Socio-Economic Planning Sciences 41 (2007) 255–268
SOCIO-ECONOMIC PLANNING SCIENCES
www.elsevier.com/locate/seps

Network flow-based strategies for identifying rail park-and-ride facility locations

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Available online 5 June 2006

Abstract

Many cities are considering introducing or expanding rail service in an effort to diversify their modal splits. Park-and-rides are integral to this strategy because they represent private auto users' access points to the system. Proper placement of such facilities is a strategic location decision, as it can conceivably decrease vehicular traffic on congested roadways while benefiting users. This paper models the decision to locate park-and-ride facilities in a network flow-based framework. From this perspective, optimal placement occurs at locations where vehicles will encounter facilities early during their journeys to a centralized area or major activity center. Locating park-and-rides in this fashion maximizes the chances of removing users from the network. These elements are demonstrated in three hypothetical placement scenarios that make use of synthetic network and traffic flow data. Results illustrate the functionality of our approach for identifying park-and-ride candidate locations. Lastly, implications of our work are discussed in light of broader planning concerns and practical demands on rail facility location.

Keywords: Rail transit; Park-and-rides; Network flow capture; Transportation planning

1. Introduction

A growing number of cities in the US are considering adding rail service to the suite of transportation alternatives they already provide. Cities such as San Francisco, Austin, Portland, and Dallas are in various stages of the rail planning process [1]. Rail transport is an attractive alternative because it potentially offers a speedy, environmentally friendly, and efficient means of connecting suburban residential locations with major activity centers people need to access [2]. Furthermore, it is believed that the provision of rail transit will help cities diversify their modal splits (i.e., reduce the automobile share of travel), which is thought to be crucial for reducing congestion [3,4].

Strategically located park-and-rides are integral to encouraging the use of rail. Typically they are large parking lots found in suburban areas. Such facilities link patrons with public transit by offering commuters an opportunity to park their vehicles and board mass transit for the remainder of their journeys. Generally, rail

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0038-0121/$ - see front matter
doi:10.1016/j.seps.2006.04.001

systems tend to be designed so that major activity centers and/or downtown areas, including the central business district (CBD), are easily accessible [5]. The combination of parking and transit service attracts ridership by offering reduced travel cost, shorter commute time, and cheaper parking as compared to solely driving to a destination [3,6].

If properly planned, rail park-and-rides can play an important role in reducing traffic and congestion [5,7]. They generally provide opportunities for vehicle traffic to exit the urban network, which ostensibly results in congestion relief, reduced energy consumption, and lower air pollution [3,7]. Moreover, careful planning of park-and-ride systems may induce other benefits, including helping to achieve broad social and economic goals. For example, park-and-rides can be incorporated into transit-oriented activity centers [8], which may help to boost local economic activity and possibly spur development in targeted locations [1,9].

Park-and-ride systems can thus offer urban areas clear, tangible benefits. However, the placement of these facilities is also critical to the effectiveness of the rail system. If a goal is to reduce traffic, then system facilities should be situated to maximize the chances for capturing vehicles en route to their destinations. Often, this means methodically placing park-and-rides in locations so that large volumes of traffic are intercepted early in their journeys to major activity centers.

Methodology for locating park-and-ride facilities can potentially address any one of many possible planning goals (e.g. to induce local development) in tandem with attempting to maximize traveler usage [9–11]. Various stakeholders (e.g. planners, policymakers) may have different objectives in the development and provision of a park-and-ride system. Irrespective of the demands placed on a new park-and-ride, clearly, infrastructure constraints, the existence of any rail lines, and travel demand figure prominently into park-and-ride placement decisions. Although there are several possible factors that can be considered when situating park-and-rides, their inherent purpose is to provide a convenient and accessible location where travelers switch modes. What this suggests is that, at a minimum, park-and-rides should be sited in a manner consistent with actual vehicular travel patterns; yet, few, if any, studies have focused specifically on modeling this aspect of the problem.

The current paper thus develops optimization approaches for finding the most advantageous rail park-and-ride locations based upon network traffic flows. Our work extends models found in the network flow capture literature [12]. These models place facilities in an effort to intercept a maximum number of vehicles as early as possible in their journeys. By maximizing the traffic intercepted, there is an opportunity to promote rail transit usage, which would theoretically result in fewer vehicles using the network. Operationally, the models are provided with a complete picture of the vehicle miles traveled (VMT) on a road network. Then, the models place facilities assuming that any flow 'intercepted' by a sited park-and-ride results in the vehicle departing the network, leading to reduced automobile VMT. Thus, the model sites park-and-rides so that large vehicle flows have an opportunity to exit the network (i.e. change travel modes) as soon as possible.

There are many factors that impact transit ridership, rail park-and-ride usage, and the overall success of a system (e.g., [9–11,13–15]). In fact, the aggregate benefits of rail transit systems can be debated [16,17], however, that discussion is not addressed here. We have chosen to pursue a network flow-based approach over other available methodologies as it allows one to focus explicitly on transportation network traffic patterns, which are essential considerations for the placement of a facility. In fact, we believe that our study is the first known attempt to adapt flow capturing techniques to the study of rail stop location.

The proposed methodology would, we feel, be most appropriately used early in the rail planning process, when initial candidate locations for park-and-rides are needed. Because sites are identified based on objective, repeatable methods and commonly available spatial data, our methods should find interest with planners actively involved in designing rail transit systems, as well as with researchers working in the area of network analysis and facility location.

