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ABSTRACT

This research report is the final deliverable for PATH Task Order 6408: "Improving Mobility through Enhanced Transit Services". The purpose of this task order is to explore alternative methods of providing transit service to areas with low passenger demand density. This report first presents analytical models for determining optimal headway and line spacing for fixed-route, fixed schedule buses, either with fixed stops or allowing buses to stop anywhere along the route. Next, transit taxi services with either fixed or flexible routes that specifically target focused demand patterns are examined. Potential savings of transit taxi services and flexible routes are quantified. Based on the insights from the theoretical analysis and our survey of real-world practices of providing transit service to areas with low passenger demand density, a pilot program is designed for future field testing of an innovative type of transit taxi operation.

Key Words: public transit, demand-responsive, transit taxi

EXECUTIVE SUMMARY

This research report is the final deliverable for PATH Task Order 6408: "Improving Mobility through Enhanced Transit Services". The purpose of this task order is to explore alternative methods of providing transit service for areas with low passenger demand density.

Fixed-route, fixed-schedule bus service for areas with low passenger demand density is notoriously expensive and inefficient. Many alternative methods of transit service provision have been proposed. They offer flexibility in scheduling or routing, or both. Any alternative service proposed for a certain area should be compared to a fixed route, fixed-schedule base-line scenario, in terms of long-term agency cost and user cost. The long term benefits should be strong enough to offset the short-term cost of transition to a flexible mode of service, including the cost for public awareness campaign and driver training.

This report first establishes a base-line mobility level that enhanced transit services should improve upon. We present an analytical model for determining the optimal headway and line spacing for a fixed-route, fixed schedule bus service on a square area, where passenger origins and destinations are assumed to be uniformly distributed. We take careful accounting of user costs in a transit system: access (walking) cost, waiting cost at bus stops, on-bus travel cost (including travel time spent to cover distances and stopping time at intermediate stops), and transfer cost. And these user costs are balanced against the transit agency's cost for operating the buses. Analytical formulas are derived to show the impact of passenger demand density on the bus headway, the line spacing, and the average trip cost. Here we see how the optimal service level drops and how the average trip cost increases as the passenger demand density decreases.

The theoretical foundation for a basic transit taxi service, for which a vehicle can stop anywhere along its route, is established next, followed by an examination of the cost impact of the basic transit taxi service. We show that if the demand pattern is not focused,

the savings from transit taxi service will be very limited.

We then examined alternative methods for providing transit services for low demand density situations. These include innovative arrangements for drivers and vehicles, demand-responsive services, and targeting focused demand patterns. Specifically, we modeled providing regional transit access to a rapid transit line, both with fixed-route operations and with flexible-route shared-ride taxi operations. Vehicle capacity requirements, cost measures and performance measures are established. It was concluded that utilizing flex-route demand-responsive transit taxi can dramatically reduce the overall per trip cost (e.g. from $27.4 per trip to $6.8 per trip) under certain circumstances.

The insight resulting from the modeling and analysis is that, to efficiently serve areas with low passenger demand density, we should target focused demand patterns, design flexible-route transit-taxi operations, and explore innovative institutional arrangements.

With criteria developed from the theoretical analysis contained in this report and from survey of real-world practices, we selected the I-15 corridor in the San Diego region as the pilot test site for a “fixed-in, flex-out” transit taxi service. This service would transport passengers to and from park-and-ride lots located along the I-15 corridor, so that they would be able to utilize the rapid transit on the I-15 in the near future. Issues related to pilot program implementation are examined.

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1 INTRODUCTION

This research report is the final deliverable for PATH Task Order 6408: "Improving Mobility through Enhanced Transit Services". The purpose of this task order is to explore alternative methods of providing transit service to areas with low passenger demand density and providing late-night or weekend transit service. One such service takes the form of transit taxi, which uses smaller-sized vehicles and the existing network of bus stops and stations to provide scheduled or on-call shared–ride service in after-hours.

Transit agencies often feel they are in a no-win situation when deciding how to provide regular fixed-route, fixed schedule bus service for areas with low passenger demand density. Even for areas where weekday peak-hour demand is high, passenger demand level drops significantly after-dark or on weekends. The problem with low demand density is that, if frequent service with good coverage is provided according to a service level standard, buses often travel with few passengers on board, and the agency's operating cost per passenger trip is very high. If the agency adopts the approach of assuming a certain demand level and tries to determine a service level that minimize the combined user cost and agency cost per passenger trip, it will find that the service level is almost unacceptable to passengers such that the previously assumed demand level is not realizable. This would force the agency to curtail service in areas or in periods of low passenger demand. But doing so also has unintended consequences. A person's mobility and accessibility needs include access to low-density areas and mobility during off-peak periods. If transit fails to provide a complete solution, it will fail to attract choice riders and lose mode share to personal automobiles.

Many alternative methods of transit service provision have been proposed. They offer flexibility in schedule, routing, stopping, or a combination of them. Any such service proposed for a certain area should be compared to other alternatives, including the traditional fixed route, fixed-schedule service, in measures related to long-term agency cost and user cost. The long term savings should be strong enough to offset the short-term cost of transition to a flexible mode of service, including the cost for public awareness campaign and driver training. In this research we conduct theoretical modeling of different types of transit services, derive cost and performance estimates under different demand levels, and propose a "fixed-in, flex-out" transit taxi service for pilot testing.

The rest of this report is organized as follows: Section 2 presents a summary of background material for research performed in the early stages of the project; Section 3 presents an analytical model for determining optimal headway and line spacing for a fixed-route, fixed schedule bus service on a square area; Section 4 examines the fixed-route transit-taxi service; Section 5 examines a wide range of alternative methods for providing transit service under low demand density situations; Section 6 presents the design of a transit-taxi pilot program; Concluding remarks are offered in Section 7.

2 BACKGROUND: REVIEW OF THE LITERATURE AND CASE STUDIES

This section provides background material of research performed in the early stages of the project. While this section presents the findings from such work in summary form, this early research has been fully documented in the following two reports (Factor, R.J. and M.A. Miller, 2006) and (Widmann, J.H. and M.A. Miller, 2006).

Due to low ridership and high operational costs, transit agencies especially in many medium-size cities have curtailed their after-dark and weekend services. Consequently, riders needing to travel during these times can go to fewer places, have to endure longer walking distances and waiting times, additional transfers, and are exposed to greater personal inconvenience and potential safety risks. There is a clear need for improvement in off-peak public transport service and this need calls for technologically innovative and cost-effective solutions.

One proposed solution is the concept of transit-taxi service ─ also referred to as late night or night owl service in North America and Nachtbus in Germany ─ as a means to satisfy the need for improvement in off-peak public transport service. Generally, transit-taxi service is publicly available, uses existing transit stop/station infrastructure as “origins” and/or “destinations, is offered when regular buses tend not to be operational, and allows for a shared-ride experience. Vehicle types range from standard 40 foot buses to smaller vans and taxis. Routing options include customary fixed route service and more flexible options with route deviation.

For many years, transit agencies as well as departments of transportation at state and local levels have been experimenting with different transit-taxi options in order to provide enhanced mobility services to their riders that went beyond traditional fixed-route and fixed-schedule transit during off-peak times. Transit-taxi alternatives may be organized into the following three service design groupings: 1) Fixed-route skeletal, 2) Fixed-route with limited deviation, and 3) Feeder/Hybrid.

Fixed-route skeletal service simply provides public transit services in a stop-to-stop style, but to a more limited extent than regular daytime bus service in terms of the number of stops the driver makes or diminished frequency or both. This typically happens during lower-demand hours when ridership levels do not necessitate full fixed-route service such as late-night hours or weekends – times when the ridership levels do not necessitate full fixed-route service. Many transit systems operate networks whereby several daytime routes are combined into a single night route. Frequently, the routes are consolidated at major boarding points, thereby facilitating transfers between buses or from trains to buses at times.

Fixed-route service with limited deviation, sometimes referred to as "flexible routing," is slightly more complex than skeletal transit service. The vehicle typically has the flexibility of a shared-taxi type service and can deviate a certain distance from designated fixed route stops based on rider request. We find a good deal of variation of this service type – both legal and illegal ad-hoc – in developing countries where informal transit markets flourish. Flexible routing is also prevalent in many U.S. and Canadian cities. Flexible routing is an especially useful service type for late-night – a time when safety concerns may prevent riders from using a normal bus service that does not deviate to bring passengers closer to their final destinations.

