COMPARATIVE ANALYSIS OF URBAN TRANSIT MODES USING SERVICE-SPECIFICATION ENVELOPES

John C. Rea and James H. Miller, Pennsylvania State University

The use of envelopes of transit service functions is proposed as a technique for comparing the output space of transit technologies. A service-specification envelope defines the boundaries within which an operator is able to specify transit service for a given technology in predefined circumstances. An envelope is defined on one side by an economic or viability boundary and on the other by a capacity boundary. The basis for comparison is the location of the service-specification envelope in an output space defined by axes representing passenger flow and level of service. Three technologies—minibus, minirail, and regular transit buses—are examined in a collector-distributor context. The bus appears to be more flexible but has poor quality of service. Thus, new technologies, such as dial-a-bus, are needed in the collector-distributor context. Five technologies—monorail, skybus, freeway flyer, busway, and rail rapid system—are examined in a line-haul context. There appears to be much redundancy in the capabilities of the first 4 systems. Busway systems (reverting to a freeway flyer mode of operation where freeways are not congested) can cater to a much wider range of demands than rail and can cater to high flows albeit at a somewhat lower service quality than rail. A comparison of transit service-specification envelopes and highway service functions indicates that rail rapid transit can offer comparable qualities of service only when flow levels are high and when freeways are congested.

•IN RECENT years urban transit has become a focus of public and governmental attention. The resurgence of interests stems from many sources, e.g., a concern for the urban environment and aesthetics; realization of the mobility needs of the young, the aged, and the disadvantaged; and a desire to provide a less resource-consuming mode than the automobile. Although public transportation may not be the panacea for all urban woes, it can at least make a positive contribution in some areas—provided that the limitations and potentials of urban transit hardware systems are realized. Although large sums are being spent on existing transit systems and on developing new technologies, relatively little work has been done to compare the capabilities and feasible areas of application of existing and proposed urban transit hardware systems.

Bouladon (1) advanced a hierarchical concept for interrelating transport technologies in a gross manner. Although the analysis identified gaps in the spectrum of transport technologies, from walking to supersonic aircraft, the method is not appropriate for a comparative analysis of urban transit systems. Rice (2) did some interesting work on the output efficiency of different transport modes in terms of fuel consumption per passenger-mile, but that is too limited an approach to be of general utility. Morlock (3) analyzed some intercity transportation modes and defined the "feasible output space" of a number of technologies. The objective of Morlock's approach is similar to that of this paper, i.e., to "make direct comparisons between different technologies in order to identify those regions of output space for which each is inherently well suited."

In this paper the approach adopted for the comparison of transit technologies rests on the concept of service functions or, rather, on the envelope of such service functions.

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The approach has the advantage of providing direct inputs to equilibrium analysis and the service-specification model for planning transit systems (4).

TRANSIT SERVICE FUNCTIONS

A transit service function is a schedule of service quality that the operator is willing and able to provide for a corresponding schedule of passenger flows. In terms of the equilibrium approach to transport system analysis as expounded by Manheim et al. (5), a transit service function can be written as

$$L = S(V, T)$$

where

L = some measure of level of service,
V = passenger volume in passengers per unit time,
T = vector describing the characteristics of the transit system, and
S = supply or service function.

The vector T may include attributes such as transit routes, speed, acceleration, station dwell time, frequency of service, seating comfort, ride quality, privacy, and safety.

Such a formulation implies that quality of service improves as use of a transit system increases because a more frequent service must be provided to cater to increasing flows (assuming, of course, that additional units are available to do this and that one does not provide for increasing volumes by maintaining a given frequency of service and increasing the length of a train). Quality of service cannot increase indefinitely, however, because the control system and operating conditions dictate a minimum operating headway that constrains service frequency. Beyond that point, service quality will degenerate because of overcrowding. The general form of a transit supply or service function under the conditions and assumptions outlined above is shown in Figure 1a. In practice, the service function will take the form of a step function as shown in Figure 1b. Frequency of service is not a continuous variable for practical scheduling reasons, and the operator will assign a given headway for a corresponding range of flows. The level of service provided by a given headway will, in fact, decline as flow increases within its designated flow range because of decreased privacy, increased personal contact, and the like. The effect is shown in Figure 1b. For the sake of simplicity, the index used for level of service measures only technological performance in a given operating context and does not measure perceived level of service. As such, the level of service is assumed to be constant for any given headway as shown in Figure 1c. Thus,

$$L = S(V; a, s, d, f)$$

where

a = acceleration-deceleration capability of the technology,
s = cruising speed in the operating context,
d = dwell time at stops, and
f = frequency of service.