2. Background and literature review

This section provides background material to aid in developing the methodological approach employed in our paper. First, general concepts relevant to the research of park-and-ride placement are discussed, including issues of congestion relief, traveler behavior, and achieving various planning objectives. Then, several complementary studies are reviewed to contextualize the contribution of our research.

2.1. Park-and-ride flow capture and guidelines for facility placement

Incorporating multiple planning criteria into the placement of park-and-ride facilities for rail transit is important; nevertheless, a fundamental objective in the siting of such a facility is making it as accessible as possible [3,9,10,13,15]. Research suggests that a viable goal in its placement is to intercept vehicles on journeys to their destinations [6,9,10,13,15,18].

Facility placement is crucial because, according to Taaffe et al. [19], "Once in the car, the typical commuter is reluctant to get out before reaching their final destination regardless of how much congestion is encountered en route." In general, commuters will not drive significantly out of their way to take advantage of public transit. It is therefore not surprising that park-and-rides located upstream of regularly congested areas generate more users than do facilities found elsewhere [10]. Commuters generally want to avoid the bottlenecks of heavy traffic [18]. This suggests that if a park-and-ride facility is encountered early in their journey, vehicular travelers may be more likely to access it before they commit themselves to entering a congested roadway. Additionally, research has also shown that misplaced park-and-rides can alter traffic patterns in unexpected ways [6]. For example, if a substantial number of motorists must deviate from their normal paths to patronize park-and-ride facilities, they may create unanticipated traffic patterns. This could have local impacts in terms of unwanted traffic on smaller feeder roads. Therefore, it would appear important to place park-and-ride facilities on a street network in order to intercept vehicles at opportune locations.

2.2. Park-and-ride market areas

Travel demand is a common basis for determining the placement of park-and-rides. The concept of a "commutershed," which is also sometimes referred to as a "catchment area," is regularly employed by researchers to estimate facility travel demand [2,3,5,10,13,15,20]. Commutersheds define the geographic service area, or buffer, in which park-and-ride patrons originate [5], and are often used as a baseline method for evaluating competing candidate locations. This theoretical geography is generally thought to take a parabolic shape, [3,5,13] with the park-and-ride at the focus of the parabola. Other studies, however, advocate alternative forms [2]. The parabolic shape inherently assumes that vehicle catchment is within a commuter's specified route, and that park-and-ride users will not travel too far out of their way to access the facility. The exact catchment area can be determined by various methods, but most consider the accessibility of potential users or their travel time costs [2,3,13,15]. Once the commutershed geographies are established, comparing potential facility locations is a matter of assessing the nature of demand within the buffers. In this regard, employment statistics of a centralized destination [5], user surveys [2], and population demographics [13,15], are all examples of data utilized to proxy demand and subsequently contrast catchment areas.

The commutershed concept is applied to siting park-and-rides in several studies. In such efforts, geographical information systems (GIS) prove to be valuable tools when assessing locations as they allow the researcher to assimilate and manage the requisite spatial data. For example, Horner and Grubesic [13] compute the demand potential for park-and-rides using a GIS-based grid containing likely patron attributes, coupled with a technique for estimating the trade areas for park-and-rides. Their model establishes potential demand areas based on the notion that motorists will not drive significantly out of their way to utilize a facility en route to the downtown area. However, a limitation of this study is that only socio-economic data are used to assess demand for potential park-and-ride locations. In particular, no assessment of regional traffic flow is incorporated into the methodology.

Farhan and Murray [15] extend traditional commutershed methods by suggesting an alternative view of market areas for park-and-ride facilities. Similar to Horner and Grubesic [13], they account for user accessibility and travel direction when evaluating boundaries that are absent in conventional market area methods. This is important, because, even if a traveler backtracks to a facility, combining such additional travel cost with that of using rail often results in total transportation costs lower than if the traveler had driven directly to his destination. Nevertheless, the approach in [15] is still based upon locating park-and-rides to capture a defined potential user population.

Because the foci in both [13,15] are on commutersheds, they ignore the issue of existing traffic flow in the park-and-ride decision. This is a general limitation of trade area methods, which the current study seeks to address by incorporating traffic flows.

2.3. Modeling rail stop locations to achieve planning goals

Beyond the application of commutershed concepts to park-and-rides, several studies consider other important dimensions of the placement problem. In this regard, models have been developed to achieve rather diverse planning goals. For example, Faghri et al. [9] designed an analytical tool to determine the optimal placement of park-and-rides based on multiple planning, criteria [9]. Collected information is stored in a knowledge-based expert system for modeling the human decision-making process. GIS is also incorporated to enhance the site evaluation process.

The resulting user-friendly system allows planners to take a wide range of considerations into account when assessing potential park-and-ride locations. In fact, the underlying methodology acknowledges that early catchment of vehicles is a noteworthy planning criterion. However, the system may differentially weight the criteria for location analysis. As a result, the goal of early catchment may not significantly influence the ultimate siting of a location. Additionally, the approach assumes predefined candidate park-and-ride locations. The system may therefore select sites that are inconsistent with the objective of removing the maximum possible number of vehicles from a road network.

