than one APERW were principally apartments and townhouses (82 percent); households having more than one APERW were principally single-family homes (78 percent). A trend of increasing APERW with greater numbers of adults and larger households was evident. An influence of transit could not be identified, possibly because very few lower-income households had members working in D.C. and were hence served by transit. Therefore, an APERW model for this subgroup should include the variability of household size in addition to dwelling type and, possibly, transit availability.

APPLICATION OF FINDINGS

In mode-choice models for work trips, APERW is a variable preferred over auto ownership or auto availability because (a) it is intuitively better, in that it reflects competition within a household for the automobile, and (b) the research findings show its correlation with mode choice to be statistically equal to or better than that of car availability. Group quarters or extremely large households can be accommodated in the data base without statistical analyses.

APERW is influenced by (a) the presence of a transit alternative, (b) the household composition (specifically the number of adults), (c) income, (d) dwelling type, and (e) household size (in the case of low-income households). For small satellite-type urban areas and suburban areas it is recommended that APERW models be estimated separately for three subgroups of the population, as follows:

1. Households with two or more adults and (1975) incomes in excess of $15 000,
2. Households with two or more adults and (1975) incomes less than $15 000, and
3. Households with one adult.

The first group has a free choice. Households in the group are able to afford more than one car and, depending on household composition, have need for more than one car unless travel needs can be satisfied by public transportation. The potential exists for APERW to be estimated using only dwelling type and transit level-of-service variables. The second group can ill afford more than one car. The study has shown that APERW models for the second group should consider household size, dwelling type, and perhaps transit service. The third group has a need for only one automobile. Thus, in most instances, it can be assumed that a one-adult household will have one automobile.

Provision of a high level of bus service will have some impact on reducing APERW for subgroups 1 and 2, but the impact is small even if transit is available to all employment destinations. Therefore, transit service alone cannot be an effective strategy in reducing automobile availability per worker.

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Abridgment

Trucks in the Traffic Assignment Process

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In order to deal with truck impacts, separate truck assignments are necessary so that the truck portion of the traffic stream on a highway link may be identified.

In some cities there are highways, parkways for example, on which trucks are specifically excluded. Then there are structures (e.g., overpasses and underpasses) whose very physical characteristics bar vehicles over a given height or weight. Conversely, there are routes whose signing encourages through truck travel. In dense urban areas, a separate assignment network should be built for trucks to reflect the policies and prohibitions on trucks. Moreover, if no such policies exist, separate network capacity should still be included within the assignment because such capability is necessary to test and evaluate the utility of such policies.

There are distinct differences among trucks in terms of size, weight, acceleration characteristics, number of axles, number of wheels, etc. Two classes of trucks are recommended. One is "auto-like" trucks, and these should be lumped in with autos. The second class would be heavy trucks and would be assigned separately. The criterion to be used is that auto-like trucks have four tires and heavy trucks have six or more tires.

A zone-to-zone trip table of truck trips is required to pursue separate truck assignments. Standardized procedures have been developed by FHWA to synthesize a table if an origin-destination survey is not available.

In addition to a truck trip table, the user should have some ground counts of truck volumes so that he or she can verify the simulation of routing and also generation and distribution, if this is required. Ideally, the truck link counts should be extensive enough to give a truck vehicle-kilometers of travel (VKMT) estimate against which simulated truck VKMT can be compared as a control.

Most existing assignment programs permit only one class of vehicles—autos, trucks, autos and trucks, or autos and truck "auto equivalents"—to be assigned. Assigning autos first and then trucks gives autos the preferred paths and tends to route trucks over longer paths if congestion is present and a capacity restraint mechanism is used. Concurrent assignment of autos and trucks with a separate account of truck volumes on links avoids the problem.

IMPACT OF TRUCKS ON HIGHWAY CAPACITY

Simplified View of Capacity

A simplified approach to the capacity of signalized intersections can be taken by finding the time required for the nth vehicle in a queue to clear the intersection and equating this to the green time. This approach is the basis for capacity determination in the microassignment process, in which all vehicles in the queue are assumed to be equally spaced and to accelerate uniformly to a specified average velocity approximately equal to the speed limit.

