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Theoretical and Practical Capacities of Transit Modes

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Presented at the Intersociety Conference of Transportation, Atlanta, 1975.

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Abstract

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2. Capacity must be considered together' with service quality, primarily operating safety and speed; and
3. There is a considerable difference b-tween theoretical and practical ·capacities of modes: the latter are important for design.·

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THEORETICAL AND PRACTICAL CAPACITIES OF TRANSIT MODES

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ABSTRACT

The transporting capacities of different transit modes are often discussed, but values quoted for different modes vary widely because of differing assumptions. This paper presents the basic theory of capacity and gives explanation of and insight to three aspects which must be carefully considered in capacity analysis:

a. Way capacity and station capacity of transit modes usually vary greatly;

b. Capacity must be considered together with service quality, primarily operating safety and speed; and

c. There is a considerable difference between theoretical and practical capacities of modes: the latter are important for design.

NOMENCLATURE

a = acceleration rate, m/s^2.
b_1, b_2 = braking rate of lead and following vehicle, respectively, m/s^2.
b_e, b_n = emergency and normal braking rate, respectively, m/s^2.
C = line capacity, per/h.
C_s = station capacity, per/h.
C_v = vehicle capacity, per.
C_w = way capacity, per/h.
d_s = spacing between rear end of lead vehicle and front end of following vehicle, m.
f_{max} = maximum frequency of vehicle arrivals, veh/h.
h_{min} = minimum headway between arrivals, min.
$h_{s\,min}$ = minimum station headway, min.
$h_{w\,min}$ = minimum way headway, min.
ℓ = vehicle (and platform) length, m.
s = spacing between consecutive vehicles, m.
s_o = required distance between two consecutive stopped vehicles, m.
$s_{w\,min}$ = minimum vehicle spacing on way, m.
s'_a, s'_b = distance required to accelerate to and brake from speed v', respectively, m.
t_b = braking time, s.
t_r = vehicle response time, s.
t_s = station standing time, s.
t'_a = time required to accelerate to speed v', s.
$\Delta t = \ell/v$, s.
v = operating speed, km/h.
v_{max} = maximum technical speed, km/h.
v' = speed at which platform clearance is assured during acceleration away from platform, km/h.
v^*_s, v^*_w = speed at which maximum station and way capacity is attained, respectively, km/h.
Π = linear passenger density, per/m.

DEFINITIONS AND BASIC EQUATIONS OF CAPACITY

Line capacity (C) is one of the basic transit mode performance measures. Simply referred to as "capacity", it represents the maximum number of passengers which a transit mode can transport past a fixed point per unit time in one direction. Line capacity is expressed by:

$$C = f_{max} C_v = \frac{1}{h_{min}} C_v . \qquad (1)$$

In transit operations the minimum headway which can be achieved along the way between stops ($h_{w\,min}$) is different from the minimum headway at stations ($h_{s\,min}$). Consequently, there are two different capacities:

Way capacity (C_w), given by:

$$C_w = \frac{1}{h_{w\,min}} C_v \quad , \qquad (2)$$

Station capacity (C_s), given by:

$$C_s = \frac{1}{h_{s\,min}} C_v . \qquad (3)$$

The smaller of these two capacities represents the line capacity:

$$C = \mathrm{Min}\,(C_w, C_s). \qquad (4)$$

WAY CAPACITY

In determining way capacity, it is assumed that there are no stops made on the observed section and that the speeds of all vehicles are equal and constant.

As shown by Eq. (2), way capacity is determined by the minimum way headway, which can be expressed as the ratio of vehicle spacing (s) and flow speed (v):

$$h_{w\,min} = \frac{s_{w\,min}}{v} . \qquad (5)$$

The minimum allowable spacing must contain the following components: the difference between the stopping distance of the following vehicle and the braking distance of the lead vehicle, a minimum distance required between vehicles for safety when both are stopped (s_0), and a distance equal to vehicle length (ℓ). Since a steady flow with uniform speed is assumed, the expression for $s_{w\,min}$ is:

$$s_{w\,min} = vt_r + \frac{v^2}{2} \cdot \frac{b_1-b_2}{b_1 b_2} + s_0 + \ell . \qquad (6)$$

This equation shows that the distance between vehicles increases with the square of speed and with the difference between braking rates of the two vehicles (b_1-b_2). Figure 1 shows all components of spacing between vehicles.