Finally, more theoretical perspectives on the park-and-ride siting problem have been presented. For instance, Wang et al. [11] introduced an economic approach in considering a linear monocentric city. An interesting feature of their model is that it determines equilibria across travel modes. Once a modal equilibrium is established, facilities are then sited based on profit maximization and social cost minimization. Results show that facilities are best located on fringes of the study area. This is a noteworthy finding as the model's objective does not explicitly seek site locations that are early in people's journeys. Thus, the implications are that a model focused on capturing vehicles early in their journey, as we propose here, might also inherently achieve other social planning objectives, such as reducing total transport costs.

2.4. Implications for park-and-ride placement on a network

Previous literature on park-and-ride placement is quite varied in its methods, although there is consistent recognition of the importance of location in conjunction with existing or proposed light rail systems [3,9,13,15]. As discussed earlier, techniques that are flow-based, or, more specifically, seek to maximize the number of vehicles intercepted by a park-and-ride facility as early as possible in their journeys, have yet to be considered in this context. The current study advocates such a network flow-based approach.

A fundamental objective of park-and-ride placement is to promote a modal split (see Section 4) to a maximized number of potential users, thus reducing roadway congestion. If candidate locations for park-and-ride facilities could be identified with the objective of reducing VMT, then they could be subjected to further scrutiny based on some of the broad planning goals discussed above. The following approach is presented as a foundation for locating park-and-rides with roadway network flow as the key criterion for the initial identification of candidate sites.

3. Model formulation

Spatial models are routinely used to site facilities in discrete space (i.e. on a network) subject to efficiency criteria. In this regard, it is the p-median problem that is perhaps among the most widely used approaches. The traditional model sites p facilities on a network given a set of candidate nodes, with the goal of minimizing patron transport costs to the facility locations (see [21] for a formulation). It has been used to address a number of diverse spatial problems, particularly in the realm of service area delineation (see [19,22] for discussions).

With respect to the problem at hand, it may be tempting to cast the rail park-and-ride location question as a traditional facility location problem, and thus attempt application of the p-median model (in order to site terminals nearest to likely patrons). However, such a strategy would be flawed. This is because the traditional p-median problem is not formulated to take advantage of traffic flow information between origins and destinations—a significant factor in the context of rail stop location. The p-median problem would, of course, be able to site stations near travelers' origins, but it would do so disregarding their destination locations. Thus, it is more desirable to use an approach that recognizes the flow of travelers or commuters between origins and destinations.

The family of spatial models dealing with the capture of flows may be extended to model the rail park-and-ride problem [12,23–25]. These models are related to the p-median problem in terms of their formulations and constraint structures (see [12,22]). Generally, flow capture problems seek to site facilities in order to intercept or capture a maximum amount of flow on a network [25]. One extension to the basic model, known as the preventative inspection model (PIM), expands on the objective of simply maximizing flow capture. The PIM also locates facilities to intercept a maximum number of vehicles *early* in their journeys through a network [24,26]. It was created in an effort to site inspection stations that would protect people living along streets from vehicles that may pose a risk. For example, if vehicles carrying hazardous materials are intercepted promptly for safety inspection, the risk to other drivers sharing the roadway, or persons living farther along the route, can be significantly reduced or eliminated. In summary, the PIM finds the optimal locations for facilities in capturing the largest amount of flow, as early as possible, on origin–destination paths [22,24].

Our study proposes that the PIM can be extended to locate park-and-ride facilities. Focusing on traffic flows, optimally located park-and-rides should be positioned to 'remove' the maximum number of VMT possible from the road network. Assuming that vehicles will be more likely to utilize a park-and-ride facility early in their journey, choosing a more upstream location should pull more VMT from the road network than might another location downstream. Usually the PIM sites facilities to protect a network based on a 'protection value' calculated for each node. In the traditional PIM, the population assumed to be living along a network arc is used to estimate the protection value. This feature has been replaced here with a measure of the VMT that would be 'removed' by siting a park-and-ride at a given node. The following formulation of the PIM is adapted from Hodgson et al. [24] and Miller and Shaw [22] for use with the rail problem:

$$\text{Maximize } (Z) \quad Z = \sum_{r=1}^{n_r} \sum_{i \in R_r} P_{ri} X_{ri} \tag{1}$$

$$\text{subject to} \quad \sum_{i \in R_r} X_{ri} \leqslant 1 \quad \forall r, \tag{2}$$

$$Y_i - X_{ri} \geqslant 0 \quad \forall r, i \in R_r, \tag{3}$$

$$\sum_{i=1}^{n} Y_i = p, \tag{4}$$

where, P_{ri} is the VMT available to path r at node i; X_{ri} the proportion of the total VMT available at node i to path r, which the facility intercepts, i.e. $0 \leqslant X_{ri} \leqslant 1 \ \ \forall r, \forall i$; r the origin–destination path number; R_r the set of all nodes on path r between, and including, origin and destination nodes; n_r the number of origin–destination flows; $Y_i = 1$ if a facility is sited; $= 0$ if not, i.e. $Y_i \in (0, 1)$; i the node index; n the number of nodes; and p the number of facilities to be sited.

The objective function (1) maximizes the number of VMT removed from the network by placing p park-and-ride facilities. In this formulation, the number of facilities to be sited, p, is user-specified. Constraint (2) ensures that, at most, 100% of the VMT along a path is used or 'removed.' Constraint (3) requires that a path cannot have VMT removed from it without a facility. Finally, constraint (4) ensures that p facilities will be sited.