FORMULATION OF TRANSIT SERVICE-SPECIFICATION ENVELOPES

It was earlier stated that a service function is a schedule of service quality that an operator is willing and able to provide for a corresponding schedule of passenger flows. The service-specification-envelope approach is oriented toward establishing the boundaries within which an operator may provide service. Two factors play a role in constraining an operator's ability to offer transit service, i.e., to use a given technology-headway combination: the economic viability limit and the physical capacity limit. The first constraint dictates that, for a given technology-headway combination and fare level, a minimum level of passenger flow must be available if a break-even operation is to be achieved. The second constraint is based on the physical ability of a given technology-headway combination to transport passengers at a given seat-standee ratio.

These limits established for a number of headways make it possible to define an envelope for a given technology bounded on the left by the viability constraint and on the right by the capacity constraint, within which a service function for that technology must be defined. How an operator defines the service function within the envelope is determined by his "willingness" to provide a high or low level of service. This concept of economic and capacity boundaries for a service-specification envelope is now illustrated by a simple example.

Consider the range of flows for which a hypothetical 60-seat bus operating at a 10-min headway may be used. If all passengers are to have a seat, the upper limit of the applicable flow range is the physical capacity, i.e., (60 × 6) or 360 passengers/hour. To establish the lower or viability limit requires that the cost of using this technology-headway combination be determined. If the cost is, for instance, \$1/mile, the cost of providing the above level of service (i.e., 10-min headway) will be \$6/mile/hour. If the average fare rate is \$0.05/mile, a flow of 6.00/0.05 or 120 passengers/hour is the minimum viable passenger flow. In general,

$$\text{Capacity flow limit} = (1 + \text{SPC})\ \text{VSC} \times \text{NVT} \times (60/\text{HDWY})$$
$$\text{Viability flow limit} = \text{CPM}\ (60/\text{HDWY})/\text{AFPM}$$

where

SPC = ratio of standees to vehicular seating capacity;
VSC = vehicular seating capacity;
NVT = number of vehicles in train (one for bus operation, generally);
HDWY = headway, in min;
CPM = cost per mile of the technology configuration, e.g., a bus or a 5-car train; and
AFPM = average fare per mile.

The above computations can be made for all operating headways for a given technology once the appropriate assumptions are made, as given in columns 2 and 3 of Table 1. Data given in Table 1 are based on the following assumptions: AFPM = 5 cents/mile, CPM = \$1, NVT = 1, VSC = 60, and SPC = 0. Use of each headway is constrained to the corresponding passenger flow range as defined by the viability and capacity limits.

It should be noted, however, that in an operating transit system the viability constraint for a given headway (service level) would not necessarily pertain to individual links but rather to the aggregate of all links offering that service level; i.e.,

$$\frac{1}{n}\sum_{e=1}^{n} F_e^s \geq F_v^s$$

where

s = particular service level (technology-headway combination),
n = number of links offering service level s,
F_e^s = directional flow on the e th link offering service level s, and
F_v^s = viability flow for service level s.

One could, of course, also aggregate the service levels and obtain a total aggregate system "break-even" criterion; such a gross level of aggregation, however, obviates the use of the concept proposed in this paper.

The computations previously described, in fact, establish only a one-dimensional output space, i.e., the manner in which the 2 boundaries of a service-specification envelope relate to flow. To portray the service specification graphically, a second dimension must be defined that encompasses other qualities of a transit technology in addition to its operating cost characteristics and physical capacity. The most logical dimension for this purpose is a level-of-service index because it is consistent with the concept of service and demand functions. Level of service is inherently difficult to define comprehensively, for it is a perceived quality and hence subjective. For the sake of simplicity, level of service in this paper is defined as the overall speed between boarding and egress points for characteristic routes in given operating contexts. That is,

$$\text{NET SPEED} = \text{ATD} \Big/ \left[\left(\frac{\text{ADBS}}{\text{MV}} + \frac{\text{MV}}{\text{ACC}} \right) \text{NLAT} + (\text{NLAT} - 1)\ \text{DWELL} + \text{HDWY}/2 \right]$$

where

ATD = average trip distance (ADBS × NLAT),
ADBS = average distance between stops,
MV = maximum velocity,
ACC = average operational acceleration and deceleration,
NLAT = number of links in average trip,
DWELL = average dwell time at intermediate stops, and
HDWY = headway offered at the boarding point.