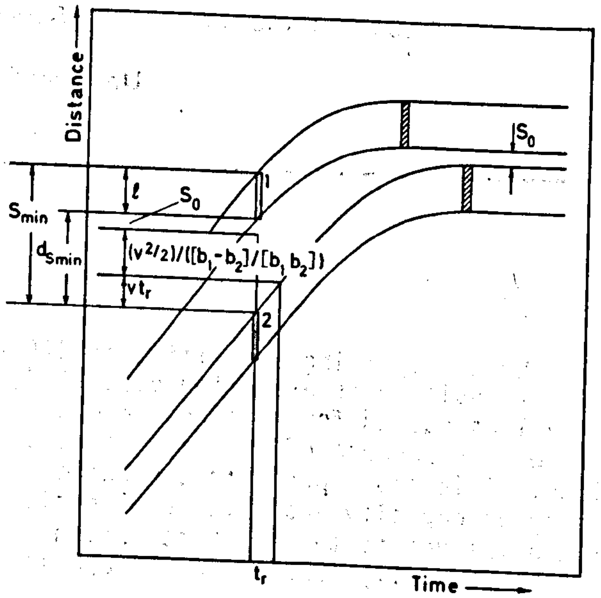

Fig. 1--Components of minimum vehicle spacing on a way.

A generalized expression for way capacity can now be obtained from Eqs. (2), (5) and (6):

$$C_w = \frac{vC_v}{vt_r + (v^2/2)\cdot(b_1-b_2)/b_1 b_2 + s_0 + \ell} \qquad (7)$$

for which conversion factors must be incorporated for each system of measures.

OPERATING SAFETY REGIMES

Assumptions with respect to the braking rates of the lead and following vehicles affect capacity and safety significantly. For analysis of these two factors and for design of transit control systems, different safety regimes must be defined, based on combinations of three types of vehicle stopping:

1. Normal braking: $b = b_n$, for which a vehicle is braked at a normal rate used in regular operation. b_n is usually governed by passenger comfort.

2. Emergency braking: $b = b_e$, for which the maximum braking capability of the vehicle is utilized, often with supplementary braking systems (e.g., a magnetic track brake). Passengers experience discomfort and certain safety hazards during such braking.

3. Instant (stone wall) braking: $b = \infty$, which represents a catastrophic collision by a vehicle. This possibility, though remote, is used as a basis for design in many rail systems.

Several authors have analyzed these types of stopping regimes, but the most systematic analysis was done by Lehner (6) in 1950. The safety regimes and capacity-speed curves studied by Lehner have been elaborated here and extended to include station capacity analysis.

A transit system safety regime is determined by the combination of the types of stopping for successive vehicles provided by the system's type of operation. Theoretically, there are 10 different safety regimes: the lead and following vehicles can assume any of the three stopping regimes defined above, making 9 permutations; The tenth regime assumes a continuous train which travels at constant speed and no stops. The latter represents a theoretical limiting case.

Of the nine permutations, those in which the following vehicle has a faster braking rate than the lead vehicle are not considered safe and can be ignored in analysis. Further, all cases for which the two vehicles have the same stopping regime actually represent the same capacity since they result in equivalent minimum way spacing. Thus, one obtains only four feasible safety regimes, which are listed in Table 1 in order of decreasing safety and increasing capacity. The hypothetical case with a continuous train is added for theoretical comparison.

For each safety regime, the minimum spacing $s_{w\,min}$ is obtained by inserting the appropriate values of b_1 and b_2 into Eq. (7). By partial differentiation of the same expression with respect to v, expressions for maximum capacity (C_w^*) and optimal speed (v_w^*) are obtained.

Regime a: $b_1 = \infty$, $b_2 = b_n$. This regime provides maximum safety, ensuring that even if the lead vehicle were to come to an instantaneous stop, the following vehicle could stop without collision at a normal braking rate at a distance s_o m from the lead vehicle. Thus, maximum passenger comfort and absolute safety are provided. For this regime:

Safety Regime	b_1	b_2	Comment
a	∞	b_n	Absolute safety and comfort; possible overdesign.
b	∞	b_e	Absolute safety; desirable.
c	b_e	b_n	Safety high, but not absolute.
d	∞, b_e, b_n	∞, b_e, b_n	In emergencies, safety not adequate.
e	NO BRAKING		Hypothetical: continuous train.