Feeder/Hybrid service is the most complex and has the most structural variety of the three service types. Broadly defined, this is a combination service whereby fixed-route transit vehicles interface with typically smaller shared-ride or dial-a-ride services that can provide door-to-door service (or at least closer point-to-point than a fixed-route service can provide) resulting in a hybrid bus-taxi service. This hybrid option can take on both a many-to-one (origins-to-bus) and a one-to-many form (bus-to-destinations). In both cases, it adds capacity and mainline mass transit usage by transporting people to/from the main corridors. Normally, this service type relies on more advanced technologies such as real-time information systems than the other two service types since it requires communication between two different vehicles, and at times, between different agencies.

In the majority of the cases where we find this service, agencies rely on taxi companies to provide feeder services (typically in the form of shared-ride taxis).

Such enterprises a generation ago were constrained by technological limitations making these attempts a little ahead of their time. Now, however, technology ─ such as real-time information systems for vehicle dispatching ─has advanced sufficiently far and is fairly inexpensive to implement to make transit-taxi a much more realistic alternative.

The literature focuses primarily on three operational strategies for the three transit-taxi concepts: 1) use of in-house vehicles (regular full-size buses or smaller vehicles) coupled with extended service hours and/or days and operators to provide owl and/or weekend service; 2) contracting out services to other transit agencies or taxi operators to provide owl and/or weekend service, and 3) completely relying on outside private services as determined by market demand for owl/weekend services (if the municipality authorizes outside services).

Once a transit agency decides to implement a weekend type service (assuming a private option is either unavailable or not sufficient), it must determine which transit-taxi service concept is most viable and logistically feasible and whether or not that service will be in-house or contracted out. These decisions will be based on a number of interrelated factors which can be very specific to a country, region or municipality, including: demographic characteristics of the region, agencies' financing sources (operational and capital budgets and resources), political and institutional environments, technological capabilities, as well as availability of external operators (in the case of contracting) and vehicles. These factors also help to determine fare structures and service levels.

To better understand attributes of successful transit taxi solutions, we conducted numerous case studies based on these three transit-taxi concepts. Several examples of agencies that operate fixed-route skeletal transit-taxi night services, including: 1) The Greater Vancouver Transportation Authority (TransLink), 2) Massachusetts Bay Transportation Authority (MBTA), 3) Bay Area Rapid Transit District (BART) /

Alameda-Contra Costa Transit District (AC Transit), 4) Singapore Bus Service (SBS), 5) Orange County (California) Transportation Authority (OCTA), 6) Los Angeles Metropolitan Transportation Authority (LA Metro), and 7) various cities in Germany. Several cases appear, especially in cities abroad, whereby fixed-route services can provide some flexibility in their routing by deviating off the direct route in one form or another. The deviation tends to provide enhanced passenger safety and convenience; moreover, most agencies utilizing these types of services rely on smaller vehicles to provide the service. We examined two agencies that provide this kind of flexible-route night service: 1) King County (Seattle) Metro Transit (Metro) and 2) Ontario, Canada (Go Transit). There are many examples of hybrid feeder services in the literature. Highlighted here are those in Rimouski, Quebec, Canada and in the City of Madison in Wisconsin. We conducted these case studies by telephone interviews with appropriately identified agency staff.

Factors contributing to the creation and continuation of transit-taxi programs for case study operators include

- Larger service area (LAMTA, OCTA, SFBA, Vancouver, Seattle Metro)
- High community demand (LAMTA, AATA, AC Transit)
- University support (Rimouski, AATA, Boston, Vancouver)
- Strong agency support (OCTA, King County)
- Relative cost savings over traditional fixed route service option
- Regulatory environment can play as large a role as financial or demographic characteristics in providing service
- Little use of technology in U.S. beyond call-in dispatching systems; more use of real-time information and GPS systems in Europe and Asia

Community pressure, in the form of advocacy groups, has contributed to transit agencies focusing beyond day-to-day operations and maintenance of existing system. Examples include Mothers Against Drunk Driving in Boston, Bus Riders Union in Los Angeles, and the Transportation & Land Use Coalition in the San Francisco Bay Area.

Innovative financing mechanisms should be considered to help deal with agency-wide financial constraints. For example, AC Transit in SF Bay Area. The fixed-route skeletal and in-house operation combination is frequent and more closely associated with larger service area agencies as expected. Cities with smaller populations with universities (Ann Arbor, 114,000 and Rimouski, 40,000) tend to have feeder/hybrid transit-taxi services, utilizing taxi cabs. Little, if any, service assessment performed.

3 AN ANALYTICAL MODEL FOR DETERMINING HEADWAY AND LINE SPACING

Designing a transit network is a practical yet complex problem, and many researchers have tried to study various parts of many variants of the problem. In this section, we limit our discussions to studies that made the following general assumptions to simplify the problem:

- The passenger demand rate, i.e. the rate at which people wish to make transit trips between various origins and destinations, is known; the rate is constant during the period of interest; and the rate is independent of the level of service provided by the transit system.
- The objective is to minimize the weighted sum of user cost and agency operating cost.
- All cost elements can be expressed in monetary terms, and the cost rates are known. For example, we can say the bus operating cost rate is some dollars per hour when a bus is in operation, despite that operating a bus involves the cost of vehicles, drivers and others, and that the marginal cost for each may not remain constant.
- The underlying street network is given, usually as an infinitely-fine grid, and movements can only take place in the NS or EW directions.

As mentioned by Newell (1979), the problem of determining route frequencies on a pre-determined route structure is a convex optimization problem for which rapid-converging computer algorithms have been developed, and the state-of-the-art on dealing with many-to-one travel demand is quite advanced. However, the combined problem of determining route structure and frequencies for a bus system that serves many-to-many travel demand is much more difficult, and no simple procedure exists. The reason for the difficulty is the concavity of passenger assignment to routes serving the same origin-destination pair.

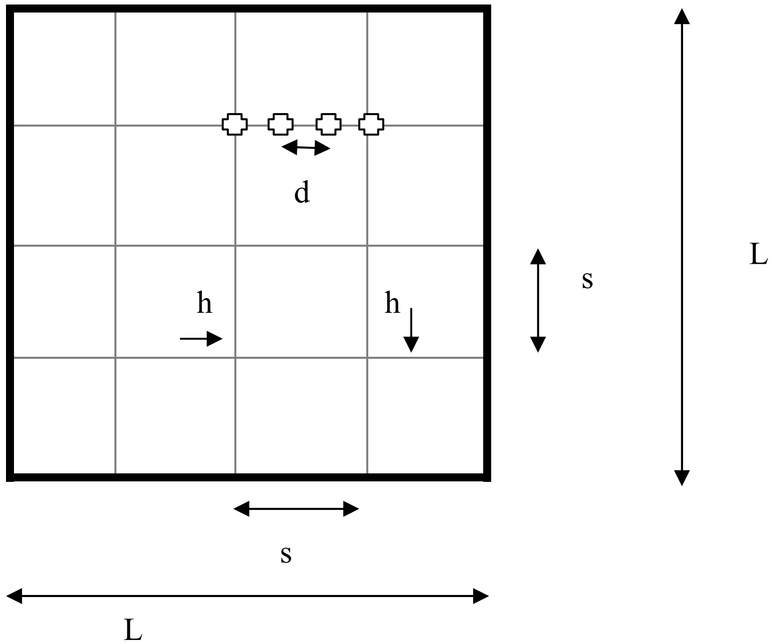
Holroyd (1965) conducted analytical modeling of designing bus routes serving many-to-many passenger trip demand. He considered an infinitely-large plane served by a system of linear bus routes, each running in either the EW and or the NS direction, and assumed the line spacings were equal in the two directions. He also assumed that all bus routes had the same headway. Newell (1979) argued that such assumptions were reasonable, given that the transfer penalty was high so two transfers on a trip were not realistic. Newell (1979) also developed the analytical model for a finite-sized rectangular area. He kept the line spacings on the two directions equal but allowed headways on the two directions to be different. He found that the resulting headways were equal when line spacings were assumed equal.

In this section, we present an analytical model that considers the vehicle stopping cost explicitly in order to develop results that will facilitate discussions on transit taxi operations under low demand density.

3.1 The Idealized Model

To demonstrate how passenger demand density affects the optimal route spacing, the headway, the operating cost, and various element of the user cost, we consider the following idealized model.

