, the total operator's cost for bus per cycle length (CL_{Bus}) is given by Equation (5):

$$\begin{aligned} TC_{Oper\_Bus} = \frac{CL_{Bus}}{H_{Bus}} * \big[2(\beta + L) * c_{Veh/kms} \\ + CL_{Bus} * c_{Veh/hours} + CL_{Bus} * c_{Invest/bus} \big] \end{aligned} \tag{5}$$

In Equation (5), coefficients $c_{Veh/kms}$, $c_{Veh/hours}$ and $c_{Invest/bus}$ are unit costs representing the operational cost per kilometer traveled, the maintenance cost per hour, and the investment cost corresponding to an hour (assuming a 10-year period of use for the vehicle). Thus, the products of the unit costs with the terms $2(\beta + L)$ and CL_{Bus} give the operational, maintenance, and investment cost of one vehicle (bus) for one full cycle, which in turn multiplied with CL_{Bus}/H_{Bus} returns the

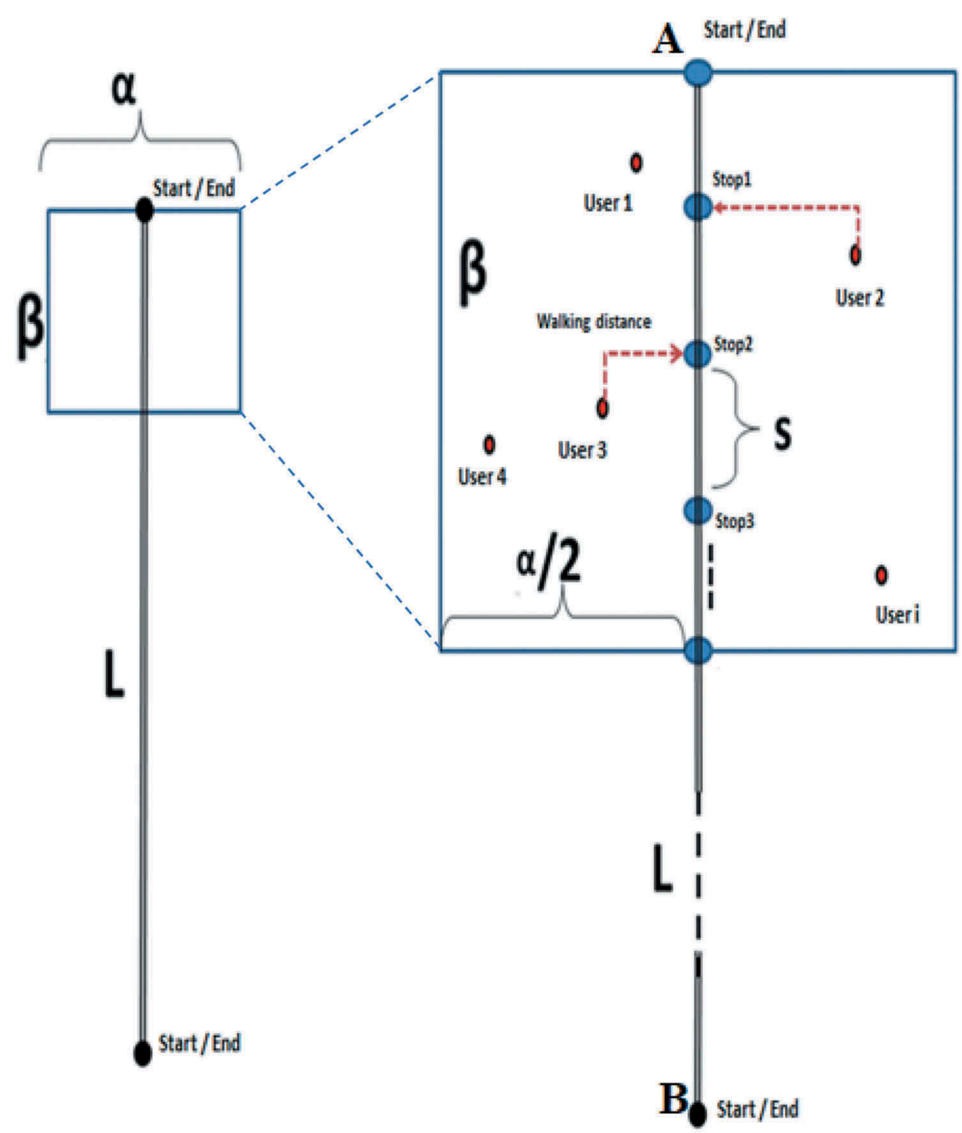

Figure 1. Bus network representation.