It is assumed that the distance between stops will permit maximum velocity to be attained. Continuous service systems such as moving belts, systems offering continuity of through movement at intermediate stations, and walk mode can be encompassed by this approach.

Suppose that the 60-seat bus described earlier is operating in a distributor-collector context with stops every ¼ mile and that it has a maximum speed of 44 ft/sec and an average operational acceleration and deceleration of 4 ft/sec^2. For an average trip length of 3 miles and an average dwell time of 10 sec, the net speed of travel on a service offering a 10-min headway is

$$3.0 \times 5{,}280 \Big/ \left(\frac{1{,}320}{44} + \frac{44}{4} \right) 12 + 11 \times 10 + 600/2 = 17.6 \text{ ft/sec}$$

The relative quality-of-service indexes computed on this basis for the hypothetical bus are given in column 4 of Table 1. The data given in columns 2, 3, and 4 of Table 1 constitute the information necessary to draw the service-specification envelope shown in Figure 2. For a real hardware system, the top of the envelope would correspond to the minimum practical operating headway as determined by the control system and operating conditions. That may differ for each technology. The bottom of the envelope would represent lowest frequency of service judged acceptable in the operating context.

In formulating the above quality-of-service index, one could argue that waiting time will not normally exceed about 10 min, for when headways are long passengers will use their knowledge of the service schedule. On the other hand, one can regard waiting time in excess of the maximum as a surrogate for the inconvenience of an infrequent service. A maximum value of waiting time can be imposed if required. Station dwell time could be computed on the basis of the number of boarding and disembarking passengers at stops en route and on the size of doors and vehicle configuration to include appropriate vehicle characteristics in the quality-of-service index.

The above quality-of-service index obviously ignores many other features of the vehicle such as ride quality, seating comfort and space, and environmental quality. A number of studies have determined the relative weight attributed by passengers to such qualities and to the various time components of a trip. A more comprehensive relative quality-of-service index could be developed on the basis of those relative weights.

ALTERNATIVE TRANSIT COST FORMULATIONS

In the above analysis, no attempt was made to define the cost of providing transit service. There are, in fact, 3 distinct approaches to determining this cost:

1. Total costs associated with providing a service, including depreciation of assets and debt service;
2. Operating costs, excluding costs associated with depreciation of assets and debt service; and

3. Marginal or direct out-of-pocket costs associated with a particular movement, including fuel, labor, and maintenance, which is a function of wage, but excluding general administrative and overhead expenses.

Economists would argue that total cost should be used so as to avoid any bias between capital-intensive and low-operating-cost systems and systems that have low capital investment but high operating costs. Unfortunately, this approach might largely obviate the use of capital-intensive systems because, in general, such systems cannot attract sufficient patronage from fare-box receipts to cover total costs.

The use of operating cost is perhaps more realistic from the local viewpoint because federal capital grant programs contribute substantially to the capital costs of a system. Such aid makes it necessary to recover only direct operating costs from fare-box revenues. Furthermore, some states (e.g., Pennsylvania) have programs to subsidize direct operating costs and, thus, the use of marginal costing becomes a possibility. This has merit especially for rail systems where marginal operating cost is a small percentage of total operating cost. Because such capital-intensive systems are installed mainly to cater to heavy peak-hour traffic, it seems reasonable to charge overhead and fixed components of operating cost against peak-hour fares. This approach would require off-peak fares to support only the marginal cost of the service. It is, of course, possible to develop many proportional costing schemes on this basis depending on local circumstances.

In this paper, viability limits are based on operating costs. The use of marginal operating cost for rail systems is, however, shown to demonstrate the effect on the service-specification envelope (Fig. 5f). Both total and marginal operating cost approaches can be encompassed by the service-specification-envelope approach.

The basic problem in defining the viability boundary of service-specification envelopes is to determine operating costs for the different technologies. A number of different approaches were examined (6), but no general operating cost model could be formulated. Technologies and operating cost data given below were used to compute viability boundaries for the technologies compared in this paper.

Technology	Data Source (ref.)
Regular bus	7
Freeway flyer and busway	8, 9
Alweg monorail, minirail, and skybus	10
Minibus	11
Rail	12

Operating costs were computed for each technology, as appropriate, in the collector-distributor and line-haul contexts described later. Because of the wide range in bus operating costs revealed by the ATA data, 3 operating cost levels were used for buses, representing the 25th, 50th, and 75th percentiles in the distribution of operating costs derived from a sample of 50 properties. The variety of source material and the uncertain reliability and generality of the cost data must be borne in mind when the results of the study are evaluated.