Figure 1: An illustration of design parameters with equal line spacing



A square area of size *LxL* is to be served by a network of E-W and N-S bus lines, from end to end. For any subarea, the passenger trip demand rate is known as δ (trips per unit area per unit time), and the destinations of these passengers are uniformly distributed over the area of *LxL*. The area is covered by an infinitely-fine street grid, such that a bus line can be placed anywhere, and a passenger can walk from home to a bus line on a path perpendicular to that line. Line spacings on both directions are assumed to be equal and denoted as *s*. All bus lines have the same headway *h*. Along each bus route, stops are evenly spaced at a spacing of *d*. Our problem is to determine the optimal values of *s*, *h* and *d* that minimize the combined bus operating cost and user cost per trip. Other relevant quantities are known as follows:

v: the cruising speed of buses;

t: time spent by a bus at each bus stop, regardless of whether there is a boarding or alighting passenger at the stop;

Co: the bus operating cost rate ($ per unit bus time);

Cw: user cost rate ($ per unit distance) when walking;

Ca: user cost rate ($ per unit time) when waiting for the bus at the bus stop;

Cb: user cost rate ($ per unit distance) when on a moving bus

Cs: user cost rate ($ per stop) for stops the bus made while the user is on the bus

Ct: user cost rate ($ per transfer) for transfers

3.2 Itemization of Costs

The transit agency's operating cost is calculated as follows. As the length of a round bus trip is *2L*, during the round trip the bus stopped $\frac{2L}{d}$ times. A bus makes the round trip in the time of $\frac{2L}{v}+\frac{2L}{d}t$, and the number of buses needed for each route is $\frac{2L(\frac{1}{v}+\frac{t}{d})}{h}$. The number of bus routes is $\frac{2L}{s}$. During the unit time, the number of passenger trips served is δL^2. Thus the operating cost per passenger trip is

$$C_o\frac{2L}{s}\frac{2L(\frac{1}{v}+\frac{t}{d})}{h}\frac{1}{\delta L^2}=\frac{4C_o(\frac{1}{v}+\frac{t}{d})}{sh\delta} \qquad (2.1)$$

Per-trip user costs consist of five parts: 1) walking to and from bus stops; 2) waiting for a bus; 3) on-bus travel when the bus is moving; 4) on-bus time when the bus stops; and 5) transfer costs.

As mentioned in Newell (1979), the inconvenience of bus transfer usually precludes passengers from transferring twice. Assuming that line spacing *s* is far smaller than the area size *L*, we can assume that each passenger trip involves two bus rides and one transfer. To enforce the one-transfer rule, we assume that a trip maker always walk to the trip destination from the closest route, and walk from the trip origin to the route that ensures one transfer. The average walking distances are the following:

From origin to 1st bus route: $\frac{s}{4}$;

On 1st bus route to boarding stop: $\frac{d}{4}$

From alighting stop, along 2nd bus route: $\frac{d}{4}$;

From 2nd bus route to destination: $\frac{s}{6}$

Thus an average passenger trip involves a total walking distance of $\frac{1}{2}d + \frac{5}{12}s$.

Assume that passengers do not adapt to bus schedules and each person's arrival time at a bus stop is uniformly distributed between the departure time of the last bus and the arrival time of the current bus. Then for each bus, the passenger waits a time of $\frac{h}{2}$ on average, and the average per trip waiting time is *h*. On average, a passenger trip involves an on-bus travel distance of $\frac{2}{3}L$, and the number of bus stops encountered is $\frac{2}{3}\frac{L}{d}$.

Therefore, the user cost per trip can be written as

$$C_w(\frac{1}{2}d + \frac{5}{12}s) + C_a h + C_b \frac{2}{3}L + C_s \frac{2}{3}\frac{L}{d} + C_t \tag{2.2}$$

Summing (2.1) and (2.2), we obtain the combined per trip cost, which we would like to minimize with regard to *s*, *h* and *d*:

$$\underset{s,h,d}{MIN} \frac{4C_o(\frac{1}{v} + \frac{t}{d})}{sh\delta} + C_w(\frac{1}{2}d + \frac{5}{12}s) + C_a h + C_b \frac{2}{3}L + C_s \frac{2}{3}\frac{L}{d} + C_t \tag{2.3}$$

3.3 Determination of Optimal Values for System Design Parameters

The objective function (2.3) has six terms. Respectively they represent the following; 1) the bus operating cost; 2) the user walking cost; 3) the user waiting cost; 4) the user on-bus travel cost; 5) the user on-bus stopping cost, and 6) the user transfer cost.

When the bus idle time per stop *t* is negligible compared to the time required for a bus to cover the distance between two adjacent stops, we find that *d* only affects term 2 and term 5 in expression (2.3). Thus the optimal *d* is not dependent on *s* and *h*. Instead,

$$d^* = (\frac{4CsL}{3Cw})^{\frac{1}{2}} \tag{2.4}$$

Thus the optimal stop spacing is not dependent on the passenger demand density δ. Note that *h* only appears in term 1 and term 3. Thus with the optimal *h*, we will find that the operating cost equals the user waiting cost, and that

$$h^* = 2(\frac{Co}{C_a\delta})^{\frac{1}{2}}(\frac{1}{v}+\frac{t}{d})^{\frac{1}{2}}s^{-\frac{1}{2}} \tag{2.5}$$

Substituting (2.4) and (2.5) into (2.3), and minimizing (2.3) with regard to *s*, we obtain

$$s^* = (\frac{24}{5})^{\frac{2}{3}}(\frac{Ca}{C_w^2})^{\frac{1}{3}}(\frac{Co}{\delta})^{\frac{1}{3}}(\frac{1}{v}+\frac{t}{d})^{\frac{1}{3}} \tag{2.6}$$

Thus

$$h^* = (\frac{5}{3})^{\frac{1}{3}}(\frac{Cw}{C_a^2})^{\frac{1}{3}}(\frac{Co}{\delta})^{\frac{1}{3}}(\frac{1}{v}+\frac{t}{d})^{\frac{1}{3}} \tag{2.7}$$

Note that both *s** and *h** are proportional to $\delta^{-\frac{1}{3}}$. Among the cost components in expression (2.3), $C_w(\frac{1}{2}d)+C_b\frac{2}{3}L+C_s\frac{2}{3}\frac{L}{d}+C_t$ is not dependent on δ. The other cost components are proportional to $\delta^{-\frac{1}{3}}$.

3.4 Bus Ridership Level and Boarding/Alighting Rates

The ridership level (i.e. the number of passengers onboard a bus) on buses deployed optimally under the assumed route structure can be determined as follows. During each headway *h*, $\delta L^2 h$ passenger trips are served. Passengers travel an average distance of $\frac{2}{3}L$ each on buses. Thus for passengers who start their trip during that headway *h,* $\frac{2}{3}L^3\delta h$ passenger miles of service are eventually provided by the transit system. On the other hand, the transit system has $\frac{2L}{s}$ lines, and each line has $\frac{2L}{vh}$ buses in service. During the headway *h*, each bus provides *vh* bus miles of service. Thus during the headway *h*, the transit system provides $\frac{4L^2}{s}$ bus miles of service. Therefore, the average bus ridership is $\frac{1}{6}L\delta sh$, a result we obtain by dividing the passenger miles by bus miles.

For each bus, the passenger boarding and alighting rates can be calculated by Little's formula. On average a passengers travels $\frac{1}{3}L$ on a bus. Thus the boarding rate is $\frac{1}{2}\delta sh$ (per unit distance). Similarly, we have $\frac{1}{2}\delta sh$ as the alight rate.

3.5 A Numerical Example

Below is a numerical example showing the break-down of the cost per passenger trip, and how the cost varies with passenger demand density.

Let *v = 20 miles/hour, t=*$\frac{1}{120}$ *hour*, *Co=$72 /hour*, *Cw=$6 /mile*, *Ca=$9/hour, Ct=$1.125 /transfer, Cs=$0.075 /stop*. These values are typical for bus transit service in the United States, although they are not the same everywhere. They can be interpreted as follows: for each stop, the bus loses half a minute; it costs $72 per hour to operate a bus. When a passenger is waiting for a bus or is onboard the bus, the value of his time spent is $9/hour. However, if the passenger is walking, the value of his time spent doubles to $18/hour. A person can typically walk 3 miles per hour. The cost for a transfer without waiting time is equivalent to 7.5 minutes of waiting time without transfer.

The table below gives the numerical results for a 8-mile wide square area for two demand levels: $\delta = 10$ *trips/(hour*square mile)* representing a moderate level of demand density (e.g. the weekday peak hour demand for a mid-sized city); and $\delta = 1.25$ *trips/(hour*square mile)* representing a low level of demand density (e.g. the demand density for the same city after dark or on weekends.)

Table 1: Numerical results for different levels of demand density

*Passenger demand density [trips/(hour*square mile)]*	*10*	*1.25*
Stop spacing [mile]	0.37	0.37
Line spacing [mile]	1.45	2.89
Bus headway [hour]	0.40	0.80
No. of passengers on board	7.74	3.87
Bus boarding rate [per mile]	2.90	1.45
Bus boarding rate [per stop]	1.06	0.53
Bus operating cost [$/trip]	3.61	7.23
User cost [$/trip]:		
*walking along route	1.10	1.10
walking off-route	3.61	7.23
waiting	3.61	7.23
*on-bus travel	2.40	2.40
*on-board stopping	1.10	1.10
*transfer	1.13	1.13
Total Cost [$/trip]	16.56	27.40

(*: Costs that are independent of demand density.)