total operator cost for all buses during one full cycle. On the other hand, the total passengers cost per cycle (TC_{User_Bus}) is derived by the sum of the average walk, waiting, and travel times of a user, multiplied by the demand (number of users served per cycle). To convert the total travel time to monetary units, the Value of time (VoT) is used for the specific area. The equation of TC_{User_Bus} thus is of the form:

$$TC_{User\_Bus} = VoT * 2d * CL_{Bus} * \left\{ \frac{\alpha + s}{4v_{walk}} * \mathrm{a}_{walk} + \frac{H_{Bus}}{2} * \mathrm{a}_{wait} + \left[\frac{L}{V_L} + \frac{1}{2} * \left(\frac{\beta}{V_\beta} + \tau_b * \frac{\beta}{s} + \tau_p * d * H_{Bus} \right) \right] * \mathrm{a}_{InVeh} \right\} \quad (6)$$

Assuming a homogeneous random spatial distribution of demand in the service area and by considering the ‘Manhattan’ distances between points (i.e. users and vehicles walk/travel only horizontally and vertically), the terms (α + s)/4v_{walk}, H_{Bus}/2 and L/V_L + 0.5* (β/V_β + τ_b * β/s + τ_p * d * H_{Bus}) correspond to the average walking, waiting at the stop and in vehicle traveling time of a passenger. Finally, coefficients a_{walk}, a_{wait} and a_{InVeh} could be used as weights to reflect the perceptions of users with respect to the walking, waiting and in-vehicle travel time (with default values of 1 in case of missing local data).

On the other hand, the operational difference of the alternative DRT service is (DRT) vehicles can pick up passengers from their home by doing lateral movements across the width of the inter-urban area (α). This additional flexibility affects both the operator and users’ costs. Figure 2 depicts the network for the DRT service.