TRANSIT-FARE STRUCTURES

In the description of the derivation of the viability boundary, use was made of an average fare per mile. In fact, operating transit systems use either a flat-fare rate or a zonal-fare structure, neither of which is strictly distance-related as shown in Figure 3. For practical reasons, a strictly distance-based fare structure will probably not be adopted until computer-operated, debit-account systems are introduced. This is of little consequence, however, if the technique is used for comparative purposes because all envelopes are derived based on this common assumption.

To determine suitable distance-based fare rates, a number of studies were examined; those by W. C. Gilmore and Company and Alan M. Voorhees and Associates (13, 14) were particularly useful. Table 2 gives the results of this study. The intra-District of Columbia and intra-Maryland routes are assumed to be collector-distributor types as indicated by the relatively short trip lengths and high per-mile fare. The District-Maryland and Maryland-District routes are assumed to be line-haul routes and have correspondingly higher average trip lengths and lower per-mile fares. Fares vary from 7.6 cents/mile to more than 12 cents/mile, and trip lengths vary from 3 to more than 7 miles.

To accommodate the dispersion of fare rates given in Table 2, service-specification-envelope data were computed for fares of 3, 7, and 11 cents/mile.

SERVICE-SPECIFICATION-ENVELOPE DATA FOR EXISTING TRANSIT TECHNOLOGIES

Data for service-specification envelopes have been developed for 3 technologies in a collector-distributor context and for 5 technologies in a line-haul context. A collector-distributor operating context was represented by a route 3 miles long with stops every ¼ mile. A line-haul operating context was represented by a route 10 miles long with stops at 2-mile intervals. The data sources given above were used to compute 3 viability boundaries for each technology based on fares of 3, 7, and 11 cents/mile. Three capacity boundaries were similarly computed for each technology on the basis of seating capacity with 0, 50, and 100 percent standees. Headways from 30 to 2 min were used for the line-haul technologies, and headways of 60 to 4 min were used for the collector-distributor technologies. Other pertinent data are given in Table 3.

In the case of minirail, the viability limit is defined in terms of 5, 10, and 20 cents/mile fares because of the high cost of operation. As discussed previously, the quality of service is measured in terms of speed (ft/sec). Table 4 gives the numerical data for the service-specification envelopes. As an example, the data for the busway have been graphed and are shown in Figure 4. By selecting different combinations of viability and capacity conditions, one can directly construct 9 different service-specification envelopes; and, of course, interpolation is also possible. The individual service-specification envelopes define the output space of a technology in terms of the flows that can be accommodated and the quality of service that can be supplied in an assumed operating context for a given fare rate and capacity definition.

COMPARISON OF LINE-HAUL MODES

Service-specification-envelope data for busway, monorail, freeway flyer, skybus, and rail rapid systems based on a 7 cents/mile fare and seating capacity with no standees are shown in Figure 5. There is a great deal of redundancy in the capabilities of these line-haul modes as demonstrated by the overlap of the envelopes. Freeway flyer is the same technology as busway but does not have the advantage of an exclusive right-of-way. Because of this separate guideway, busway has a lower operating cost and, hence, a lower viability boundary and can offer a slightly better level of service. For all practical purposes, however, busway and freeway flyer occupy the same output space. It seems reasonable, therefore, to use the freeway flyer mode until its quality of service is adversely affected by competing freeway traffic and only then resort to the busway mode. Skybus occupies a similar region of the output space as do freeway flyer and busway. Having a higher vehicular capacity, skybus has a capacity boundary that is to the right of those for the other modes. Skybus can be formed into trains, and its capacity boundary can be moved yet farther to the right as extra units are added; the viability boundary would also move slightly to the right in the latter event.

It would appear that busway and rail complement each other in their coverage of the output space. However, the service-specification-envelope technique somewhat obscures the ability of the busway, for instance, to handle larger corridor flows. Although a 2-min headway might be as close a headway as is reasonably required at any given station in a corridor, the guideway as such can accommodate much closer headways and, thereby, provide a much greater "corridor" capacity. Skip-stop operation would give rise to this condition. Thus, in fact, a busway system can be used for higher corridor flows than those indicated by the service envelope. It can serve high flows, although the quality of service may be somewhat lower than that of rail, and it can also

Figure 1. Transit service functions.