When $\delta = 10$ trips/(hour*square mile), the costs that are dependent on δ total $10.8, and other costs total $5.7. When δ drops to 1.25, the density-dependent costs doubles to a total of $21.7, and one-third of that is the bus operating cost.

When $\delta = 1.25$ trips/(hour*square mile), both the line spacing and the bus headway are very large. Therefore, many passengers have to walk a long distance to access a transit line, and have to wait a long time to board a bus. If the transit agency plans transit operations this way with the assumed demand density, it is likely that the presumed passenger demand density would drop even lower, as the bus service level is too poor.

3.6 Limitations of the Idealized Model

Clearly the analytical model presented in this section has its limitations. This model determines key system configuration variables on the basis of an overall system performance standard, i.e. minimum total cost. This is the so-called performance-based determination.

There are two other principal ways to determine the stop spacing, the headway, and the line spacing, as described below.

- demand-based determination: The level of service provided by some agencies on certain routes is directly related to the passenger load and the vehicle capacity.
- policy-based determination: Some agencies simply establish a policy or a service-level standard, especially when the demand rate is low and service-level below a certain standard will significantly reduce demand rate.

Our performance-based model assumes a uniformly distributed demand. Theoretically, even when the demand level is very high, bus headways and line spacing can be adjusted such that buses would not have ridership levels that exceed the capacity. However, in the real world, the demand level can be very high along certain corridors, and the bus capacity is a real concern. In this situation, the transit agency would use demand-based determination.

Policy-based determination addresses the concern raised previously on demand realization. However, policy-based determination has its drawbacks. Assume that during the off-peak hours the transit agency keeps running buses using the line spacing and headway optimized for the peak-hour density of $\delta = 10$ trips/(hour*square mile). The per-trip user cost would be kept in control, but the operating cost per passenger trip would skyrocket to $29 (approximately 8 times of $3.61), which is an expensive proposition for the transit agency.

4 FIXED-ROUTE TRANSIT-TAXI SERVICE FOR AREAS WITH LOW PASSENGER DEMAND DENSITY

In the model presented in Section 3, it is assumed that the bus would stop at every designated stop, and stop-skipping is not allowed. When the passenger demand density is low, it is advantageous for buses to skip stops where no one gets on or off. One concept of transit taxi service is to allow buses running on a route to stop anywhere along the route, as if they were taxis running on the fixed route. This is equivalent to the scenario where there are a huge number of stops on the route and the bus is allowed to skip stops.

In this section, we first establish the theoretical basis for transit-taxi operations under low demand density, then examine of the cost impact of transit taxi service on fixed routes serving the demand pattern described in Section 3.

4.1 Theoretical Basis for Transit-taxi Operations

Consider a bus line. Denote ρ the density (along the bus line) of trip origins and trip destinations for passengers who board or alight the same vehicle during one headway. Thus ρ is measured in the number of passengers per unit distance.

If there is no passenger boarding or alighting at a stop, the bus may skip the stop. The tradeoff in determining the proper stop spacing *d* mainly involves two components of the user cost:

- the cost of travelling (walking) along the transit line (not from the line to the final destination) for passengers boarding or alighting at a stop; and
- the cost for through-passengers on the vehicle to make the stop (only the portion of lost time due to acceleration, deceleration, door opening and door closing should be considered, because the stop spacing does not affect the lost time due to actual boarding and alighting).

Consider the above costs incurred over a segment of length *d* along the transit line during one headway. A stop is located in the center of the segment. Part 1 of the cost is $\rho d \cdot \frac{d}{4} \cdot C_w$, where ρd is the total number of passenger boarding and alighting, $\frac{d}{4}$ is the average walking distance along the line, and C_w is the user cost rate (per unit distance) for walking. The second part is $N \cdot \tau \cdot P \cdot C_r$, where N is the expected number of passengers onboard, τ is the average lost time for each stop made, P is the probability that the vehicle makes a stop over the segment *d*, and C_r is the user cost rate (per unit time) due to stopping.

Per Little's Formulae, $N = \frac{\rho}{2} l$, where *l* is the average passenger trip length.

If we assume that the passenger demand for boarding and alighting over *d* is a Poisson process with an occurrence rate of ρd, then $P = 1 - e^{-\rho d}$.

Summing up the two parts of the user cost, and averaging the sum over the segment *d*, we obtain the cost over a unit distance:

$$\frac{C_w}{4} \cdot \rho d + \frac{C_r \rho^2 l \tau}{2} \cdot \frac{1 - e^{\rho d}}{\rho d}$$

This is the cost we want to minimize with regard to *d* in order to determine the optimal stop spacing. Minimizing this cost is equivalent to minimizing

$$\frac{C_w}{2 C_r \rho^2 \, l \tau} \cdot \rho d + \frac{1 - e^{-\rho d}}{\rho d}$$

with regard to *d*.

If ρ is small such that ρd is likely to be small compared to 1, we can approximate $e^{-\rho d}$ as $1 - \rho d + \frac{(\rho d)^2}{2}$ using the second-order Taylor's Expansion. Accordingly,

$\frac{1-e^{-\rho d}}{\rho d} = 1 - \frac{\rho d}{2}$.

When ρ is small such that $\frac{C_w}{2C_r\rho^2 l\tau}$ is greater than $\frac{1}{2}$, then the objective function increases with d. Minimization of the function requires that $d = 0$. This is equivalent to a taxi running along a line. The taxi may stop anywhere to pick up a passenger but the likelihood that it stops at anywhere is very small.

We can apply this result to the idealized model developed in Section 3. Notice that passenger boarding rate and alighting rate are both $\frac{1}{2}\delta sh$, thus $\rho = \delta sh$, which is proportional to $\delta^{\frac{1}{3}}$. Let $\rho = K\delta^{\frac{1}{3}}$, where K is a parameter not dependent on ρ. When $\delta = 10$, we have $\frac{1}{2}\rho = 2.90$, according to Table 1. Thus $\frac{1}{2}K \cdot 10^{\frac{1}{3}} = 2.90$, which gives K=2.7. Take values for other parameters as follows: $C_w = \frac{\$6}{mile}$, $C_r = \frac{\$9}{hour}$, $l = \frac{8}{3}\, mile$, $\tau = \frac{1}{120}\, hour$. We find that when the demand density δ is much less than 8 passenger trips per hour per square mile, transit-taxi is the preferred way of operating buses on the fixed route.

4.2 Cost Impact of Transit-taxi Service

Now we examine the cost impact of transit-taxi service on the fixed-routes described in Section 3. The model that gives theoretical basis for transit-taxi operations considers only the user cost but not the bus operating cost. However, if a bus can pick up and drop off passengers anywhere along the route, whether it would make more or fewer stops than the scenario of using the regular stops depends on the passenger demand rate. The number of stops made affects the bus operating cost and the on-board stopping cost. The table below gives the comparison of the various costs under different operating strategies and at different passenger demand rate levels.

Table 2: Comparison of regular bus and transit-taxi Service

	Regular Bus		*Transit Taxi*	
Passenger demand density [trips/(hour*square mile)]	10	1.25	10	1.25
Stop spacing [mile]	0.37	0.37	0	0
Line spacing [mile]	1.45	2.89	1.50	2.77
Bus headway [hour]	0.40	0.80	0.42	0.77
No. of passengers on board	7.74	3.87	8.35	3.55
Bus boarding rate [per mile]	2.90	1.45	3.13	1.33
Bus boarding rate [per stop]	1.06	0.53		
Bus operating cost [$/trip]	3.61	7.23	3.75	6.93
User cost [$/trip]:				
*walking along route	1.10	1.10	0	0
walking off-route	3.61	7.23	3.75	6.93
waiting	3.61	7.23	3.75	6.93
*on-bus travel	2.40	2.40	2.40	2.40
*on-board stopping	1.10	1.10	1.52	0.68
*transfer	1.13	1.13	1.13	1.13
Total Cost [$/trip]	16.56	27.40	16.31	24.98

(*: Costs that are independent of demand density.)

Therefore, the transit-taxi service could save very little when the demand rate is moderate (about 10 passengers per hour per square mile). When the demand rate is low (about 1.25 passenger per hour per square mile), operating transit-taxi service saves of 9% of the total cost. Still, the per trip cost for areas with low demand rate is too high, and the service level is poor. This is the result of our intrinsic assumption in Section 3 about the distribution of trip origins and destinations. When trip origins and destination are evenly distributed over a square service area, simply allowing buses to stop anywhere on the route is not going to solve the problem of high cost.