When the PIM is modified for use with the park-and-ride problem, site selection dictates that P_{ri} be calculated as the product of the vehicle flow on a specific origin–destination route that intercepts node i, and the miles traveled from node i to the destination node j. Formally, this appears as

$$P_{ri} = f_{rij} \times d_{rij}, \tag{5}$$

where f_{rij} is the traffic flow on path r from node i to destination node j ; and d_{rij} the distance traveled on path r from node i to destination node j with all other notation as defined earlier. The PIM is route, or path-based, where the specific paths of flow between trip origins and destinations are accounted for in the objective function. The formulation assumes that *a priori* network flows are available, which are a common output from travel demand modeling [19].

Recall that our version of the PIM resembles that of Hodgson et al. [24] and Miller and Shaw [22] with Y_i specified as a binary integer variable, and X_{ri} presented as a continuous variable bounded from zero to one. The implication of a fractional X_{ri} is that a park-and-ride sited on a given path does not necessarily have to 'intercept' all flow that passes it; the idea being that some traffic could be potentially 'removed' by another facility farther along the path from origin to destination. However, in the small networks utilized here, we found that these decision variables took on exclusively binary integer values (i.e., sited facilities removed 100% of the VMT passing through their locations).

Gendreau et al. [26] suggest that the X_{ri} variables will take on binary integer values in applications so long as Y_i is specified as a binary integer variable. Readers interested in additional insights into these models, and detailed examples illustrating the PIM notation, are referred to Hodgson et al. [24] and Gendreau et al. [26].

4. Computational experiment

We designed a computational experiment that assumes station locations must be found for a planned rail system. Multiple scenarios were analyzed with commercial optimization software to learn more about how and where the model sites facilities. Specifically, our experiment sites park-and-rides on a hypothetical street network under three general scenarios that might be encountered in planning practice.

Scenario 1 allows the model to freely search the entire road network when locating a facility. This is essentially an application of the unmodified PIM appearing in Eqs. (1)–(4). Under this scenario, all traffic analysis zones (TAZs) are considered candidates for park-and-ride placement. Scenario 2 limits the model to certain origin–destination paths on the network chosen for examination. This is done to mimic the case where it is necessary for stations to be sited along predefined corridors, so that proposed or established rail lines follow vehicular network routes.

Scenario 3 can be considered a hybrid of Scenarios 1 and 2. The model is free to search the entire road network, with no predefined corridors. However, there are predefined areas, or sets of nodes where a new facility can be sited. This extension gives Scenario 3 some direction in terms of a generalized region in which to locate facilities. However, the solution is a function of roadway network flow rather than existing rail geography.

4.1. Experimental setting and data description

As noted previously, our study utilizes a hypothetical road network with multiple origins and a single destination. However, since the PIM can account for specific route/path configurations, there can be multiple destinations considered if needed in a specific application. Origin–destination flows are assumed to be based upon interactions between TAZs. The model recognizes TAZ centroids as the origin of flow (i.e. node locations i). The origin–destination path, r, is the route that vehicle flow, originating from a particular TAZ, takes to the centralized destination. In a real-world network however, there could be multiple paths from a TAZ that travel to a single destination. For example, alternative rail alignments considered during the planning phase might consist of multiple routes or paths linking a single traffic generator to a given activity center. These variations can be incorporated and accounted for in the proposed model. Nevertheless, for simplicity in illustrating these concepts, the sample street network reflects the single shortest path between each origin and the single destination.

The test network appears in Fig. 1. The objective in its construction was to create a situation simplistic enough to test the model, but complex enough to illustrate its applicability to a real-world scenario. The origin nodes (TAZ 1-22) and the single destination node (TAZ 23) can be easily discerned. Distance values were arbitrarily assigned to each link on the network along all origin to destination routes. (Note that network links

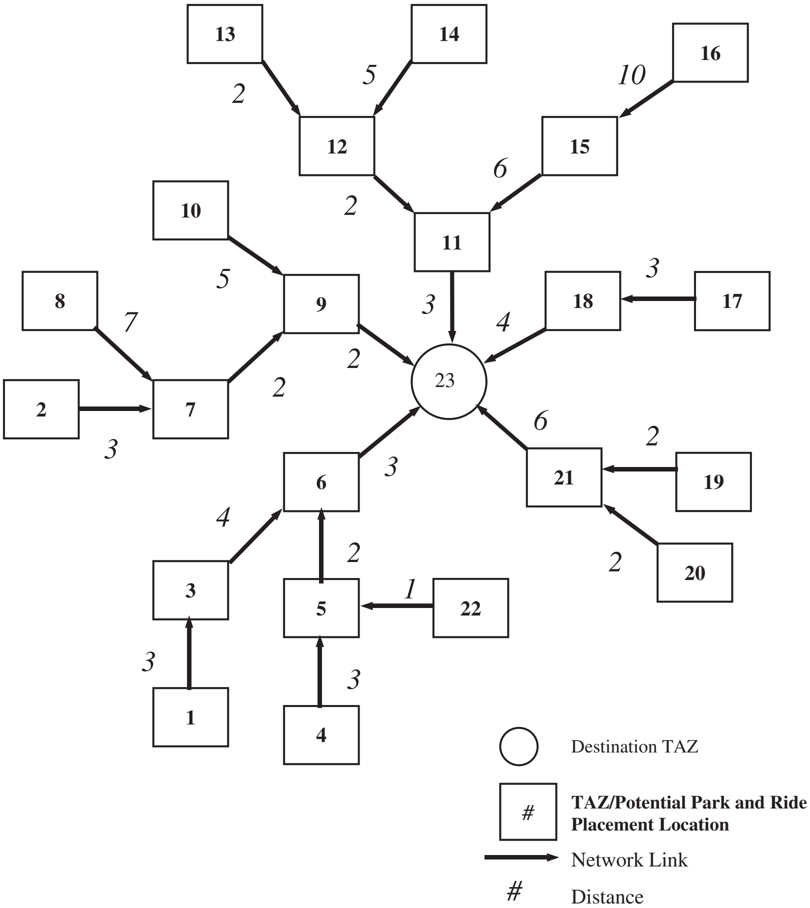

Fig. 1. Base study network (Note: network links not drawn to scale).