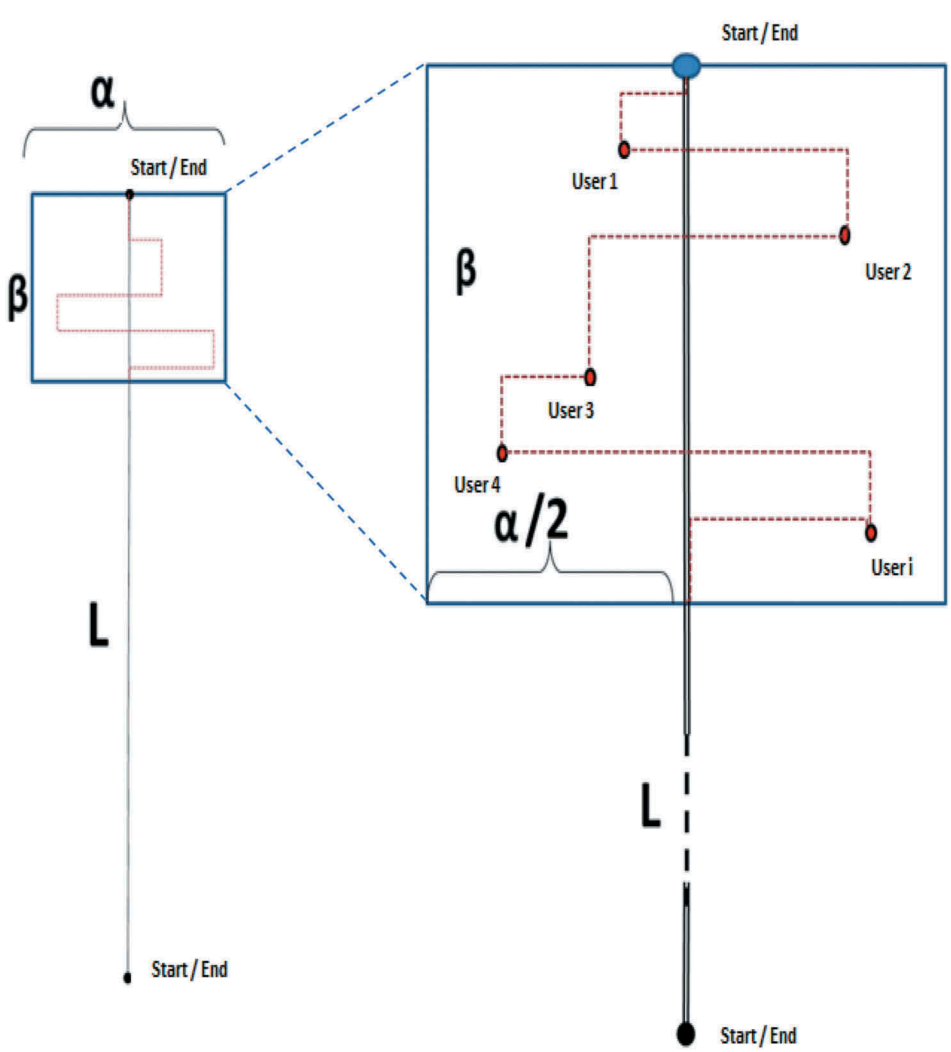

Figure 2. DRT network representation.

Also, the DRT service operates with smaller vehicles (common practice is using 16 or 22 seaters), hence it has a lower operator cost per vehicle. DRT costs are also broken down to operator and users' cost. The operator cost for DRT is described by the following form:

$$TC_{Oper\_DRT} = \frac{CL_{DRT}}{H_{DRT}} * \left[2\left\{ \beta + L + \frac{a}{2} + \frac{2a}{3} * (dH_{DRT} - 1) \right\} * c_{Veh/kms} + CL_{DRT} * c_{Veh/hours} + CL_{DRT} * c_{Invest/DRT} \right] \quad (7)$$

In Equation (7), the additional average lateral movement of a DRT vehicle is described by the term $[\frac{a}{2} + \frac{2a}{3} * (dH_{DRT} - 1)]$, which represents the average random distance of two passengers across length α for (d_{HDRT} − 1) passengers served per bus and direction, plus a length α/2 which expresses the sum of the average lateral distances from the starting point (A) to the first passenger (α/4) and the last passenger within the area to the beginning of L (α/4). Also, assuming the same demand the cycle length of a DRT vehicle is longer than a bus vehicle and is described as follows:

$$CL_{DRT} = \frac{2L}{V_{L\_DRT}} + \frac{2\beta + a}{V_{\beta\_DRT}} + \frac{2a(dH_{DRT} - 1)}{3 * V_{\beta\_DRT}} + 2dH_{DRT} * (\tau_{DRT} + \tau_p) \quad (8)$$

DRT is assumed to provide a door-2-door service, i.e. all DRT passengers are picked up/dropped off at their point of origin/destination (term $2dH_{Bus}(\tau_{DRT} + \tau_p)$ in Equation (8)). In practice, passengers may be concentrated in common points so Equation (8) describes an upper bound of the average cycle time for DRT.

Finally, the total cost of the users for DRT is represented by the following equation:

$$TC_{User\_DRT} = \mathrm{VoT} * 2\mathrm{d} * CL_{DRT} * \left[\frac{H_{DRT}}{2} * a_{wait} + \left(\frac{L}{2V_{L_{DRT}}} + \frac{CL_{DRT}}{4} \right) * a_{InVeh} \right] \quad (9)$$

For DRT users there are only waiting and in-vehicle travel time (no walking time). The average in-vehicle time is derived by diving CL_{DRT} by 4 (equals to the half time the bus spends across the area and L per direction) and adding $L/2VL_{DRT}$ to compensate for the half time of users traveling across L.

Our design problem is to find the optimal values of the decision variables (H_{Bus}, s for bus and H_{DRT} for DRT) which minimize the total cost for the two services for alternative demand levels and study the trade-off between operator and user costs.

Results

The models developed are used to evaluate the potential introduction of a DRT service for Lagkadas, an interurban area of Thessaloniki, Greece. Lagkadas has a population of 19,587 residents and is located in the northeast part of Thessaloniki regional area, in a distance of approx. 20 kilometers from Thessaloniki's center (Figure 3).

The existing bus network connection is represented by the network layout and the analytical models developed in Section 2. Table 1 summarizes the parameter values used to model the bus and DRT services.