5 ALTERNATIVE METHODS OF PROVIDING TRANSIT SERVICES FOR LOW DEMAND DENSITY

It is inefficient for fixed-route transit service to serve the many-to-many type of passenger travel demand when the demand density is low. In light of the analytical results developed in the previous sections and the survey of real-world practices, service for situations of low passenger demand density should focus on three aspects: 1) to utilize other types of drivers and smaller vehicles, in order to lower the vehicle operating cost per hour significantly; 2) to explore demand responsive transit (DRT) services (dial-a-ride, checkpoint, and subsidized taxi rides) that seek to reduce passenger walking cost and waiting cost; 3) to target demand patterns that are more focused.

5.1 Drivers and Vehicles

Simply reducing the vehicle size by replacing a bus with a van or shared-ride taxi without changing the type of labor force that operates the vehicles is unlikely to produce significant cost savings, as the major portion of the transit operating cost is the labor cost. Furthermore, although smaller vehicles are cheaper to purchase and are more fuel efficient, having a mixed fleet of different vehicles often complicates vehicle maintenance jobs and may require more labor inputs that will eventually increase the cost for a transit agency. Innovative and flexible driver arrangements are needed to realize meaningful savings.

Many western European cities provide transit-taxi service during afterhours as a hybrid between conventional bus transit and taxi service (see Committee (2001)). Taxis are dispatched at regularly scheduled intervals, e.g., hourly or every 30 minutes and visit bus stops along a route. Customers travel from stop to stop for a fare approximately twice the regular bus fare. These transit-taxi trips are not exclusive, that is, they may involve ride sharing among multiple customers.

Campbell (1997) reported in the following on the use of transit-taxi in New Zealand:

> *"In Christchurch, New Zealand, taxi companies tender alongside the bus companies to provide Sunday services on the city's bus routes. They run to a fixed schedule but are more cost effective (and efficient) than full sized buses on lightly patronized Sunday services.*
>
> *As a background to current practice in New Zealand transit provision. No public transport in NZ is directly provided by the Government. The regional councils regulate and tender for the provision of services by the private sector. In Christchurch this involves setting the routes to be serviced, the minimum frequency for each route, minimum vehicle standards, and maximum fare to be charged. Private companies bid for each of the routes offered for tender. The company which asks for the smallest subsidy (or offers the most) to run the route gets the contract. This keeps the system very efficient with competition between different bus operators to provide the lowest price.*
>
> *Since this form of competitive tendering of routes came into effect subsidies for transit system have dropped in Christchurch by around 20% and several routes are now run un-subsidized."*

Innovative and flexible driver arrangements involve many institutional issues, some of which have been examined in the interim reports for this project. Interested readers can read Factor & Miller (2006) and Widmann & Miller (2006).

5.2 Dial-a-ride and Subsidized Taxi Rides

In the U.S., the alternatives for providing transit services when demand density is low include (but are not limited to) dial-a-ride (DAR) services, checkpoint services and subsidized taxi rides. Currently, these services are mostly door-to-door and are directed to specific segments of the community such as the mobility impaired or the elderly.

The major benefits of door-to-door services are that passengers do not need to walk, and they can wait for the vehicles at home instead of on the street. In addition, transfers are typically not necessary. However, these savings in user costs have to be balanced against large operating cost. For example, in 2003 the demand-responsive transit service for AC Transit averages $24.8 in operating expense and $1.5 in fare revenue per passenger trip.

Dial-a-ride is the common means for operating paratransit services for persons with disabilities, as mandated by the American Disabilities Act (ADA). ADA complementary paratransit provide door-to-door service in geographic areas that are served by fixed-route buses. The customer usually needs to call a day in advance to arrange a trip on a shared-ride van.

While dial-a-ride can be adopted to provide transit service to the general public in areas where demand density is low, Cervero (1997) found that nearly all DAR services currently in place target special groups, and the only significant DAR services open to the public are airport shuttles. This is not surprising because airport shuttles are running under the one-to-many distribution scheme. Many-to-many distribution is inherently much less cost-effective. In fact, a great deal of DAR service is contracted to taxi companies, which means the per-trip cost is comparable to exclusive taxi rides.

Li et. al. (2007) pointed out that, although at some boundary-level of passenger demand density, fixed-route service and DAR service would have similar overall cost, there is a danger in transitioning from fixed-route to DAR at that level. When the demand level falls below the threshold, changing from fixed-route to DAR would greatly alter the distribution of the cost burden on users and the operator, although the sum changes very little. When the demand density is low, fixed route buses must run on large line spacing and headways. DAR service is much more attractive to the passengers but also much more expensive for the operator to provide. As a result, the demand level may jump so much that the operator is no longer capable of serving all the requests. Then not providing any service becomes the practical option. This is exactly the reason that some door-to-door services (including one that was provided in the Santa Clara County) to the general public failed, not because of the lack of ridership but the opposite. Therefore, access to such subsidized systems must be restricted. Otherwise DAR would suffer from the curse of success.

Checkpoint-type service has been proposed as a means to reduce the cost. In a checkpoint DRT system, passengers are picked up and dropped off on demand at predetermined checkpoints near their trip ends. They must walk to and from the checkpoints to complete their trips. Daganzo (1984) demonstrated that under low demand density, this is rarely more cost-effective than a door-to-door DAR service. Li et. al. (2007) showed that the window of demand levels that makes checkpoint service attractive is much larger than allowed in Daganzo (1984). However, since checkpoint service is demand-responsive, the issues of punctuality and scheduling complexity need to be addressed.

Since the need to make advance reservations is a significant inconvenience with DAR and checkpoint systems, some communities eventually choose to subsidize taxi rides for customers in need. Examples in California include the Guaranteed Ride Home program in San Diego for commuters and the Taxi Scrip program in Berkeley for the elderly. Because of the high cost of taxi rides, subsidized taxi rides programs must also target special groups and limit the usage by any customer.

5.3 Targeting Focused Demand Patterns

Efficient transit service must serve focused demand to reap the benefit from the economy of scale. Focused demand can be along a corridor. It can also be that all trips share a single point or a line as their common origin or destination. Below we develop models for both fixed-route operations and shared-ride flexible-route taxi operations that transport passengers from anywhere in the service area to a line.

5.3.1 Fixed-route operations

We now compare the costs and service levels for a system of parallel routes that deliver passengers to a line, to those for the many-to-many scenario described in Section 3.

Consider the same *LxL* square service area described in Section 3 but now assume that a rapid transit line runs on the west border. There is a demand for passengers to travel between their homes, uniformly distributed over the service area, to the rapid transit line. For this purpose, bus service is provided on a system of parallel routes running in the E-W direction. We assume that buses could stop anywhere along the route to pick up passengers, so walking along the line is not needed. Stopping costs are ignored as they are not a significant part of the total costs analyzed in Section 3, and ignoring them would not alter the results in any meaningful way.

The average combined per-trip cost is:

$$C_w \frac{s}{4} + C_a \frac{h}{2} + C_b \frac{L}{2} + C_o \frac{L}{s} \frac{2L}{vh} \frac{1}{\delta L^2}$$

Where s is the line spacing and h is the bus headway. Other parameters are known as follows:

v:	the cruising speed of buses;
Co:	the bus operating cost rate ($ per unit bus time);
Cw:	user cost rate ($ per unit distance) when walking;
Ca:	user cost rate ($ per unit time) when waiting for the bus at the bus stop;
Cb:	user cost rate ($ per unit distance) when on a moving bus

Minimizing the combined per-trip cost with regard to s and h, we obtain that

$$s^* = \left(\frac{16 C_o C_a}{v C_w^2 \delta}\right)^{\frac{1}{3}},$$

and

$$h^* = \left(\frac{2 C_o C_w}{v C_a^2 \delta}\right)^{\frac{1}{3}}$$

The table below compares the results for two demand patterns. Region-wide access denotes the many-to-many demand pattern, and line-access denotes the focus demand pattern. i.e. everyone is taken to the rapid line. We see that with focused demand pattern, the total per trip cost is greatly reduced.