are not drawn to scale.) VMT available for potential removal on paths was based on arbitrarily setting values for traffic generated of $f_{rij} = 100$ at each TAZ.

4.2. Computational environment

Each test is formulated using data from the sample networks and solved with commercial optimization software (CPLEX version 6.6) running on a Windows XP equipped Pentium 4 @ 2.2 MHz PC with 1 GB of RAM. Text files containing the problems and data were input into CPLEX. CPLEX solves the problem of interest and reports the objective function at its maximum (Eq. (1)) as well as the configuration of park-and-rides. Solution times are not reported because the models quickly solved to optimality (all less than 1 s) due to the relatively small problem sizes considered. Readers are referred to Hodgson et al. [24] for computational experience with larger, related problems from the flow capture family.

5. Analytical results

Each of the three scenarios previously outlined is now discussed. We analyze selected objective function values and also comment on how and where the model locates facilities in order to illustrate the nature of the results. It is important to understand that the model chooses the best locations as if siting park-and-rides would physically 'remove' vehicles from the network. Clearly, this represents a theoretical case because vehicles will not absolutely and deterministically be removed by the placement of any facility. A mode choice must still take place. Thus, the 'removed' VMT (the objective function value (1) for a given p) should perhaps be considered an objective index measuring the potential benefit of siting a facility. In this way, candidate locations can be compared with one another in terms of the VMT they would potentially capture. Facilities that reduce high levels of VMT must intercept larger vehicle flows early in their journeys; obviously, it is these types of locations that would be desirable to identify.

5.1. Scenario 1: model is free to site park-and-rides anywhere

Each TAZ is designated as the origin node of a specific origin–destination route. Thus, because there are 22 origin nodes on the sample network, there are also 22 routes/paths, and an opportunity to site 22 locations within the network. Scenario 1 was applied with $p = 1, 2, 3, \ldots, 22$ to enumerate the possibilities; but, in practice only a subset of nodes would receive actual facilities. It is thus for smaller values of p that the findings are perhaps most meaningful. All results are shown in Table 1.

Understanding how the model tracks VMT removal is quite straightforward. When $p = 2$, facilities are sited at TAZs 16 and 6. The total VMT removed by siting park-and-rides at these TAZs is 3700. TAZ 16 removes 1900 VMT from the network because a flow of 100 is placed from this location and travels 19 miles before reaching the destination. TAZ 6 captures flows that originate at five other TAZs (1,3,4,5,22) that must travel through TAZ 6 to reach the destination. A flow of 600 travels 3 miles from TAZ 6 to the destination, thus allowing for possible removal of an additional 1800 VMT.

Based on the mechanics of Scenario 1, it is not surprising that, when $p = 1$, TAZ 16 is chosen as the optimal location. Put into perspective, VMT removal associated with this site is 1900, which is approximately 12% of the total network's VMT. Siting a single park-and-ride could thus remove a significant number of VMT.

As seen in Table 1, when the number of located facilities increases, the combination of sited TAZs differs. For example, when $p = 6$, TAZ 6 is no longer used, as it was when $p = 2$. This is a result of the model seeking locations that are upstream of large vehicle flows. Thus, the total VMT available for removal by a park-and-ride is maximized by placing locations upstream of TAZ 6.

Table 1
Results from unrestricted network analysis of park-and-ride(s) locations

Facilities (p)	TAZ location (#) of sited facilities	Potential VMT removed (thousands)	Network VMT removed (%)
1	16	1.9	12.02
2	6-16	3.7	23.42
3	6-16-21	5.5	34.81
4	6-11-16-21	7.0	44.30
5	6-8-12-16-21	8.3	52.53
6	1-3-5-8-12-16-21	9.4	59.49
7	3-5-8-12-15-16-21	10.3	65.19
8	3-5-8-12-15-16-18-21	11.1	70.25
9	3-5-7-8-12-15-16-18-21	11.9	75.32
10	3-5-7-8-10-12-15-16-18-21	12.6	79.75
11	3-5-7-8-10-12-14-15-16-18-21	13.1	82.91
12	3-5-7-8-10-11-12-14-15-16-18-21	13.4	84.81
13	3-5-6-7-8-10-11-12-14-15-16-18-21	13.7	86.70
14	3-5-6-7-8-10-11-12-14-15-16-17-18-21	14.0	88.61
15	3-4-5-6-7-8-10-11-12-14-15-16-17-18-21	14.3	90.50
16	2-3-4-5-6-8-9-10-11-12-14-15-16-17-18-21	14.6	92.41
17	1-2-3-4-5-6-8-10-11-13-14-15-16-17-18-21	14.9	94.30
18	1-2-3-4-5-6-8-10-11-13-14-15-16-17-18-20-21	15.1	95.57
19	1-2-3-4-5-6-8-10-11-13-14-15-16-17-18-19-20-21	15.3	96.84
20	1-2-3-4-5-6-8-10-11-12-13-14-15-16-17-18-19-20-21	15.5	98.10
21	1-2-3-4-5-6-7-8-10-11-12-13-14-15-16-17-18-19-20-21	15.7	99.37
22	1-2-3-4-5-6-7-8-10-11-12-13-14-15-16-17-18-19-20-21-22	15.8	100.00