In the following, trade-offs between the operator and user costs are explored and the optimal values of the decision variables are identified. In Figures 4 and 5, the total operator and users' costs for bus together with their various components are presented for d = 100 passengers/hour/direction as a function of H_{Bus}. It is evident that the increase of H_{Bus} reduces the number of buses and in turn results in an exponential reduction of the operational cost which constitutes the major component of the total operator's cost (approx. 75%).

Figure 3. Thessaloniki area and Lagkadas.

Table 1. Parameter values for Lagkadas PT network.

Parameter	Decription	Value
α (km)	Lagkadas Area width	1
β (km)	Lagkadas Area length	1.5
L (km)	Lagkadas–Thessaloniki city	21.5
$C_{Invest/bus}$ (€)	Investment cost, bus/hour	5
$C_{Invest/DRT}$ (€)	Lagkadas Area width	2
$c_{Veh\_hour/bus}$	Cost per Veh/hour for bus	75€
$c_{Veh\_hour/DRT}$	Cost per Veh/hour for bus	55€
$c_{Veh\_km/bus}$	Cost per Veh/km for bus	0.6€
$c_{Veh\_km/DRT}$	Cost per Veh/km for DRT	0.4€
$a_{walk}, a_{wait}, a_{InVeh}$	Weights of users' costs	1
$V_{\beta\text{-bus}}$, $V_{L\text{-bus}}$	Speed of bus across b & L	15, 45
V_{β_DRT}, V_{L_DRT}	Speed of DRT across b & L	20, 60
τ_{Bus}, τ_{DRT}	Delay in stops (bus & DRT)	1/60 h

On the other hand, as H_{Bus} increases (fewer buses) passenger cost increases as well, showcasing the trade-off between the operator and users' costs. It is stressed that users' cost is increased linearly through the waiting time at stops and thus does not overweigh the gain from the reduction of the operational cost for any value of H_{Bus}.

However, for H_{Bus} >0.30, the reduction rate of operational cost savings drops (Figure 3) and thus users' costs start to affect more the total cost of bus service (Figure 4). As a result, the optimal values for H_{Bus} lie within the range 0.3–0.5, which yield approximately 500 and 1800 euros of operational and users cost, respectively (H_{Bus} = 0.35).

Figures 6 and 7 present the total operator and users' costs for DRT. It is noteworthy pointing out the distinct patterns of costs compared to bus, both for operator and users' costs. In the case of

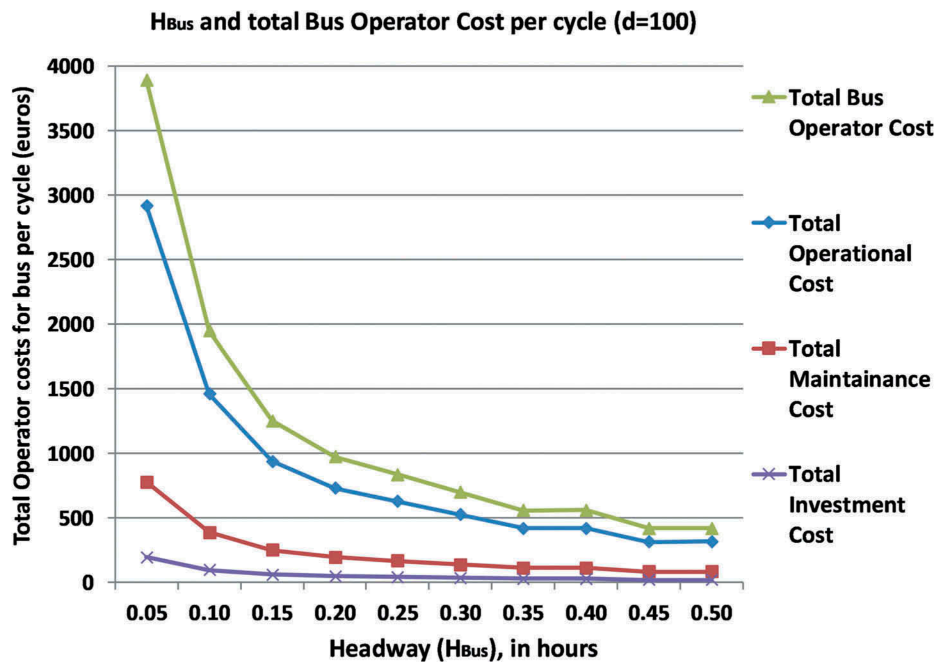

Figure 4. Components of bus operator cost (d = 100).