Table 1--Safety regimes of transit operation: combinations of braking rates for successive vehicles.

$$C_w = \frac{vC_v}{\ell + s_o + vt_r + \frac{v^2}{2b_n}} \; ; \qquad (8)$$

$$C_w^* = \frac{C_v}{\sqrt{2(\ell + s_o)/b_n} + t_r} \; ; \qquad (9)$$

$$v_w^* = \sqrt{2(\ell + s_o)b_n} \; . \qquad (10)$$

Regime b: $b_1 = \infty$, $b_2 = b_e$. This regime provides for avoiding a collision in the case of stone wall stop of the lead vehicle only if the following vehicle applies an emergency braking rate or greater. With lower safety, lower passenger comfort than regime a, regime b may still be considered satisfactory in the design of some control systems, particularly those with automated operation. Here:

$$C_w = \frac{vC_v}{\ell + s_o + vt_r + v^2/2b_e} \quad ; \qquad (11)$$

$$C_w^* = \frac{C_v}{\sqrt{2(\ell + s_o)/b_e} + t_r} \quad ; \qquad (12)$$

$$v_w^* = \sqrt{2(\ell + s_o)b_e} \quad . \qquad (13)$$

Regime c: $b_1 = b_e$, $b_2 = b_n$. This regime provides for normal braking of the second vehicle if the lead vehicle stops at an emergency rate. Since it does not provide for conditions under which stone wall stop can occur, this regime is not absolutely safe. The expressions for this regime are:

$$C_w = \frac{vC_v}{\ell + s_o + vt_r + \frac{v^2}{2} \cdot (b_e - b_n)/b_e b_n} \; ; \qquad (14)$$

$$C_w^* = \frac{C_v}{\sqrt{2(\ell + s_o)(b_e - b_n)/b_e b_n} + t_r} \quad ; \qquad (15)$$

$$v_w^* = \sqrt{2(\ell + s_o)(b_e b_n)/(b_e - b_n)} \quad . \qquad (16)$$

Regime d: $b_1 = b_2$. It can be seen from Eq. (7) that the v^2-term becomes zero when $b_1 = b_2$. Thus, way capacity is the same regardless of the type of braking so long as both vehicles apply the same braking rate. This regime is unacceptable under normal conditions since the following vehicle is required to stop instantaneously if the lead vehicle does so. Since:

$$C_w = \frac{vC_v}{\ell + s_o + vt_r} \quad , \qquad (17)$$

it is obvious that capacity increases monotonically at a decreasing rate as speed becomes greater. Theoretically, the capacity asymptotically approaches the value:

$$C_w \to \frac{C_v}{t_r} \quad \text{as } v \to \infty \, . \qquad (18)$$

Regime e: No braking. This regime assumes travel of a continuous train of vehicles, or a continuous conveyor system, running at constant speed without stops. The regime is useful for analysis since it represents the theoretical limiting case for way capacity. For this regime:

$$C_w = \Pi \, v \quad , \qquad (19)$$

where Π is the linear passenger density, or the number of persons per unit length of train. Here, way capacity is a linear function of travel speed.

The five safety regimes described above have particular influence on the way capacity-speed relationship for any mode. To illustrate this, the five safety regimes are plotted in Fig. 2 for a system with a single vehicle with the following characteristics:

$\ell = 12$ m	$t_r = 5.0$ s
$C_v = 84$ per	$b_n = 1.3$ m/s^2
$\Pi = 7.0$ per/m	$b_e = 2.1$ m/s^2 .
$s_o = 1$ m	

These values are introduced into Eqs. (8), (11), (14), (17) and (19) to obtain capacity vs. speed curves for regimes a through e respectively.

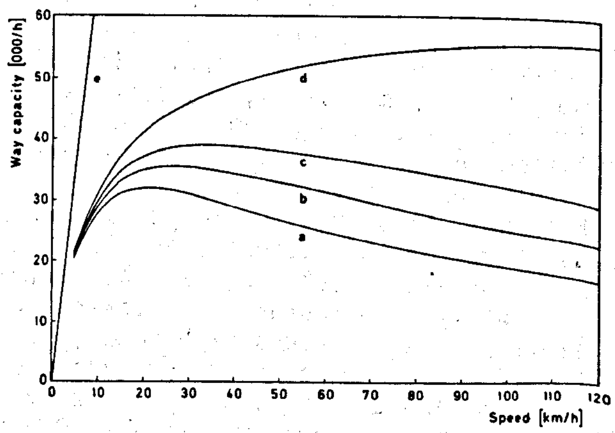

Fig. 2--C_w vs. v for single vehicle operating under various safety regimes.

The obtained diagram, plotted for speeds of up to 120 km/h, shows that regime a (the most important one for application on centrally controlled systems) has the lowest capacity due to its absolute safety. Greater way capacity and a higher optimal speed, together with lower safety, are characteristics of other regimes. Regimes d and e, of course, do not have a finite maximum capacity.