When the number of facilities allowed to be sited increases, the VMT removed continues to increase, but at a decreasing rate. This effect demonstrates that Scenario 1 accounts for potential VMT removal as additional facilities are sited on the network. In Scenario 1, a minimal number of locations can be sited to have significant impact on VMT; a little more than 50% of the network's VMT is thus removed by the placement of only five facilities. However, a clear limitation of Scenario 1 is that the model investigates the entire street network for park-and-ride placement. Facility configurations can thus be problematic because the model may miss needed sectors, or excess park-and-rides may be allocated to a single line. These aspects of park-and-ride planning will be addressed below in Scenarios 2 and 3.

5.2. Scenario 2: rail corridors are predefined and the model accounts for incoming flow

In the case of start-up rail systems, park-and-rides are usually designed around existing rail lines or large thoroughfares leading to a common destination, such as the central business district (CBD). In such a radial system, numerous origins may connect to one destination. However, as the proposed model is formulated and applied in the previous scenario, there is no control over the number of facilities that may be placed on a given rail transit line. In fact, with respect to start-up systems, and locating the terminus, a desired constraint is that there should be no more than one park-and-ride allotted per line. This additional constraint can be easily incorporated into the model of (1)–(4), allowing for more realistic types of rail planning scenarios. It may be expressed as

$$\sum_{i \in R_r} Y_i \leqslant 1 \quad \forall r. \tag{6}$$

To implement constraint (6) with our sample network, predefined rail corridors lines must first be constructed. To do this, TAZs in the road network are differentiated in terms of whether they are to be considered candidate sites, and the network is subsequently simplified to deactivate links connected to non-candidate TAZs. The results of these network refinements to construct rail corridor lines are depicted in Fig. 2. Scenario 2 will only consider the TAZs within these lines for park-and-ride placement. Other TAZs are inactive as candidates, but still contribute traffic flow to the network. Under Scenario 2, network flows from inactive candidates are assigned to the active candidate TAZs to which they are connected. For example, TAZ 11 is assumed to produce a flow of 300, because in addition to its own 100, it also receives flows from TAZ 15 and 16. There will thus be a trade-off between siting facilities as upstream as possible, and placing them as close as possible to large generators.

The model will only consider the TAZs within these lines for park-and-ride placement. Constraint (6) prohibits the model from siting more than one facility on each route. This safeguard ensures against maximizing the number of VMT that can be removed from the network by placing more than one facility on a single rail route.

The results from running Scenario 2 are shown in Table 2. In Scenario 2, $p = 1, 2, \ldots, 5$ park-and-ride locations are sited. Obviously, since there are only five routes chosen for analysis, the model does not allow for more than five facilities to be placed on the road network. More than 50% of the network VMT is removed by siting five facilities. Scenario 2 also demonstrates how flow-based models can be used in situations where predetermined transit lines are required. But a limitation of using predetermined transit lines is that the analyst must significantly reduce the number of TAZs considered for facility location, and construct lines *a priori*. A compromise situation might thus be needed where the analyst can choose to subdivide the study area into regions for more detailed analysis, but the entire network remains available for site placement.

5.3. Scenario 3: model restricted to site park-and-rides within defined regions

In the final scenario, the road network is divided into regions, with clusters of nodes defined beforehand. Here, the model allows for all nodes within a grouping to be considered candidates for park-and-ride placement. Thus, every TAZ/node within the network can be directly investigated without any preaggregation of travel demand. Again, the difference from Scenario 2 is that, here all nodes are considered candidates for placement. Such a model configuration allows the planner to investigate an entire network while focusing on