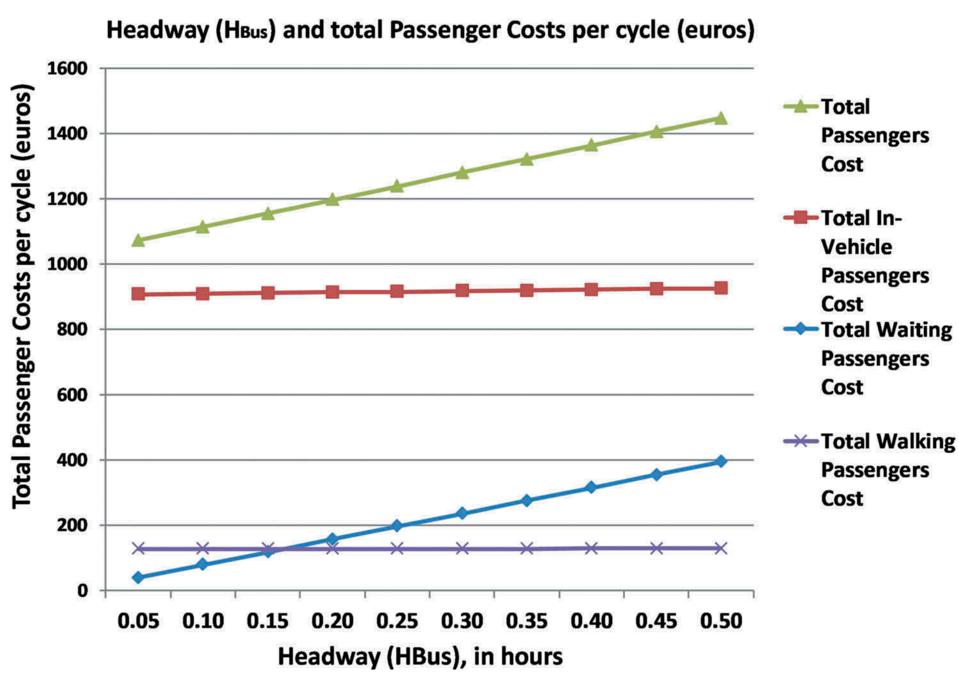

Figure 5. Components of bus users' cost (d = 100).

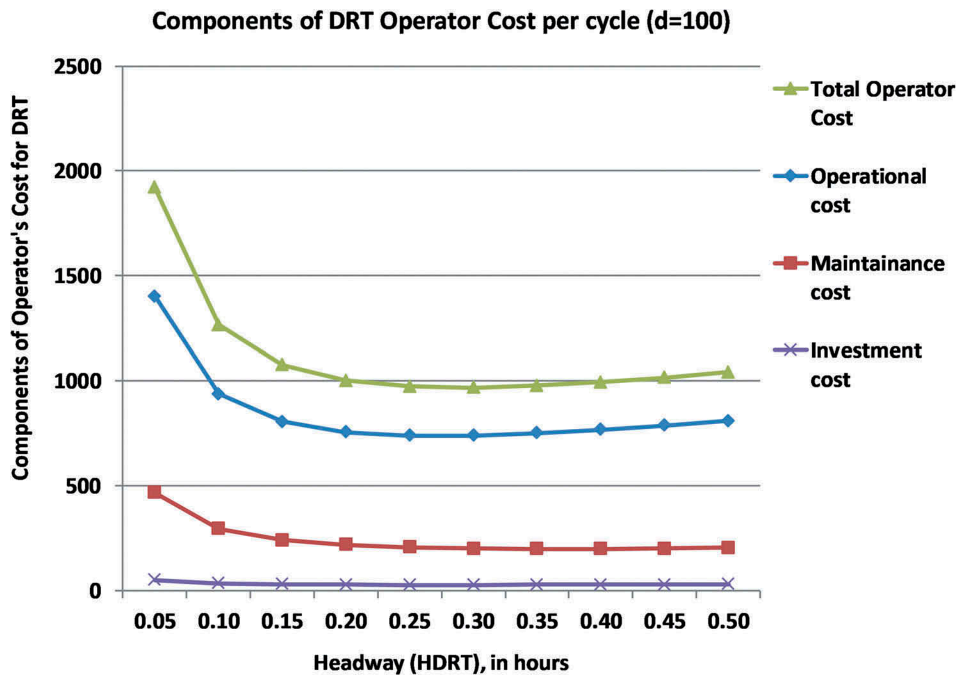

Figure 6. Components of DRT operator cost (d = 100).