Such curves may be plotted and compared for any set of characteristics and for any mode; their numerical values would vary, but their shapes and relationships would remain the same.

STATION CAPACITY

As mentioned earlier, the capacity of lines at stations is usually considerably lower than that of ways between stations. Analysis of station capacity is therefore critical for a correct evaluation of capacity of all modes with on-line stations, i.e. a vast majority of existing modes.

For analysis of the basic elements of station capacity, the following assumptions are made:

1. Stations are on-line;
2. Platform (station) length is equal to vehicle length;
3. The following vehicle cannot enter the station until clearance of the platform by the lead vehicle is assured;
4. All vehicles have equivalent dynamic capabilities and behavior;
5. All vehicles decelerate to a station from constant speed v;
6. Acceleration and deceleration rates (a and b) are constant from v=0 to constant speed and from constant speed to v=0, respectively;
7. Standing times (t_s) are equal for all vehicles and all stations;
8. Vehicle length is less than the distance required to accelerate to constant speed;
9. The travel way is straight with no curves or gradients;
10. Vehicle control is centralized with continuous monitoring (zero block length).

A generalized schematic diagram for determination of minimum station headway under the defined conditions is shown in Fig. 3; variation in assumptions can be easily introduced through slight modifications in the diagram and the expressions derived from it. From the diagram:

$$h_{s\,min} = t_s + t'_a + \Delta t + t_r + t_b \qquad (20)$$

The diagram is constructed in such a way that it is not possible for any portions of the two vehicles to occupy the station simultaneously--either while in movement or in stopped positions. This requirement is accomplished by sliding the shadow (the spacing in front of the following vehicle, equal in depth to its stopping distance) to a point in time (A) for which the clearing of the station by the lead vehicle is first assured. At this time the rear end path of the lead vehicle stopping positions (dot-dash line) crosses the distant end of the station platform. (Note: When a stone wall stop of the lead vehicle is assumed, The locus of stopping positions coincides with the vehicle's rear end path (solid line).) At the time the locus of rear end stopping positions crosses the platform end, the vehicle has reached speed v' and its rear end is at a distance $s'_b = v^2/2b_1$ from the end of the station.

The speed v' can easily be determined knowing that the distance traveled by the vehicle during acceleration to v' (s'_a) plus the distance required for braking from v' to a stop (s'_b) is equal to ℓ, the platform or vehicle length. Thus:

$$\ell = s'_a + s'_b = \frac{v'^2}{2}\left(\frac{1}{a_1} + \frac{1}{b_1}\right) . \qquad (21)$$

Solving this expression for v' and introducing that value into the expression for t'_a gives:

$$t'_a = \frac{v'}{a_1} = \sqrt{\frac{2\,b_1 \ell}{a_1(a_1 + b_1)}} . \qquad (22)$$

From Fig. 3 it is obvious that:

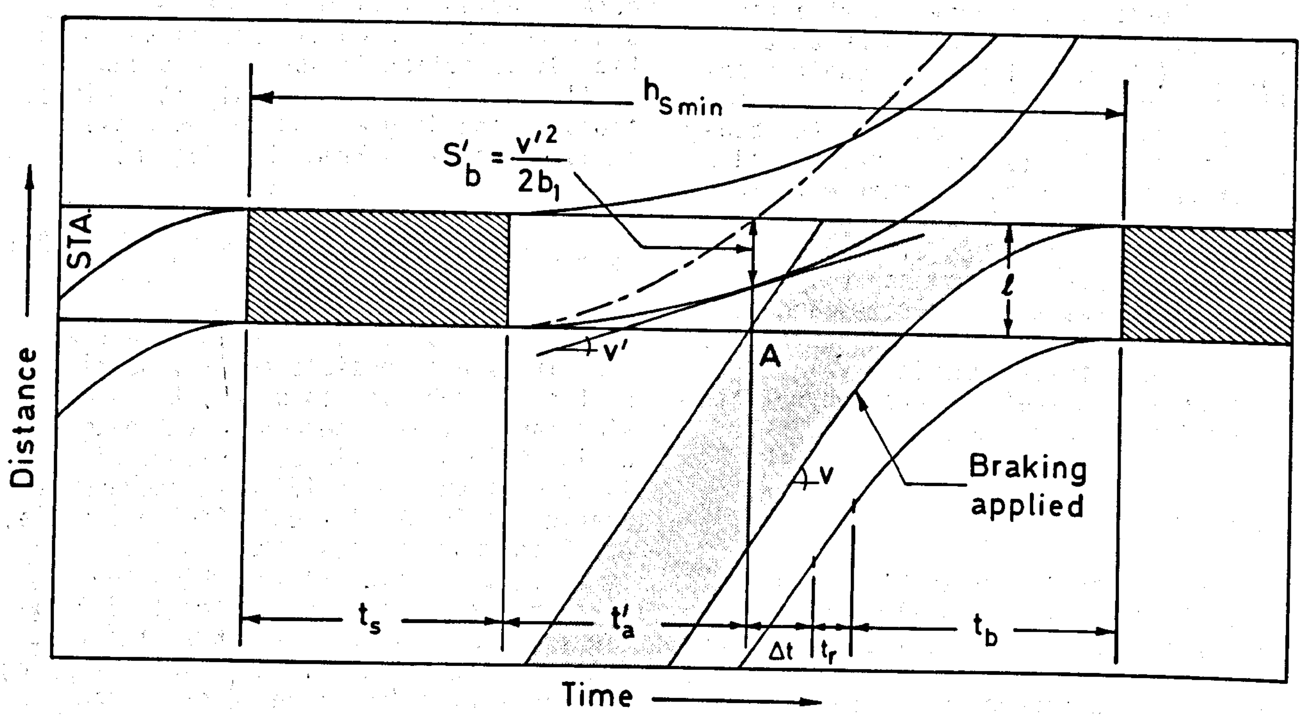

Fig. 3--Time components of minimum station headway: platform clearance assured.

$$\Delta t = \frac{\ell}{v} \quad . \tag{23}$$

Now, all time components can be introduced into Eq. (20):

$$h_{s\ min} = t_s + t_r + \frac{\ell}{v} + \frac{v}{b_2} + \sqrt{\frac{2\ b_1\ \ell}{a_1(a_1 + b_1)}} \ . \tag{24}$$

Then the expression for station capacity can be obtained by introducing this value of $h_{s\ min}$ into Eq. (3).

SAFETY REGIMES AT STATIONS

The regimes of safety defined in Table 1 apply with some modifications to station operation. Regime e, of course, does not apply to stations since it requires non-stop operation. Furthermore, regime d does not have equal station capacities for all values of $b_1 = b_2$, as it does for way capacity. Using the same procedure, however, expressions for station capacity (C_s), maximum possible station capacity and the optimal speed for the maximum capacity can be derived for each safety regime using the following generalized expressions:

$$C_s = \frac{C_v}{t_s + t_r + \frac{\ell}{v} + \sqrt{\frac{2\,b_1 \ell}{a_1(a_1 + b_1)}} + \frac{v}{b_2}} \ ; \tag{25}$$

$$C_s^* = \frac{C_v}{t_s + t_r + 2\sqrt{\ell / b_2} + \sqrt{\frac{2\ b_1 \ell}{a_1(a_1 + b_1)}}} \ ; \tag{26}$$

$$v_s^* = \sqrt{\ell\, b_2} \ . \tag{27}$$

For regimes a, b and c, the same conditions as shown in Table 1 for b_1 and b_2 apply. For regime d there are only two realistic cases: $b_1 = b_2 = b_e$ (regime d_1) and $b_1 = b_2 = b_n$ (regime d_2).

The station capacities for these safety regimes are plotted in Fig. 4 for the same vehicular and operating characteristics as selected for the way capacity curves in Fig. 2.

Comparing these two figures, the following observations can be made: First,

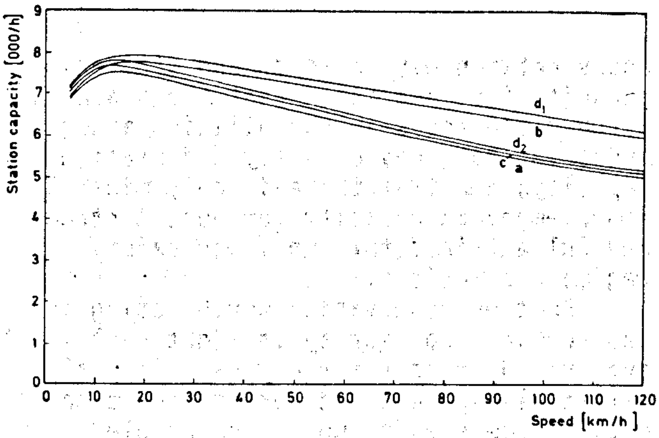

Fig. 4--C_S vs. v for single vehicle operating under various safety regimes.

both way capacity and station capacity are functions of operating speed. Second, the speed at which maximum capacity (C^*) is reached in each regime is somewhat greater for way capacity than for station capacity. And third, there are significant differences between way capacity and station capacity for all regimes of safety. Regimes a-e, for example, have four to five times greater way capacity than station capacity for any given speed.