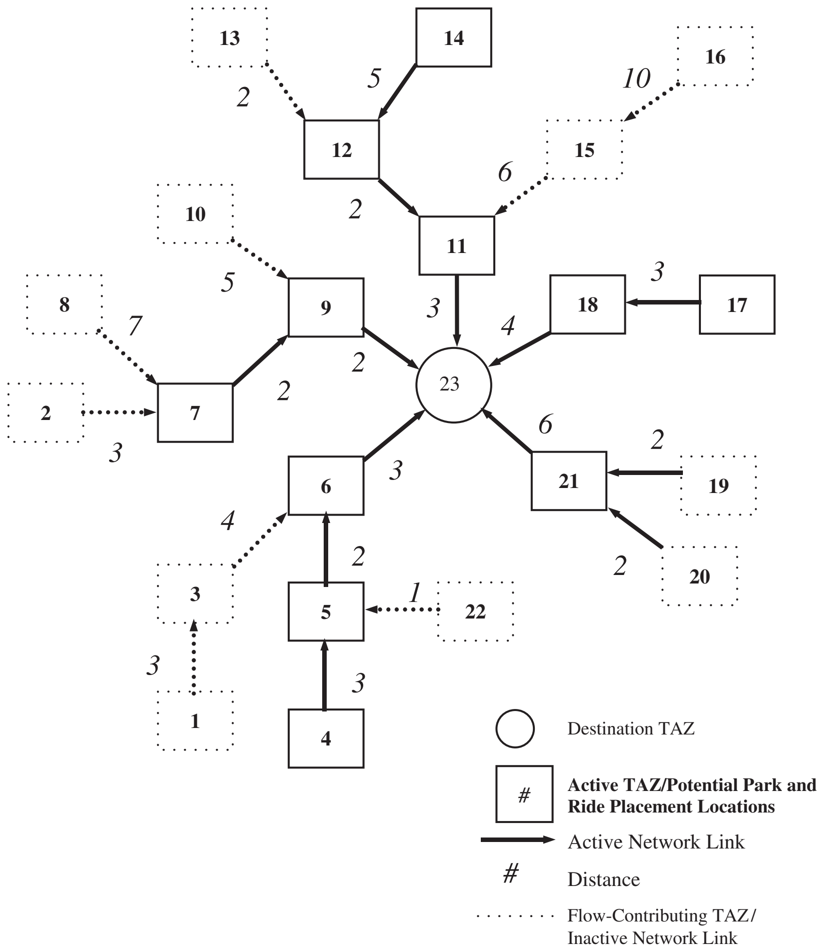

Fig. 2. Network configured for analyzing predefined rail corridors.

Table 2
Results of park-and-ride location analysis based on predefined rail corridors

Facilities (p)	TAZ # sited	VMT removed (thousands)	Network VMT removed (%)
1	21	1.8	13.33
2	11-21	3.6	26.66
3	6-11-21	5.4	40.00
4	6-7-11-21	6.6	48.89
5	6-7-11-18-21	7.4	54.81

well-defined geographical regions to which facilities may be sited. Analogous to Scenario 2, operationalizing this strategy entails adding an additional constraint to Eqs. (1)–(4). However, in Scenario 3, the constraint forms the basis for regions and specifies the number of facilities that can be sited within each one. To account for this condition, constraint (6) is replaced by

$$\sum_{i \in L_l} Y_i \leqslant q_l \quad \forall l, \tag{7}$$

where L_l is the set of all origin nodes (TAZs) in node region l; and q_l the user-specified maximum number of stations/facilities to be sited in each region l.

Constraint (7) allows for user flexibility in determining the maximum number of park-and-rides to be sited within a region. For example, Scenario 3 can be run so that, for l_1, $q = 2$, while l_2, $q = 1$, and so on, for all regions (l) in the street network.

To test this network-based, regional scenario, constraint (7) is formulated where $q = 1$ and 2 for all defined clusters shown in Fig. 3. For simplicity, the study areas were delineated such that the TAZ paths in a given region converge into main thoroughfares that directly connect to the central destination. Scenario 3 was run for $p = 1, 2, \ldots, 5$, facilities for both configurations of q. When $q = 2$, 10 facilities can potentially be sited; but, for comparative purposes, the model was only used to identify five locations. Results for both configurations are shown in Table 3. Note that they appear similar when one to three facilities are sited. However, when four and five facilities were sited, the combination of selected nodes differed. This is due to the regional constraint forcing the model to find optimal arrangements; i.e. those that maximize the early removal of VMT from the network. Additionally, under Scenario 3 about 50% of the network VMT was removed when five facilities were sited.

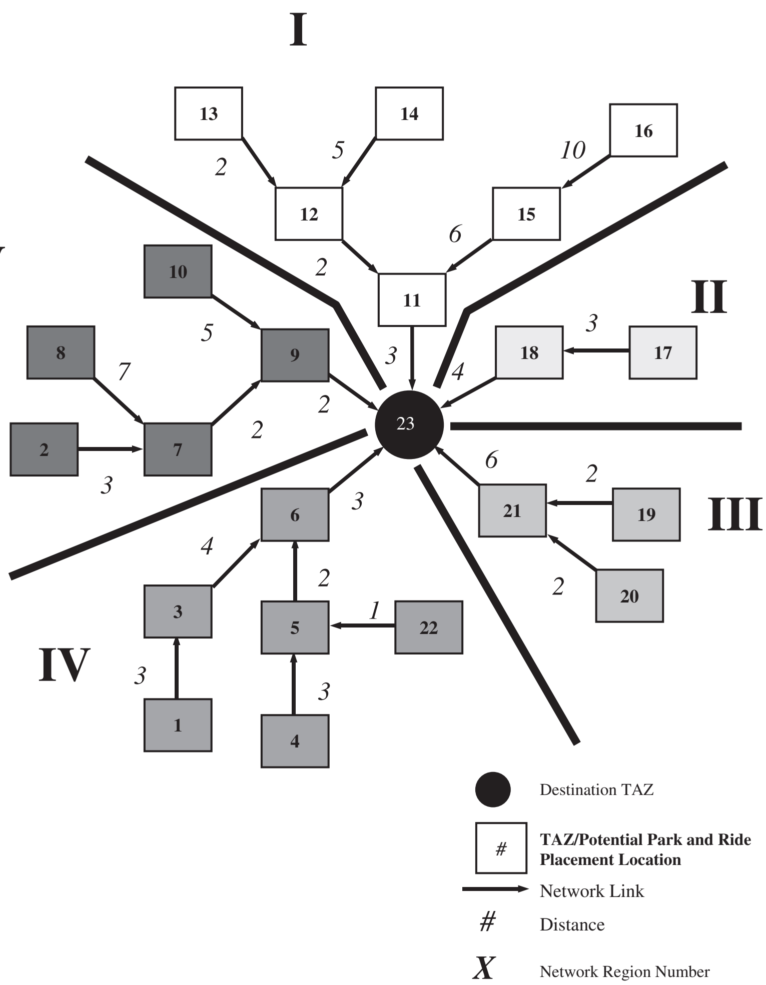

Fig. 3. Network configured for analyzing defined regions.