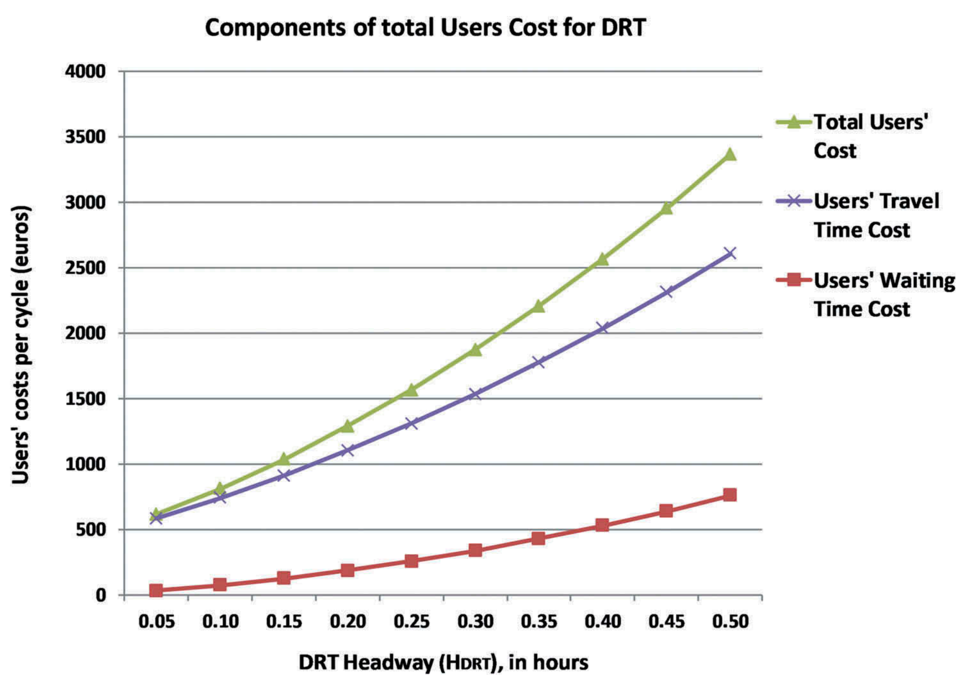

Figure 7. Components of DRT users' cost (d = 100).

DRT, the increase of headway (H_{DRT}) up to a value of 0.2 (12-min frequency), reduces the operational cost whereas further increase leads to higher operational and in turn higher total operator costs, as opposed to bus. This can be explained by the fact that at a certain point (for H_{DRT} >0.20), the benefit (cost saving) of having fewer DRT vehicles is outweighed by the high increase of CL_{DRT} as a result of the additional Veh/kms due to the lateral movements of the fewer DRT vehicles (see Equations (7) and (8)).

With respect to the users' cost, DRT users experience an exponential increase of their total cost as H_{DRT} gets higher, due to (mainly) the consequent increase of the in-vehicle travel time.

There is no walking time and in-vehicle travel time constitutes the major determinant of users' cost (~90% on average) and, once more, the total user cost is significantly affected by the amount of lateral movements per vehicle through CL_{DRT} (Figure 7).

The optimal values of H_{DRT} that minimize the total DRT cost sit in the range 0.15–0.25 (9–15 min). Within this range, DRT seems to achieve a good balance between operator and users cost, equal to approximately 1400 euros and 2500 euros, respectively, per cycle (H_{DRT} = 0.20). Furthermore, there is a capacity constraint which has to be respected, namely $Capacity_{(DRT)} \geq d^*H_{DRT}$ (which denotes the number of passengers per vehicle and direction). The constraint