COMPARISON OF CAPACITIES FOR SELECTED MODES

An interesting comparison of theoretical capacities of actual transit modes can be obtained through application of the derived expressions for C_W and C_S. Table 2 shows sets of technical characteristics for the five selected transit modes to be compared. The given vehicle models (GM, ACEC, etc.) are used to obtain these sets of characteristics. It is pointed out that the individual characteristics listed can range in their values significantly for any mode and that generalizations based on these assumptions must be qualified. It is also emphasized that the five modes have been selected with the purpose of illustrating influences of different mode characteristics (e.g. vehicle capacity, train composition, dynamic characteristics, type of guideway, etc.). Consequently, the assumed modes do not necessarily represent the most common vehicle capacities and train compositions. Thus, the assumed bus vehicle is of typical size, while light rail is considerably larger than the standard operating unit with a 2-car train with articulated vehicles; on the other hand the selected 6-car rapid transit train is shorter than the maximum composition of 8- and 10-car operating units which most systems utilize.

All systems are assumed to have a high number of standees (except personal rapid transit (PRT) which by design requires all passengers to be seated).

Vehicle response time is assumed to be 5 seconds for rapid transit, 2 seconds for light rail and bus, and 1 second for automated systems. Emergency braking rates for rail and bus vehicles are based on actual specifications and measured values, respectively. Since all its passengers are assumed seated, PRT is allowed the highest deceleration rate. Acceleration rates for all modes are assumed to be apprximately 10 per cent less than their respective normal braking rates.

Two capacity comparisons of the selected modes are shown in Figs. 5-8. First, the way and station capacity curves are derived for each of the five modes assuming that safety regime a (maximum passenger safety and comfort) is provided by each mode. For the second comparison the same curves are derived allowing each mode to operate under a safety regime considered most realistic for that mode.

MODE	STANDARD BUS	LIGHT RAIL	RAPID TRANSIT	MED. CAPACITY AUT. TRANSIT	PRT
MODEL / CHARACTERISTIC	GM	ART. BOEING	MUNICH	AIRTRANS	ARAMIS
Vehicles/Train	1	2	6	2	1
ℓ (m)	12	42	108	13	2.3
C_v (per)	80	438	870	80	4
s_o (m)	1	2	2	1	1
t_r (s)	2	2	5	1	1
t_s (s)	30	25	20	20	30
v_{max} (km/h)	90	100	80	30	70
b_n (m/s^2)	1.4	1.2	1.1	1.4	1.6
b_e (m/s^2)	4.0	2.7	1.8	4.0	5.0
a (m/s^2)	1.3	1.1	1.0	1.3	1.4

Table 2--Technical specifications of compared transit modes.

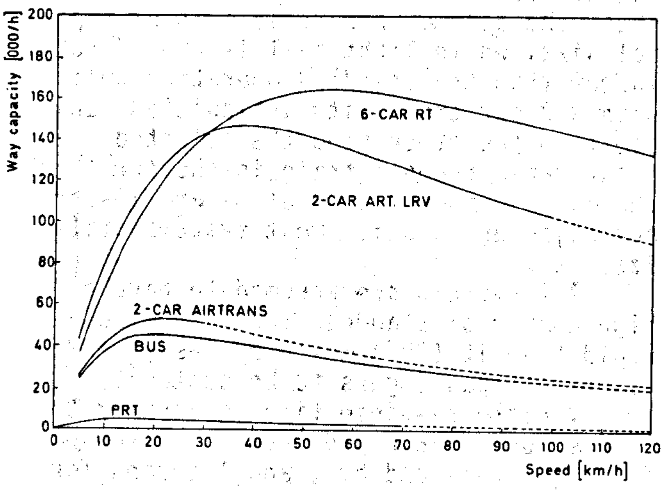

Fig. 5--Way capacity vs. speed for selected transit modes operating in safety regime a.