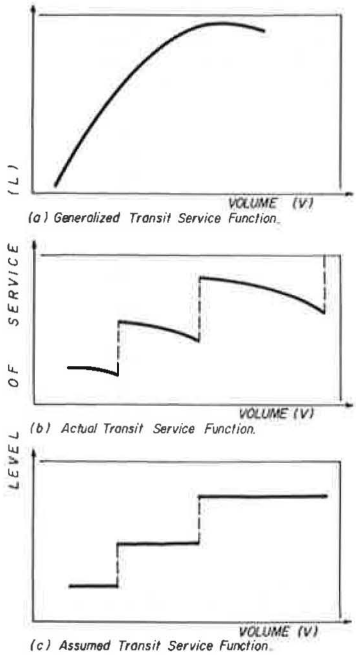


Figure 2. Service-specification envelope.

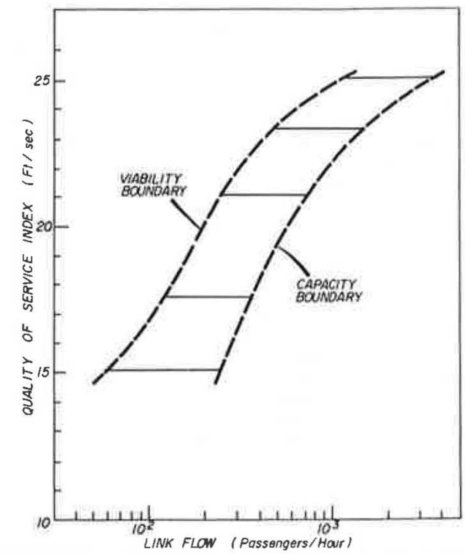


Table 1. Service-specification-envelope data for hypothetical 60-seat bus.

Operating Headway (min)	Viability Flow Limit	Capacity Flow Limit	Relative Quality of Service (ft/sec)
1	1,200	3,600	25.1
2½	480	1,440	23.4
5	240	720	21.1
10	120	360	17.6
15	60	240	15.1

Table 2. Average distance and fare paid in District of Columbia area.

Route	Avg Trip Length (min)	Avg Fare (cents)	Fare (cents/mile)
Intra-District	3.12	29.7	9.52
District-Maryland	7.20	54.7	7.60
Maryland-District	6.58	57.5	8.74
Intra-Maryland	3.68	44.5	12.09

Figure 3. Comparison of fare schedules.

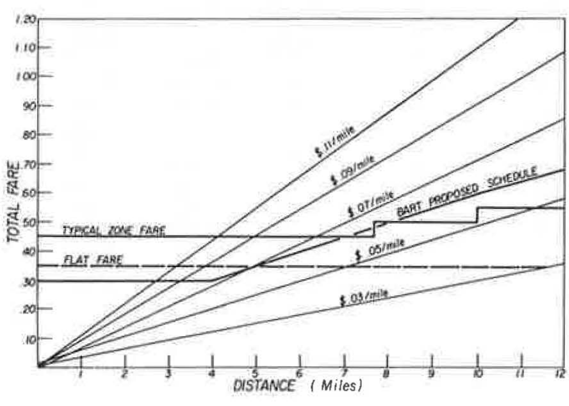


Figure 4. Service-specification envelopes of busway for 3 fares and capacities.

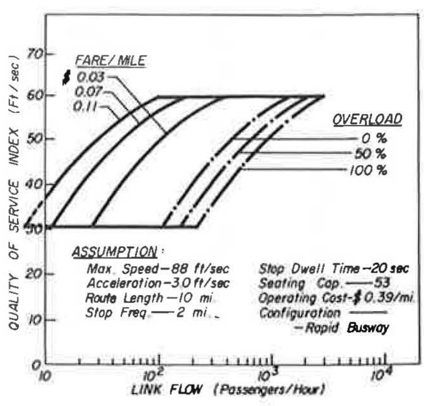


Table 3. Summary of transit technology data.

Technology	Context	Operating Cost (dollars/mile)	Passenger Capacity	Max Speed (ft/sec)	Acceleration (ft/sec)	Route Length (miles)	Station Frequency (miles)	Dwell Time (sec)
Monorail	Line haul	0.75	35	92.0	3.5	10	2	20
Rail								
Total cost	Line haul	5.60[a]	360	110.0	4.0	10	2	20
Marginal cost	Line haul	0.625[a]	360	110.0	4.0	10	2	20
Skybus	Line haul	0.35	70	73.0	3.5	10	2	20
Freeway flyer	Line haul	0.81	53	73.0	3.0	10	2	20
Busway	Line haul	0.39	53	88.0	3.0	10	2	20
Regular bus								
1	Collector-distributor	0.62	53	44.0	3.0	3	1/4	20
2	Collector-distributor	0.74	53	44.0	3.0	3	1/4	20
3	Collector-distributor	0.89	53	44.0	3.0	3	1/4	20
Minibus	Collector-distributor	0.49	22	44.0	3.0	3	1/4	20
Minirail	Collector-distributor	4.90	28[b]	13.0	2.0	3	1/4	20

[a]5-car train. [b]Per train with 7 cars.