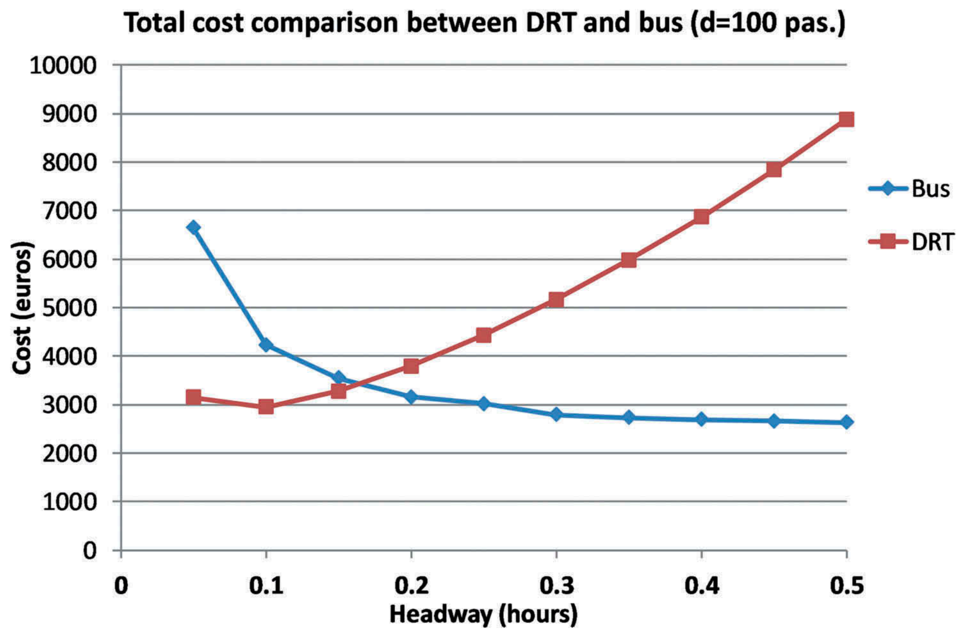

Figure 8. DRT vs. Bus total cost (d = 100).

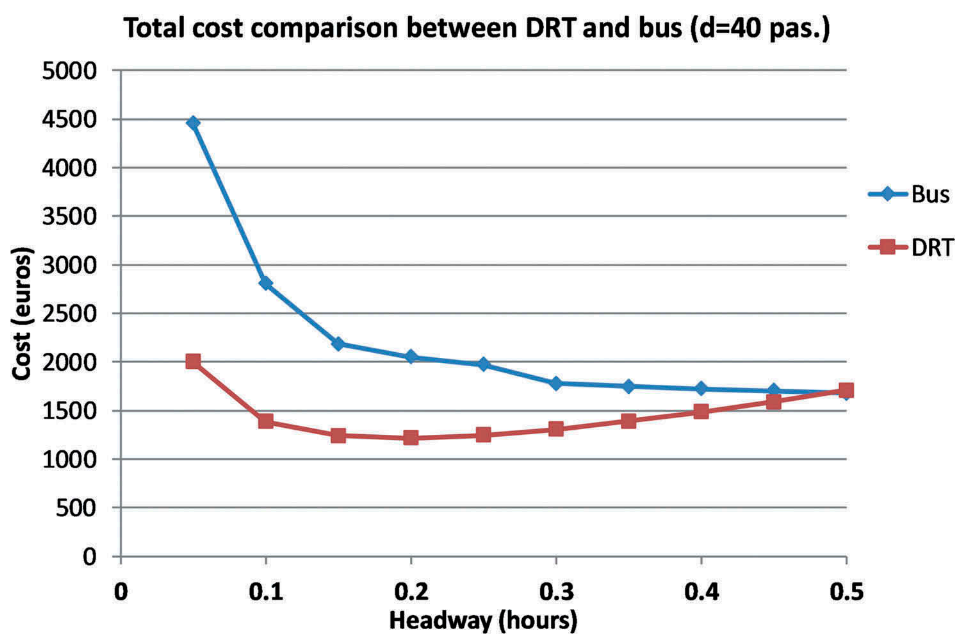

Figure 9. DRT vs. Bus total cost (d = 40).

yields $H_{DRT} \leq 0.22$ which constitutes the upper bound of H_{DRT} when d = 100.

Figure 8 summarizes the information of Figures 4–7, by comparing the total costs of Bus and DRT as a function of headway (H). It can be seen that when d = 100, even though the optimal values of total bus cost are taken for $H_{Bus} > 0.30$, the bus service remains more efficient for values of headway higher than 0.15 (9-min frequency). DRT is more efficient for H ≤ 0.15 (9 min), resulting in a total (DRT) service cost of almost 3200 euros/cycle.

It is anticipated as demand level drops, DRT will become more efficient for higher values of headway. Figures 9 and 10 compare the total costs of DRT and bus for demand levels (d) equal to 40 and 70, respectively.