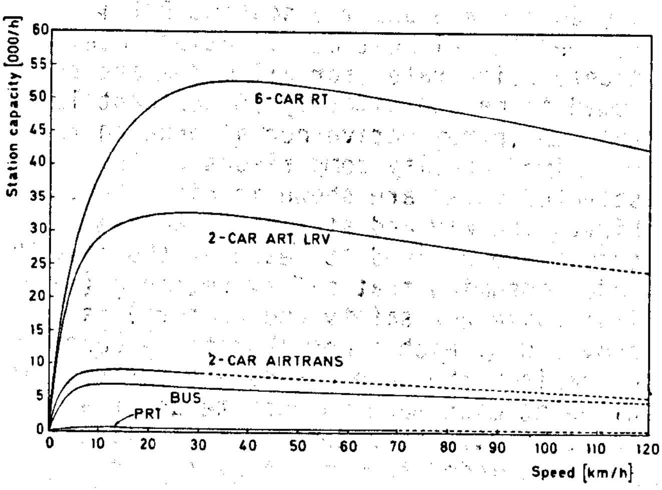

Fig. 6--Station capacity vs. speed for selected transit modes operating in safety regime a.

Buses may be assumed to operate under regime c, for which their capacity is particularly increased over regime a due the high bus emergency braking rate. Light rail vehicles on non-signalized sections may operate under regime b since their drivers must maintain a higher degree of safety than bus drivers. Rapid transit is assumed to always operate under regime a. Finally, PRT is assumed to operate under regime b.

Comparing Figs. 5-8 it is apparent that there are again significant differences between way capacity and station capacity for each mode; that there are large differences in capabilities among modes for both way capacity and station capacity; and that there is only minimal improvement in capacity for bus, Airtrans and PRT attained through lower safety regime assumptions.

Another observation worth noting is the seeming superiority of light rail over rapid transit for way capacity at almost all speeds, and for station capacity at low speeds, under comparable safety regime conditions. Two factors contribute to this somewhat misleading relationship: (1) the lower safety regime of light rail compared to rapid transit,

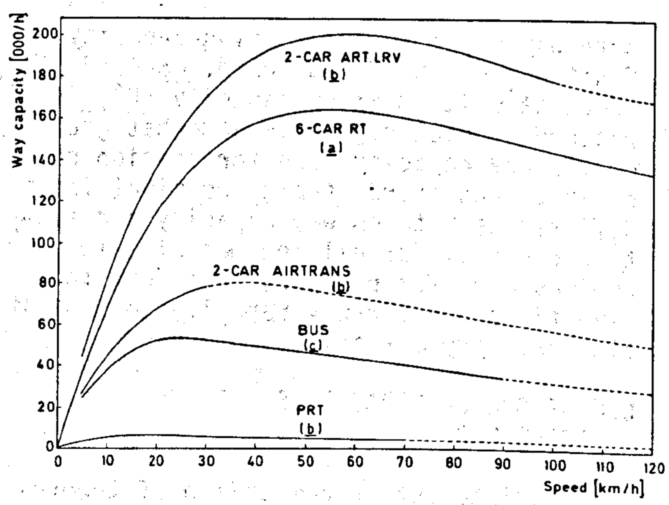

Fig. 7--Way capacity vs. speed for selected transit modes operating under typical safety regimes (x).

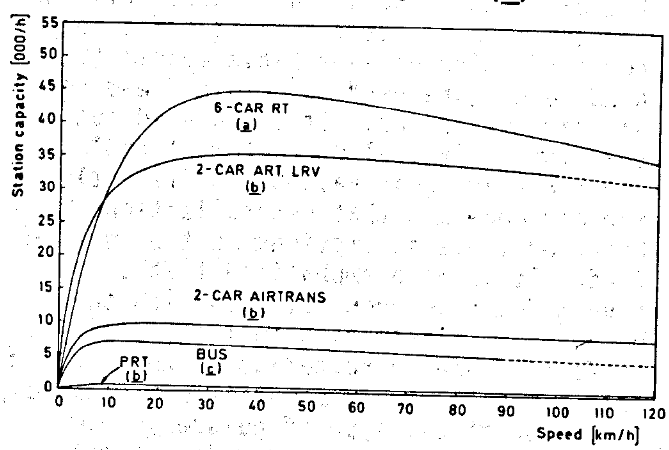

Fig. 8--Station capacity vs. speed for selected transit modes operating under typical safety regimes (x).