Table 3: Comparison of costs under different demand patterns

	Region-wide Access		Line-Access	
Passenger demand density [trips/(hour*square mile)]	10	1.25	10	1.25
Stop spacing [mile]	0	0	0	0
Line spacing [mile]	1.50	2.77	1.13	2.26
Bus headway [hour]	0.42	0.77	0.38	0.75
No. of passengers on board	8.35	3.55	34	17
Bus boarding rate [per mile]	3.13	1.33	4.25	2.13
Bus operating cost [$/trip]	3.75	6.93	1.69	3.39
User cost [$/trip]:				
*walking along route	0	0	0	0
walking off-route	3.75	6.93	1.69	3.39
waiting	3.75	6.93	1.69	3.39
*on-bus travel	2.40	2.40	1.80	1.80
*on-board stopping	1.52	0.68	ignored	ignored
*transfer	1.13	1.13	0	0
Total Cost [$/trip]	16.31	24.98	6.88	13.96

(*: Costs that are independent of demand density.)

In the above table, the number of passengers on board for the line-access type of service is the maximum number, not the average. This is because the demand is focused to the end point of the bus route. When a bus collects passengers, no one gets off until the bus reaches the end point, i.e. the common destination of all passengers.

It is important to note that when the demand pattern is focused, passengers no longer need to transfer. They will have much better control for their own schedule. They can time their departure times to coordinate with the schedule of the buses. As such, waiting cost will be further reduced. Considering this factor, it will be advantageous to choose smaller line spacing and increase the bus headways.

When the demand density is low, the optimal line spacing for fixed routes is still large. This may discourage potential clients from taking transit. In such situations, adopting the flexible routing that characterizes the many-to-one type of dial-a-ride service can be beneficial. For example, shared-ride taxis can be deployed at terminals along a rapid-transit line to take passengers home after dark or in the weekend, when the demand density is low.

5.3.2 Flexible-route Shared-ride taxi operations

Consider shared ride taxis which are deployed at terminals along a rapid-transit line. Each taxi has a passenger capacity of x. The taxi can take whatever route, and the round trip time for delivering passengers is T. We assume that T is coordinated with the rapid transit line's headway, and the rapid transit's headway can be set to match T. We seek to determine the optimal x and T. The area of the service region is A. The rate by which passengers are carried to the region A is r per hour.

Under idealized situations, each taxi would only serve one subarea. Denote λ the spatial density of destinations during that delivery trip. Then $\lambda = \frac{rT}{A} = \delta T$, where δ is the demand density, in units of passengers per hour per square mile.

The distance between two adjacent passenger delivery stops, assuming the taxi takes the shortest path for the delivery route, can be approximated by $k(\delta T)^{-\frac{1}{2}}$, where k is a constant, independent of the demand density but dependent on the shape of the service area and the road geometry. Typically *k* is between 0.7 and 1. For convenience, we set k=1. Thus the following equation holds approximately:

$$vT = x(\delta T)^{-\frac{1}{2}}$$

This equation gives

$$x = v(\delta T^3)^{\frac{1}{2}}$$

For an average passenger, his trip takes a travel time of $\frac{T}{2}$, at a cost rate of C_a per unit time. The taxi served *x* passengers, at a cost rate of C_o per unit time. Minimize the combined cost for an average per-passenger trip with regard to T:

$$Min\ \ \frac{C_a T}{2} + \frac{C_0 T}{v(\delta T^3)^{\frac{1}{2}}}$$

We find that

$$T^* = \left(\frac{C_o}{C_a}\right)^{\frac{2}{3}} v^{-\frac{2}{3}} \delta^{-\frac{1}{3}}$$

Accordingly, the optimal passenger load (and taxi capacity) should be

$$x = \frac{C_o}{C_a}$$

Note that the optimal load or capacity is not dependent on demand density. This is good news as vehicles of the same size would be able to serve areas of different demand densities.

For the numerical example, assume C_a =\$9/hour and *v=20* miles/hour. We can make two assumptions about the taxi's operating cost rate *Co*. It can remain the same as that for a bus, \$72/hour, or under innovative institutional arrangement, be reduced to \$36/hour, or half of the \$72/hour rate that we used previously for buses. When *Co*=\$36/hour, we should have *x=4*, For which a large car or a small van is appropriate. When *Co*=$72/hour, we should have *x=8,* for which a large van or a small bus is needed.

Table 4: Flexible-route transit-taxi operations under different vehicle operating cost rates

	Flexible-route Transit-taxi (with Co=$72/hour)		Flexible-route Transit-taxi (with Co=$36/hour)	
Passenger demand density [trips/(hour*square mile)]	10	1.25	10	1.25
Vehicle headway [hour]	0.25	0.50	0.16	0.32
No. of passengers on board	8	8	4	4
Operating cost [$/trip]:	2.27	4.54	1.43	2.86
User cost [$/trip]:				
walking off-route	0	0	0	0
waiting	0	0	0	0
on-vehicle travel	1.13	1.27	0.71	1.43
Total Cost [$/trip]	3.40	6.80	2.14	4.29

Caution should be taken to interpret the above result. The model presented here for flexible-route transit-taxi works best when the line-haul distance between the transit terminal and the taxi's service zone is small. A large square area will involve different line-hall distances for different taxis, and the cost impact is potentially large. Accordingly, transit-taxis should be different sizes, and larger taxis should be used to serve passengers further away from the rapid transit line.

Also note that the major portion of the total cost for the flexible-route service is the operating cost. This is different from the situation in fixed-route transit, where user cost dominates. A per-trip operating cost higher than the user cost is characteristic of flexible-route services, and a budget-constrained transit agency should take this into account when planning flexible route services.

6 DESIGN OF A TRANSIT-TAXI PILOT PROGRAM

Having explored the transit-taxi concept from a theoretical perspective, we conclude that to effectively satisfy passenger travel demand when the demand density is low, it is important to target focused demand patterns, implement flexible service design, and explore innovative institutional arrangements that bring down the per-hour cost of operating a transit vehicle.

In this section, we present the design a pilot program for transit taxi that applies these principles. First, we describe the mode of operations for the transit-taxi service that is to be pilot-tested. Then we describe the pilot site selection criteria and the profile of the suggested site. We then proceed to detail various aspects of the pilot program design.

6.1 Mode of Operations for the Transit-taxi Program

The mode of operations for the pilot program we conceived is the following:

- A fixed-route, fixed-schedule rapid transit line runs through a medium-sized suburban community, stopping only at a limited number of terminals, which often collocate with park-and-ride facilities and activity centers.
- A few transit-taxis (vans, large taxis, or small buses) are assigned to each terminal during times when regular local service is non-existent or significantly cut-back. Each transit taxi has its own service area within the chosen suburban community.
- A round trip by a transit taxi consists of an "in" portion that runs on a fixed-route towards the terminal, and an "out" portion that distribute passengers from the terminal to anywhere within its designated service area, with no pre-determined route. Such a service is called a "fixed-in, flex out" service, similar to the Local Initiative for Neighborhood Circulation (LINC) service briefly experimented by the Seattle City Engineering Department jointly with Metropolitan King County (1995).
- The transit taxi does not pickup any passenger while in the "out" portion of the service, but allows passengers to alight along the fixed route while in the "in" portion of the service. The "in" portion has a scheduled start time but no designated stops. Passengers hail to get onboard.

- The transit taxi is coordinated with the rapid transit line with good on-schedule performance. A passenger can also take an "in" taxi to the terminal, and head out on an "out" taxi to their final destination within the service area.
- The fixed-in portion of the service may follow different routes during different times of the day, if the demand patterns are consistently different. For example, if in the morning more passengers want to go to the terminal, the transit-taxi may take a circulation-type of fixed route. In the evening when more passengers want to go home, the fixed route to the terminal can be a more direct one. The fixed-route can also be tailored to meet the needs of subscription passengers.

With this "fixed-in, flex out" mode of operations, passengers would be able to conduct their whole trips with transit. They would experience little wait time when transferring between the transit-taxis and the trunk line, or transferring from one transit-taxi to another at the terminal. The service captures a significant portion of transit travel demand, and the service provision is cost-saving compared to dial-a ride because of the following: 1) each transit-taxi only travels between a subarea and a terminal; 2) the shared-ride transit-taxi does not lose time waiting for passengers at their doorsteps; and 3) the need for a reservation system is eliminated. Thus this service could be a win-win solution for both the passengers and the transit operator.

6.2 Pilot Site Selection and the Profile of Suggested Site

6.2.1 Pilot Site Selection Criteria

The criteria for selecting a pilot site in California are based on the principles derived from the theoretical analysis presented in previous sections. Specifically, we want that:

- A medium-sized suburban community, of 5 to10 square miles in area, has a population density of 3000-6000 persons per square mile. The size of the community need to be limited to control the cost of the pilot program. The population density needs to be within a range because the transit mode share is usually correlated positively with the population density. Too large a density will make fixed-route service more appealing, while too small a density would make dedicated taxi service more appealing. For a point of reference, the area served by AC Transit in the East San Francisco Bay region has an overall population density of about 4000 persons per square mile.