Table 4. Data and assumptions for service-specification envelopes.

Technology	Headway (min)	Quality of Service (ft/sec)	Viability Limit by Fare[a] 3 Cents/Mile	7 Cents/Mile	11 Cents/Mile	Capacity by Percentage of Standees 0 Percent	50 Percent	100 Percent
Monorail	30	31.33	50	21	13	70	105	140
	20	38.11	75	32	20	105	158	210
	15	42.74	100	42	27	140	210	380
	12	46.10	125	53	34	175	263	350
	10	48.65	150	64	40	210	315	420
	6	54.70	280	107	68	350	525	700
	4	58.32	375	160	102	575	788	1,050
	3	60.32	500	214	136	700	1,050	1,400
	2	62.46	750	321	204	1,050	1,575	2,100
Rail								
Total cost	30	32.5	373	159	101	720	1,080	1,440
	20	40.0	559	239	152	1,080	1,620	2,160
	15	45.0	746	319	203	1,440	2,160	2,880
	12	49.0	933	399	254	1,800	2,700	3,600
	10	52.0	1,119	479	305	2,160	3,240	4,320
	6	59.0	1,866	799	509	3,600	5,400	7,200
	4	63.0	2,799	1,199	763	5,400	8,100	10,800
	3	65.5	3,733	1,599	1,018	7,200	10,800	14,400
	2	68.0	5,599	2,399	1,527	10,800	16,200	21,600
Marginal cost	30	32.5	41	17	11	720	1,080	1,440
	20	40.0	62	26	17	1,080	1,620	2,160
	15	45.0	83	35	22	1,440	2,160	2,880
	12	49.0	104	44	28	1,800	2,700	3,600
	10	52.0	124	53	34	2,160	3,240	4,320
	6	59.0	208	89	56	3,600	5,400	7,200
	4	63.0	312	133	85	5,400	8,100	10,800
	3	65.5	416	178	113	7,200	10,800	14,400
	2	68.0	624	267	170	10,800	16,200	21,600
Skybus	30	29.0	23	9	6	140	210	280
	20	34.5	34	14	9	210	315	420
	15	38.5	46	19	12	280	420	560
	12	41.0	58	24	15	350	525	700
	10	43.0	69	29	19	420	630	840
	6	47.5	116	49	31	700	1,050	1,400
	4	50.5	174	74	47	1,050	1,575	2,100
	3	52.0	233	99	63	1,400	2,100	2,800
	2	53.5	349	149	95	2,100	3,150	4,200

Table 4. (Continued).

Technology	Headway (min)	of Service (ft/sec)	Viability Limit by Fare[a] 3 Cents/Mile	7 Cents/Mile	11 Cents/Mile	Capacity by Percentage of Standees 0 Percent	50 Percent	100 Percent
Freeway flyer	30	31.03	54	23	14	106	159	212
	20	37.67	81	35	22	159	239	318
	15	42.18	109	46	29	212	318	424
	12	45.45	136	58	37	265	398	530
	10	47.93	163	70	44	318	477	636
	6	53.79	273	117	74	530	795	1,060
	4	57.29	409	175	111	795	1,193	1,590
	3	59.29	546	234	149	1,060	1,590	2,120
	2	61.28	819	351	223	1,590	2,385	3,180
Busway	30	30.58	26	11	7	106	159	212
	20	37.01	39	17	10	159	239	318
	15	41.36	53	22	14	212	318	424
	12	44.50	66	28	18	265	398	530
	10	46.86	79	34	21	318	477	636
	6	52.45	133	57	36	530	795	1,060
	4	55.78	199	85	54	795	1,193	1,590
	3	57.60	266	114	72	1,060	1,590	2,120
	2	59.55	399	171	109	1,590	2,385	3,180
Regular bus 1	60	6.0	21	9	6	53	79	106
	30	9.5	41	17	11	106	159	212
	20	11.5	61	26	16	159	239	318
	15	13.0	82	35	22	212	318	424
	12	14.0	103	44	28	265	378	530
	10	15.0	123	53	33	318	477	636
	6	16.5	206	88	56	530	795	1,060
	4	17.5	309	132	84	795	1,193	1,590
Regular bus 2	60	6.0	25	11	7	53	79	106
	30	9.5	49	21	13	106	159	212
	20	11.5	73	31	20	159	239	318
	15	13.0	98	42	26	212	318	424
	12	14.0	123	52	33	265	378	530
	10	15.0	147	63	40	318	477	636
	6	16.5	246	105	67	530	795	1,060
	4	17.5	369	158	100	795	1,193	1,590
Regular bus 3	60	6.0	30	13	8	53	79	106
	30	9.5	59	25	16	106	159	212
	20	11.5	88	38	24	159	239	318
	15	13.0	118	50	32	212	318	424
	12	14.0	148	63	40	265	378	530
	10	15.0	177	76	48	318	477	636
	6	16.5	296	127	80	530	795	1,060
	4	17.5	444	190	121	795	1,193	1,590
Minibus	60	6.0	10	5	3	22	33	44
	30	9.5	19	9	5	44	66	88
	20	11.5	29	14	7	66	99	132
	15	13.0	39	19	9	88	132	176
	12	14.0	48	24	12	110	165	220
	10	15.0	58	29	14	132	198	264
	6	16.5	97	48	24	220	330	440
	4	17.5	146	73	36	330	495	660
Minirail	60	5.0		49	24	28	42	56
	30	7.0		97	48	56	84	112
	20	8.0		146	73	84	126	168
	15	8.75		195	97	112	168	224
	12	9.25		244	122	140	210	280
	10	9.5		293	146	168	252	336
	6	10.25		489	244	280	420	560
	4	10.75		734	367	420	630	840