City	Street	Vehicles per hour	Spaces* per hour	Actual pass/h	Ref.
Bus on street: two lanes, multiple boarding					
New York	Hillside Avenue	170	13,600	8,500	(4)
San Francisco	Market Street	155	12,400	9,900	(4)
Philadelphia	Market Street	143	11,440	8,300	(4)
Washington	Pennsylvania Ave.	120	9,600	9,480	(4)
Bus on freeway: two lanes, no stops (Way capacity)					
New York	Lincoln Tunnel	735	58,800	32,560	(4)
New York	I-495	490	39,200	21,600	(4)
San Francisco	Oakland Bay Br.	327	26,160	13,000	
New York	Geo. Wash. Br.	136	10,880	9,468	(12)
Light Rail: single track, multiple boarding					
Hamburg	Moenkeberg St.	120x2	28,800	20,000	
Hannover	Messe Abfahrt**	80x2	19,600	18,000	(8)
Philadelphia	Mkt. St. Tunnel	157	18,840	n.a.	(5)
Dusseldorf		92	n.a.	14,000	(8)
Rapid Transit: single track, on-line stations					
New York	IND 6&8 Ave. Expr.	32	n.a.	71,800***	(2)
New York	IND 8th Ave. Expr.	30	n.a.	69,600	
Toronto	Yonge Street	28	n.a.	39,840	
London	(several lines)	36-40	n.a.	n.a.	

*Assumed: 80 persons per bus
**Single boarding
***Passenger volume rate counted during the peak 15-20 min. Offered capacity is slightly higher.
n.a.= not available

Table 3--Actual recorded volumes for selected transit modes.

and (2) the atypically large light rail operating unit and relatvely short rapid transit train, as mentioned before. Likewise, bus system capacity can be improved (although not greatly) through the use of articulated vehicles.

All of the analyzed modes are assumed to operate on a single lane, fully-controlled right-of-way with no interference from outside traffic and no opportunity for passing. These features (and other assumptions which have been stated earlier) are obviously characteristics not shared by all modes to the same degree, and so there are discrepancies between theoretical capacities and those actually achievable under real world conditions.

COMPARISON OF THEORETICAL AND ACTUAL CAPACITIES

Table 3 summarizes data for selected actual transit operations: bus on street, bus on freeway, light rail and rapid transit. Capacity data for Airtrans and PRT are not available from actual working systems.

For each category shown, the maximum recorded capacity of the line is given. Buses were again assumed to have an 80-person capacity.

Bus on street

The maximum recorded capacity of bus on street is 170 buses per hour in New York City, or an equivalent of 13,600 spaces per hour. However, this capacity is a result of multi-lane operation with overtaking and simultaneous loading at stations. This explains the discrepancy between theoretical and actual capacities. Single-lane bus operation at capacity conditions is not practical.

Bus on freeway

The maximum bus way capacity as recorded for the Lincoln Tunnel in New York City is 735 buses per hour, or about 58,000 spaces per hour. (The estimate of 80 passengers per bus is somewhat high for this case however). The reasons for the high capacity value are the relatively low speeds (about 16 km/h), low safety, and multi-lane operation.

Light Rail

Most available data for this mode must be derived from European systems. Relative to the high theoretical estimates cited earlier, actual capacities for light rail are significantly lower. This difference is due primarily to randomness factors in operation caused by non-uniform station standing times and external influences caused by a shared right-of way. (Among the quoted light rail data in Table 3, only Philadelphia's system has exclusive right-of-way; other systems operate in streets).

Rapid Transit

Rapid transit line capacities can vary greatly, depending on a number of factors: train size, type of control, departure control techniques, etc. The signal system and random influences at stations are the major factors diminishing achievable rapid transit capacity in comparison to theoretical values.

CONCLUSION

This paper has attempted to clarify some basic concepts of transit mode capacity analysis. The following points have been demonstrated:

1. There is a considerable difference between way capacity and station capacity for all transit modes. The latter is almost always 4 to 5 times smaller and it determines the line capacity of a mode.

2. Capacities of transit modes should not be compared alone: regime of safety and operating speed are important service quality factors which must be examined simultaneously with capacity. And

3. There is a considerable difference between theoretical and practically achievable capacities primarily due to the following factors:

- Station design: number of boarding locations, multiple boarding, fare collection methods, boarding control, etc.
- Type of right-of-way: exclusive, semi-exclusive, street.
- Way design: number of lanes/tracks, geometry, etc.
- Type of control: automated, block signal, visual, etc.
- Vehicle design: seat/standee ratio, high-level boarding, etc.
- Dynamic characteristics: electric propulsion, braking, etc.
- Technology: guidance, ability to operate trains, conduciveness to automation, etc.

The influence of many of these factors on capacity has not been adequately researched to date.

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