- The community has the shape of a long rectangle, and a major transportation corridor runs through the community along the direction of the long edge. This would allow each transit-taxi to have a service area that is not far from the trunk transit line.
- The streets offer good connectivity, such that back-tracking by the transit-taxi would not happen too often, and passengers can easily walk to the fixed portion of the transit-taxi service. Many suburban residential communities are specifically designed for personal auto travel to major highway intersections, with a hierarchical road network and cul-de-sacs that prevent local circulation. Such communities would not be good candidates for the pilot test.
- A trunk (rapid or express) transit service runs on the major transportation corridor for most of the day, and the trunk buses stop only at a limited number of terminals along the corridor within the community. The terminals should be close to local activity centers and have ample parking and maneuvering space.
- A significant portion of the community members' travel demand is between their homes and the activity centers or the terminals along the trunk transit line.
- The region's transit planning institutions are proactive in testing new ideas that enhance mobility of community members, and have a track record for innovative institutional arrangement and collaboration with stakeholders.
- The region's transit operator has experience with non-fixed-route, demand-responsive transit.

With so many criteria, it would be a mission-impossible to run through the profiles of communities in California to find the right candidate. Fortunately, the researchers of this project have recently been involved in developing the Concept of Operations for the I-15 Integrated Corridor Management for the San Diego Association of Governments, and gained knowledge about the communities along the studied corridor, the transportation facilities, the transportation plans, and related organizations. Supplementing this knowledge with additional research, the authors suggest that the Rancho Bernardo community of San Diego be selected as the pilot test site.

6.2.2 The Rancho Bernardo Community as the Pilot Site

Rancho Bernardo is the northern-most residential community within the city of San Diego. It is about 20 miles N-NE of downtown San Diego. It is about 2 mile (E-W) by 4 mile (N-S), or 8.9 square miles in size. Interstate 15 runs N-S through the center of the community.

Figure 2: The San Diego I15 ICM corridor
(source: SANDAG (2008))

According to Census 2000, Rancho Bernardo has a population of 39571 when the Census was conducted. The medium household income was $63254 at that time. The population has remained steady over the past decade. Thus the population density is about 4446 per square mile. Satellite maps shows the community's road network has good connectivity.

In 2000, among the 17119 households in the community, 6% have no vehicle. However, only 1% of workers aged 16 and older take public transportation to work. 82% drive alone and 9% carpool. The travel time to work is distributed as follows:

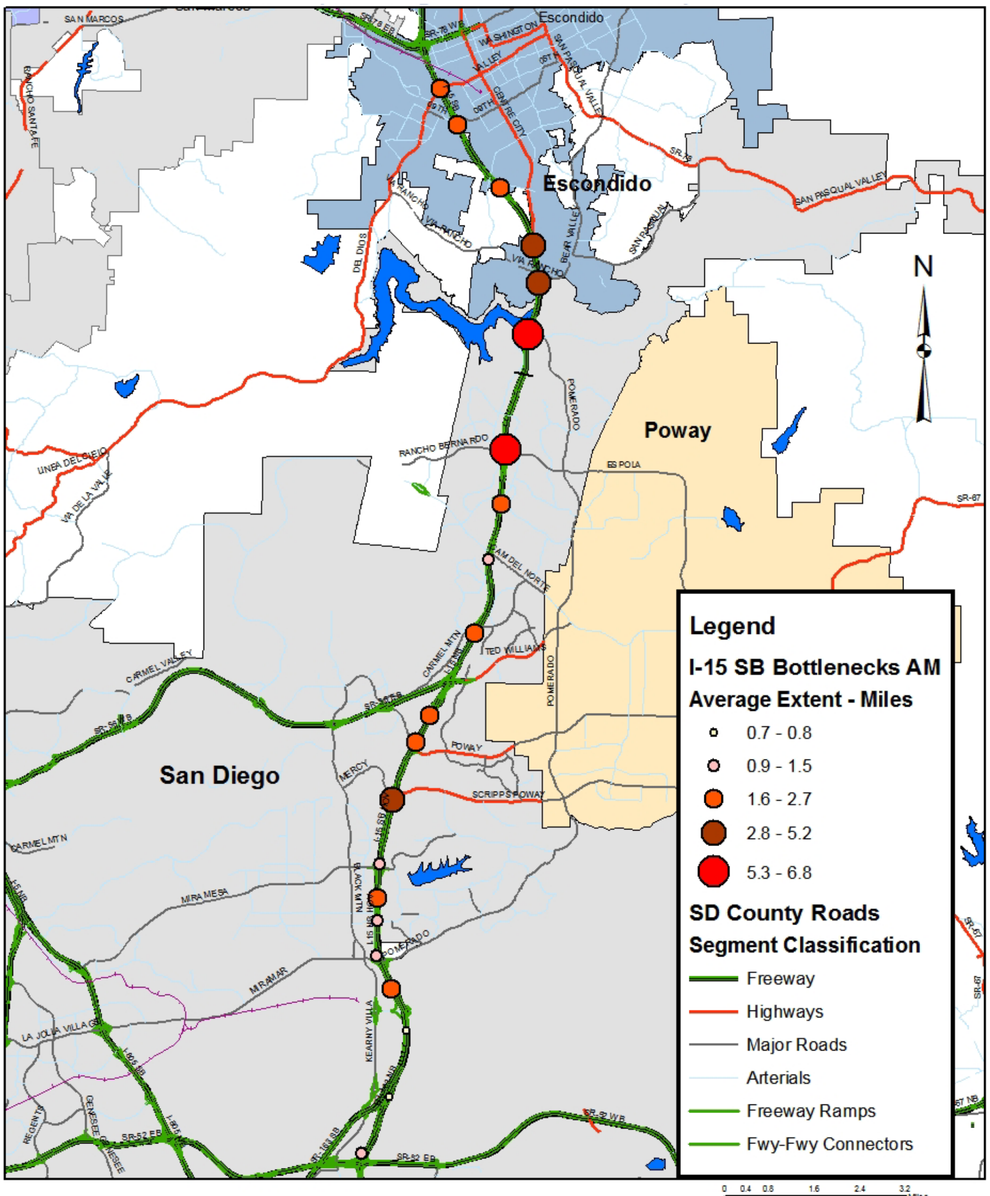
Table 5: Travel time to work for workers from Rancho Bernardo
(Source: SANDAG (2003))

Total Workers	*16844*	*100%*
Did not work at home	15951	95%
Less than 10 minutes	2078	12%
10 to 19 minutes	4053	24%
20 to 29 minutes	2567	15%
30 to 44 minutes	4962	29%
45 to 59 minutes	1536	9%
60 to 89 minutes	382	2%
90 minutes or more	373	2%
Worked at home	893	5%

The average travel time to work is 27 minutes. Therefore, a large portion of the workers must utilize the I-15, which connects the community to major employment centers. However, drivers experience significant traffic congestion, as shown in the figure below.

Figure 3: Traffic congestion on I15 that affects Rancho Bernardo

(Source: SANDAG (2008))



To deal with the traffic congestion problem on the I-15, bus rapid transit has been planned to run on the I-15 from Escondido to downtown San Diego, and Rancho Bernardo is one community that the BRT strives to serve, as shown in the figure below.

Figure 4: I-15 BRT stations in 2012

(Source: Transportation Management and Design, Inc. (2006))

Transportation Management and Design, Inc. (TMDI) prepared the I-15 Bus Rapid Transit Operations Plan for SANDAG. TMDI(2006) specifies the following BRT service options:

"Option 1:

- *Core BRT all-day service for all stops to downtown*
- *10-minute peak period BRT express service from Escondido*
- *10-minute peak period BRT express service from Rancho Bernardo*
- *Optional 30-minute peak period BRT express services from Rancho Penasquitos and Carmel Mountain Road*

Option 2:

- *Core BRT all-day service for all stops to downtown*
- *15-minute peak period BRT express service from Escondido*
- *15-minute peak period BRT express service from Rancho Bernardo*
- *Additional all day BRT service to Sorrento Mesa/UCSD/University City."*

Both options would provide highly-frequent BRT service from Rancho Bernardo. The BRT access plan prepared by TMDI focuses on Park & Ride. It projects that the peak parking demand at the Rancho Bernardo station will be 265 spaces, and proposes to construct 300 spaces at a capital cost of $8 million, in 2005 dollars. If an interest rate of 6% is assumed, each parking space would cost $1600 per year. That could be money well spent to provide transit access to the station. We propose an alternative vision of significantly increasing transit's role in providing access to the BRT station.