[a]For minirail, the fares are 5, 10, and 20 cents/mile.

serve low flows. In the latter instance, rail systems can compete only by resorting to a marginal-cost approach, and that is hardly a feasible policy for peak-hour operation without high subsidies. The complementarity of the modes is thus superficial; in fact, they compete with each other.

Skybus has the disadvantage of requiring a fixed guideway at all levels of flow. It, thus, does not have the flexibility of the freeway flyer and busway combination, nor does it have the high service quality of rail. One could argue that skybus is not, in fact, intended to function in the line-haul mode but rather in a collector-distributor context. The use of a fixed guideway in such an operating context would, however, require special conditions. Monorail also requires a special guideway for all flow levels, and the above comments apply. In addition, at least on the basis of the assumptions made, monorail has a very thin envelope and would be suitable only in special situations. In selecting a system, the planner must trade off the flexibility and wide viable range of the busway and freeway flyer against the superior service of a fixed-route rail system.

COMPARISON OF COLLECTOR-DISTRIBUTOR MODES

The service-specification envelopes of minibus, conventional bus, and minirail systems are shown separately in Figure 6. It is immediately apparent that minirail is not a viable system. Even at a fare rate of 20 cents/mile, the viability boundary and the capacity boundary are virtually coincident. The difference between the regular bus and the minibus system is largely one of capacity because there is little difference between the viability boundaries of the 2 systems. Informal discussions with transit operators, moreover, indicate that maintenance problems exist with current minibus vehicles, that upkeep is expensive, and that they lack operational flexibility. It would thus appear from a comparison of modes in a collector-distributor context that the regular urban bus is superior to the other modes. The term superior is perhaps inappropriate, however, for the quality of service offered compares poorly with the performance of the automobile in a similar context. It is evident that there is need for a much better technology for the collector-distributor function if any but captive riders are to be attracted to transit. It is just this area, of course, to which the dial-a-bus and PRT technologies are addressed.

COMPARISON OF TRANSIT AND HIGHWAY SERVICE FUNCTIONS

The previous sections have dealt only with transit service functions, and it is illuminating to compare those with highway service functions. Service-specification envelopes for rail, busway, and regular bus and service functions for different types of highways are shown together in Figure 7. The highway service functions relating vehicular flows and operating speed were taken from the Highway Capacity Manual (15) and converted to passenger flows based on 1.3 passengers/vehicle.

As expected, a 3-lane expressway is superior to rail rapid transit up to approximately 5,000 passengers/hour. However, if automobile occupancy were increased to 4 persons/car, a 3-lane freeway would be superior to rail rapid transit for flows up to about 10,000 passengers/hour. Private automobile transportion is superior in most cases to transit even at high volumes because automobile transportation involves no waiting time and provides nonstop service from origin to destination. The line-haul envelopes do not include the time required to gain access to the facility from the trip origin nor the time required to reach the trip destination after using the line-haul mode. Only when highways become congested does rail rapid transit become a viable alternative in terms of quality of service.