For d = 40, DRT is more efficient than bus for all values of headway up to 0.5 (30 min), constituting the dominant option (also the capacity constraint is respected as $Cap_{DRT} \geq d{*}maxH_{DRT} = 20$). In case d = 70, feasible solutions for DRT are obtained for H_{DRT} up to 22/70 ≈ 0.31, however as Figure 10 shows DRT is more efficient for H ≤ 0.25, with the minimum cost value (~2080 euros) obtained for $H_{DRT} = 0.10$ (6 min).

Discussion

This research developed tools to evaluate the potential introduction of a DRT service as compared to conventional bus for low demand interurban areas. The contributions of this study were threefold;

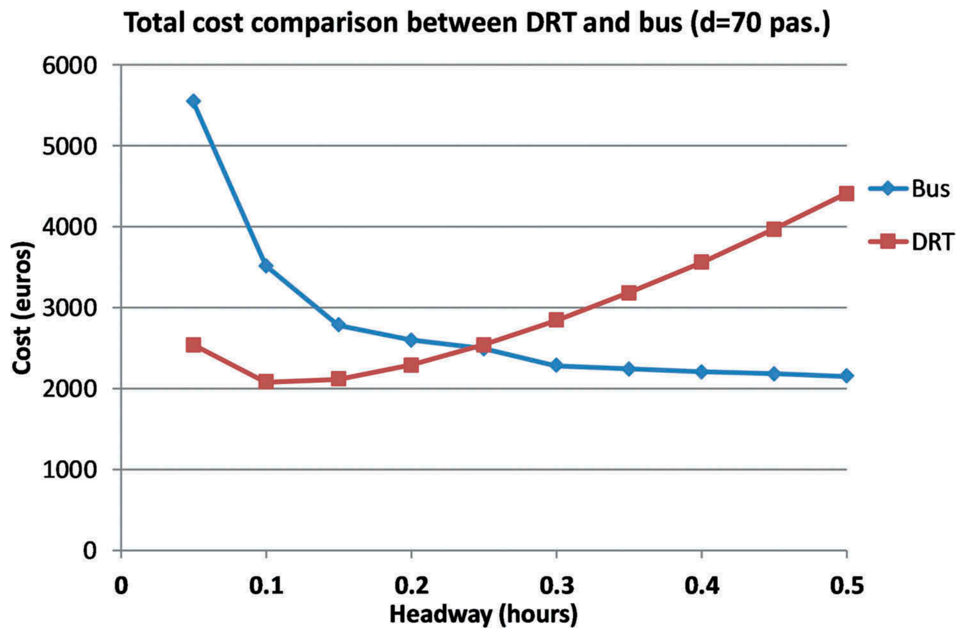

Figure 10. DRT vs. Bus total cost (d = 70).

Firstly, we compared DRT with bus for different levels of demand including both operator and user costs. Secondly, we developed generic analytical expressions for a network layout frequently found in DRT business models, aimed at enhancing the decision-making process for innovative mobility services. Finally, we studied the trade-offs between operator cost and quality of service by capturing the interactions between the various cost components between bus and DRT. The latter is a key consideration of transport operators for designing efficient PT networks.

For Lagkadas PT network, findings showed DRT constitutes the dominant option for demand up to 40 pas/hour/direction. For demand levels between 40 and 70 pas/hour/direction, DRT remains the most preferable option, however as demand increases (d closer to 70pas), bus becomes efficient for higher values of headway (>0.25 or more than 15 min). The average daily demand between Thessaloniki and Lagkadas is 4000 passengers (Ronald, Thompson, and Winter 2015) with seasonal variations up to 40%. On average, this value provides an hourly demand of 110 pas/direction in 18 h of operation. However, this value also fluctuates, with off-peak demand being less 50% of the average. Thus, a potential introduction of a DRT service could be explored for off-peak hours, offering a hybrid service of fixed service during peak hours and DRT service during off-peak. However, this decision should be taken as part of a wider investment scheme in smaller vehicles and after a detailed analysis of demand (e.g. using stated preference experiments). The static treatment of demand is a limitation of the current research, which does not consider demand shifts due to the potential introduction of the new mode (DRT). Extensions of this research can look at the supply and demand interactions in the models to capture the behavioral change of existing and new PT users.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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