Without the BRT in operation, it would be valuable to find an express transit route that currently provides service for much of the day through the community, and pilot test the transit-taxi service to provide connections to the express transit service. Doing so would provide valuable inputs for designing future access plan for the BRT.

Fortunately, such an express route exists. It is Route 20, which closely parallel I-15. It passes through Rancho Bernardo, with a stop at the terminal at the intersection of W. Bernardo Dr. and Rancho Bernardo Rd. The terminal is adjacent to a park-and-ride facility and an activity center with many businesses. On both weekdays and weekends, the service headway is 30 minutes. On weekdays, the service runs from 4:54am to

10:27pm. On Saturdays and Sundays, it is 6:29am to 9:39pm. However, there is only one local transit line (Route 845) providing very limited local service within the Rancho Bernardo community. Route 845 does not operate as frequently as Route 20, and the operating time window is shorter. This means many passengers using Route 20 at Rancho Bernardo have to rely on the Park & Ride facility. If transit-taxi service is provided at the terminal, it would greatly improve the situation.

The San Diego region's transportation planning organizations have a reputation for trying out new ideas. As early as 1982, the San Diego Transit Corporation operated a taxicab feeder service to fixed-route systems as a demonstration program for the Urban Mass Transportation Administration (UMTA), the predecessor of the Federal Transit Administration. According to Murray (1997),

"*Because the demonstration was so successful, San Diego Transit continued it with its own funds. It has since added two routes in high income areas that were not being served because of low ridership potential and long travel distances. These feeders give the new areas service without the costs of fixed-route buses*."

In addition, the City of San Diego has been leading innovations in the regulation and operation of taxicabs, according to Kirby (1981).

Last but not least, we want that the region's transit operator to have experience with non-fixed-route, demand-responsive transit. The Rancho Bernardo community is well qualified in this aspect. For many years, the Metropolitan Transit System (MTS) has provided the DART service to Rancho Bernardo. DART (Direct Access to Regional Transit) is a community shuttle service that pickup and drop off passengers at any location within the Rancho Bernardo service area, and passengers transferring to and from bus routes receive priority reservations. Thus there is an existing stock of suitable vehicles and well-trained drivers that could meet the requirements of the transit-taxi pilot program. Due to the state budget cuts, the DART service was discontinued in 2008. The transit-taxi service we propose should be a suitable substitute of DART for the Rancho Bernardo community, as it would enhance transit service, meet the mobility need of the community, and save cost at the same time.

6.3 Rancho Bernardo Transit-Taxi Pilot Program Design

6.3.1 Program Objectives

The objectives of the pilot program are:

- To measure public acceptance of the new service
- To discover unexpected problems and barriers at the stage of program design
- To develop a realistic cost model for continued operation and wider adoption

6.3.2 Program Administration

The pilot program should be administered by the San Diego Association of Governments, which is the region's transportation planning organization.

6.3.3 Program Operator

Two options are identified for budget considerations.

- Option 1: The Metropolitan Transit System (MTS), the transit operator for the City of San Diego
- Option 2: Full Access & Consolidate Transportation (FACT) : the Consolidated Transportation Service Agency (CTSA) for San Diego County as designated by SANDAG

If budget allows, Option 1 is preferred, as MTS had experience in operating DART in Rancho Bernardo. MTS will need to negotiate with the labor union on staffing the service. However, if the budget tightness persists, FACT could recruit volunteer drivers with the help of community service organizations to implement the pilot program.

6.3.4 Service Area

The service area is same as the Rancho Bernardo DART area when DART was in operation. The area covers 8.9 square miles, which can be divided into four subareas by the I-15 and Rancho Bernardo Road.

6.3.5 Length of Demonstration

The pilot project should last 6 months. Less than that, it is difficult to measure the impact. Longer time costs more.

6.3.6 Days and Hours of Service

The service should be offered 7 days a week, from 5:00am to 11:00pm on weekdays, and from 6:00am to 10:00pm on weekends, to match the service offered by Route 20, the express regional transit line.

6.3.7 Mode of Operations

Transit-taxis are stationed at the Park & Ride facility at the intersection of W. Bernardo Dr. and Rancho Bernardo Rd. Their schedules are coordinated with the schedule of Route 20. Transit-taxis adopt the mode of operations described in Section 6.1.

6.3.8 Type of Vehicle

If the service is operated by the MTS, small buses with capacity for 8-10 passengers should be used. Such buses should be ADA approved. The MTS may have inventory of such buses from the discontinued DART service, or may have procurement contracts already established with vendors. New buses would cost approximately $50000 each.

If the service is operated by FACT or a community service organization and uses volunteer drivers, large taxis or minivans are preferred. Insurance is a factor that should to be explored.

The vehicles should go through minor modifications to meet safety standards, and to facilitate easy identification by potential passengers. The vehicles can also be fitted with taxi-meter type equipment to register ridership, as well as GPS and wireless communications device to record customer destinations and track vehicle trajectories. These data will be used in the follow-up analysis.

6.3.9 Number of Transit-taxis

Five vehicles are required. Initially one vehicle is assigned to each of the four subareas of the region. A transit-taxi would take 30 minutes to complete a round trip. One vehicle is the reserve vehicle that deals with overflow at the terminal and it only performs flex-out services.

6.3.10 Passenger Fare

The "fixed-in" portion should be free. The "flex-out" portion should be free for a person who present a valid transit ticket used in that day (or a transfer ticket), but a moderate amount should be charged to other "flex-out" passengers.

6.3.11 Community Involvement and Public Awareness

A Community Advisory Committee should be established with members from the Rancho Bernardo community. The committee would meet once every a few weeks. Members would help promote the transit-taxi service in the community, provide input to the pilot project, evaluate the outcome of the pilot project, and recommend future actions and other measures to enhance transit service.

Brochures should be made for distribution at key locations in the community and on buses of Route 20 and Route 845.

The Seattle LINC pilot project sponsored a "LINC Bus design contest" with participation from local schools. Similar activities could be conducted in the Rancho Bernardo community.

6.3.12 Cost for the Pilot Program

6.3.12.1 Start-up cost: $50,000-100,000

The startup cost would be incurred before the service is rolled out. This would include labor cost associated with 1) program development and service planning; 2) operator training program development; 3) operator training time; 4) vehicle preparation.

6.3.12.2 Program Operations Cost: $500,000-1,000,000

The program operations cost would depend heavily on the type of driver used for the service. The operations cost would include salary and benefits to drivers, vehicle depreciation, vehicle maintenance and fuel, project management, staff training, transit planning, and insurance. Each vehicle needs to provide about 3000 hours of service during the 6-month pilot test period. Five vehicles would be 15000 hours of service. With professional drivers, the program operations cost could easily reach $1 million. With volunteer drivers paid at much lower rate, the cost could be within $500,000.

6.3.13 Performance Evaluation

Performance of the pilot program should be measured using data collected automatically onboard of transit-taxi vehicles and data collected from passenger survey. The change of the transit-taxi ridership during the pilot test period should be tracked, as well as the impact of the transit-taxi service on the ridership of trunk transit line (i.e. Route 20). The percentage of passengers who use the service for travel between places within the Rancho Bernardo area should also be measured, because the transit-taxi service also provides local circulation within Rancho Bernardo through one seamless transfer.

The performance of the pilot program should be compared to other services provided for areas of similar size and demand density. They can be either fixed-route or demand-responsive. For example, we could compare the pilot program with the DART service previously provided for the Rancho Bernardo community.

7 CONCLUDING REMARKS

After conducting extensive modeling of both fixed route and demand-responsive services, with special attention placed on transit-taxi operations, we concluded that when origins and destination are evenly distributed over a square service area, simply allowing buses to stop anywhere their routes is not going to solve the problem of high cost. Utilizing flex-route demand-responsive transit taxi can dramatically reduce the per trip system cost (e.g. from \$27.4 per passenger trip to \$6.8 per trip) under certain circumstances. We gained the following insight: to efficiently serve areas with low passenger demand density, we should target focused demand patterns, design flexible-route transit-taxi operations, and explore innovative institutional arrangements.

With criteria developed from the theoretical analysis and from survey of real-world practices, we suggest the Rancho Bernardo community in the San Diego region as the pilot test site for a “fixed-in, flex-out” transit-taxi service. This service performs two functions: first, it transports passengers to and from a centrally located transit terminal, so passengers can connect to regional transit service; second, it provides local circulation within Rancho Bernardo via one seamless transfer. Various elements of service design have been presented, including innovative institutional arrangements to deal with tough budget constraints. This proposed transit taxi service would be a good substitute for the recently-discontinued DART service in Rancho Bernardo, and would provide a model for providing transit access to the I-15 corridor when Bus Rapid Transit starts to operate in 2012.

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