Table 3
Results from park-and-ride(s) location in defined regions

Facilities (p)	$q = 1$			$q = 2$		
	TAZ # sited	VMT removed (thousands)	Network VMT removed (%)	TAZ # sited	VMT removed (thousands)	Network VMT removed (%)
1	16	1.9	12.02	16	1.9	12.02
2	6-16	3.7	23.42	6-16	3.7	23.42
3	6-16-21	5.5	34.81	6-16-21	5.5	34.81
4	6-8-16-21	6.8	43.04	6-11-16-21	7.0	44.30
5	6-8-16-21-18	7.6	48.10	6-8-12-16-21	8.3	52.53

5.4. Summary

Our proposed model performed as intended by placing park-and-rides in the paths of significant traffic flows and upstream of a centralized destination. Additionally, all variations showed that adding such facilities could have significant impacts on the reduction of the network's VMT. Differing optimal park-and-ride combinations arose based on the number of facilities to be sited and the planning scenario under consideration. This demonstrates the flexibility of network flow-based approaches to accommodate various rail planning conditions and needs.

6. Discussion and conclusions

This paper has discussed how flow-based optimization techniques can be extended to siting rail park-and-rides on a street network. We presented a basic model for this task, which seeks to 'capture' vehicles as early as possible in their origin to destination routes, while simultaneously maximizing the amount of potential traffic that facilities remove from the system. Two model enhancements were also explored that represent route designs with relevance to the rail planning process. In sum, our results and experience with flow-based approaches illustrate their utility in establishing candidate locations for park-and-ride facilities.

The motivation for this study centered largely on expanding the scope of techniques available to analysts and decision makers engaged in rail planning and design. Our review of the literature showed that many researchers have successfully applied GIS-based service area delineation strategies, econometric modeling, and other approaches to the rail park-and-ride location issue. However, there has been limited consideration of network flows in the modeling-oriented rail literature despite their obvious implications for park-and-ride site suitability and overall system performance. This paper has addressed that need by documenting the relevance of network flow-based methods in the rail planning decision process. As stated at the outset, this work represents the first known attempt to extend flow capture principles to the study of rail park-and-ride locations.

Our methods are of a theoretical nature and focused exclusively on the use of network flows to identify optimal facility locations. Therefore, if used in practice, our approach may be best suited for augmenting existing means of siting rail park-and-rides. Some existing techniques weigh travel demand geographics, trip generation characteristics and political concerns (see [13]). From a policy perspective, however, using flow-based techniques in a supportive role may hold certain advantages in terms of helping to build consensus and stakeholders' overall support for station location recommendations. Findings from flow-based modeling may be more readily accepted by citizens and decision makers than recommendations based on less scientific approaches. This consideration takes on significance in situations where individuals or interest groups contest planned stop locations. For example, conflict could easily erupt if there were other development types competing for the space to be occupied by a planned facility, if there were doubts over the accessibility of a chosen park-and-ride location, or if there were worries about negative changes to nearby property values and other NIMBY (not in my back yard) concerns. Thus, at the policy formulation and design phase, we would recommend that flow-based methods be considered as a means of providing additional decision support, with an understanding that doing so may aid in building consensus.

We note that this was a first effort to merge the needs of rail park-and-ride siting with the capabilities of flow-based approaches. As such, there are several issues to which we did not attend that should make for interesting additional research. First, we would like to see these techniques utilized in large-scale urban case studies with a detailed street layout, multiple destinations, and complex regional travel flow. Clearly, this would facilitate additional model evaluation and subsequent refinement to improve effectiveness.

In terms of the work conducted here, our analysis assumed a homogenous population. Further research could thus refine the calculation of potential VMT removal by controlling for the population most likely to utilize the rail system under study. To be sure, considering any of those travelers who are bound for a centralized location (as was done here) is one way of attacking the issue. However, future work could also segment the population by its predisposition to choosing rail. Market segmentation for rail studies is routinely performed [13,15] and has been frequently used to build detailed profiles of likely ridership.

In closing, as an increasing number of cities consider the rail alternative, there likely will be a sustained need to deal with commensurate facility location issues in a systematic, analytical fashion. The flow-based approaches presented here offer valuable insights into such efforts.

Acknowledgments

An earlier version of this paper was presented at the January 2005 Meeting of the Transportation Research Board in Washington, DC. The first author would like to recognize David Nicosia of Texas State University, San Marcos for his preliminary research investigating methods of rail system planning. The authors thank Mike Kuby of Arizona State University for insightful discussion and comments on a previous draft of this paper. The authors gratefully recognize the research assistance of Bernadette Marion, Florida State University. Lastly, the authors express their gratitude to Dr. Barnett Parker, Editor-in-Chief, and the anonymous referees for their helpful comments and critiques which improved the paper.

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