SUMMARY

The analysis has demonstrated that the concept of supply or service-function envelopes is a useful device for comparing technologies and can also be used in equilibrium modeling. The approach outlined in this paper is capable of considerable refinement as indicated in the discussion, and extensions of the technique are being investigated. It would be most desirable to derive service-specification envelopes on the basis of

Figure 5. Service-specification envelopes of 6 technologies for 7 cents/mile fare and 0 percent standees.

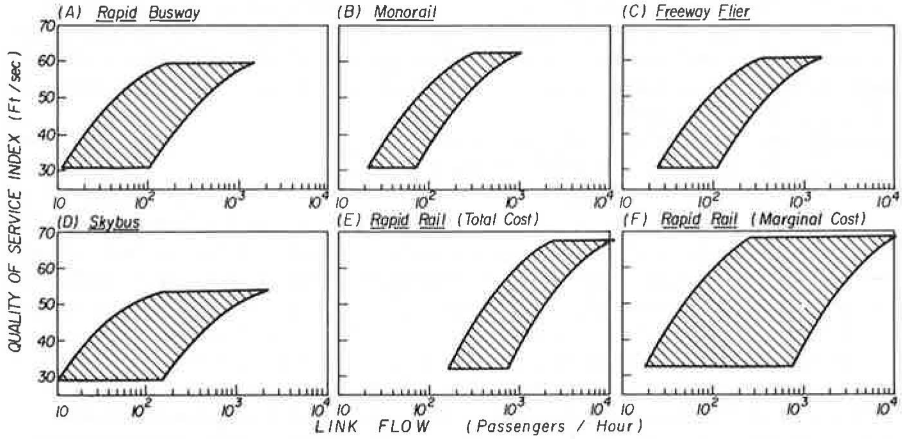


Figure 6. Service-specification envelopes of 3 technologies for fares of 7 cents/mile (bus and minibus) and 11 cents/mile (minirail).

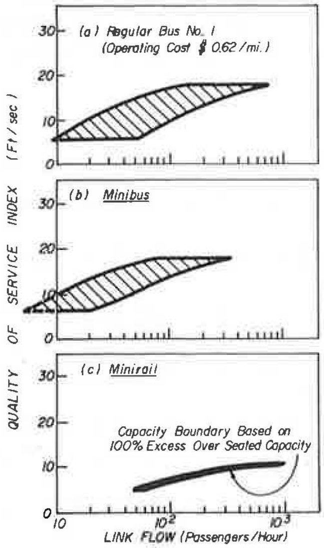
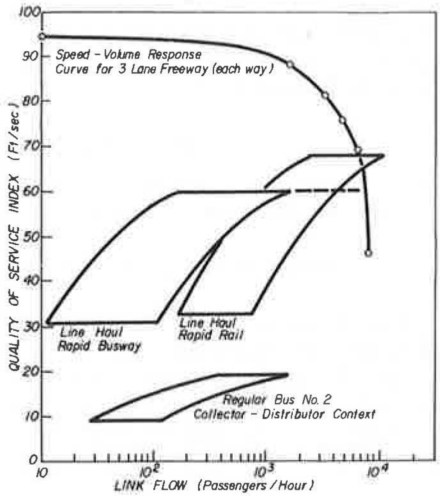


Figure 7. Service-specification envelopes for 3 technologies and service functions for highways.



total costs, for that would provide further insights into the flexibility and viability of the various modes. In addition, it would be interesting to extend the study to include other technologies in such a comparative analysis; the service-specification-envelope approach indicates the intrinsic merits of existing and possible future technologies. Indeed, the approach could be used to define normative specifications of future modes to replace or complement existing modes, and that may be one of the most interesting and fruitful applications of the technique.

The analysis indicates that, of the collector-distributor modes studied, the regular urban transit bus has the greatest flexibility in that it is able to cater to a wide range of demand levels. The quality of service offered, however, is quite poor, and there is a need to devise superior technologies for this type of service. In the line-haul context there appears to be much redundancy. Two technologies, namely, busway and rail systems, appear to complement each other in their coverage of the output space although the complementarity is more superficial than real. The application range of the busway system is greater than that of rail, and it seems to be a more flexible mode because, when freeways are uncongested, it can revert to the freeway-flyer mode and avoid the cost of a separate guideway. The quality of service is, however, slightly lower than that for rail in the line-haul context. When they are compared with the automobile, all transit technologies perform poorly. Only when flow levels are high and when freeways are congested can rail rapid systems offer a comparable quality of service.

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