There are two (mutually exclusive and exhaustive) cases to be considered:

1. No vehicle in the queue reaches the specified velocity by the time it clears the intersection.
2. One or more vehicles in the queue reach the specified velocity before clearing the intersection.

In the following formulations, which were written in customary units, let

- $t(n)$ = time for nth vehicle to reach the intersection,
- C_1 = reaction time of the first vehicle (seconds),
- C_2 = reaction time of other queued vehicles (seconds),
- D = spacing of vehicle (feet),
- V = free flow velocity (feet per second),
- a = acceleration rate,
- N_2 = the number of the queue position from which a vehicle can accelerate to free flow velocity by the intersection, presuming the green time allows it ($N_2 - V^2/2Da$),
- t = time spent accelerating (seconds), and
- t_v = time spent traveling at terminal velocity (seconds).

Since the nth vehicle in the queue cannot start moving until the vehicle immediately ahead of it moves, the time for the nth vehicle to clear the intersection is the sum of the reaction time of the first vehicle, the reaction time of the following n - 1 vehicles, and the time for the nth vehicle to travel to the intersection.

For the first case this is

$$t(n) = C_1 + (n - 1)\,C_2 + t \qquad (1)$$

But, since the average velocity of the nth vehicle in this case is $at/2 = nD/t$, from which $t = \sqrt{2nD/a}$, then

$$t(n) = C_1 + (n - 1)\,C_2 + \sqrt{2nD/a},\ n < N_2 \qquad (2)$$

For the second case, where one or more vehicles reach average velocity before clearing an intersection ($n > N_2$), we must add a term to Equation 1 that accounts for the time spent traveling at terminal velocity by the nth vehicle. Therefore, for case 2

$$t(n) = C_1 + (n - 1)\,C_2 + t_v + V/a \qquad (3)$$

But

V/a = the time to reach V and
$V/2$ = the average velocity during t.

Therefore $(V/a)\,(V/2) = V^2/2a$ = the distance covered in t, so that $t_v = [nD - (V^2/2a)]/V$. Finally, substituting for $t_v + (V/a)$ in Equation 3, we get

$$t(n) = C_1 + (n - 1)\,C_2 + (nD/V) + (V/2a);\ N > N_2 \qquad (4)$$

The first vehicle in the queue to reach terminal velocity at the intersection (N_2), providing that there is sufficient green time, can be found by dividing the distance required to achieve terminal velocity by the average spacing of vehicles in the queue: N_2 = distance/spacing = $(V/2)(V/a)(1/D) = V^2/2aD$. Therefore, the time required for this vehicle (N_2) to clear the intersection is

$$t_{(N_2)} = C_1 + [(V^2C_2)/2aD] - C_2 + (V/a) \qquad (5)$$

As an example, if we let $C_1 = 1.9$, $C_2 = 1.4$, $V = 44$ ft/s, $a = 4.4$ ft/s^{-1}, and $D = 25$, then substituting these values in Equation 5 gives $t(N_2) = 22.82$ s. Thus, for green times in excess of 23 s, given the above constants, Equation 4 would be utilized. However, for green times in the range of 15-23 s, Equation 4 gives essentially the same results as Equation 2, and therefore the following discussion will be in terms of Equation 4, which carries the assumption that the traffic stream will reach the terminal velocity during the green phase.

Equation 4 can be expressed as a linear function of the form $t(n) = K + bn$, by setting $b = C_2 = D/V$ and $k = C_1 - C_2 + V/2a$. Then, by substituting the values given above, we get $t(n) = 2n + 5.5$. This can also be thought of as an expression for capacity. For instance, if an hour is divided into cycles of duration C (seconds) and green time of G (seconds), the hourly capacity of a lane of through traffic is

$$\text{Capacity} = (G - k)/b \times 3600/C = 1800\,[(G - 5.5)/C] \qquad (6)$$

Note that, if the green time is 100 percent of cycle time and cycle time is one hour (approximately free flow conditions), the lane capacity is about 1800 vehicles per hour, which seems about right.

Using Equation 6, the hypothetical hourly capacities for different signal splits and cycle lengths would be as shown in the table below.

Green Time (s)	Cycle Length (s) 60	80	100
30	735	551	441
40	1035	776	621
50	1335	1001	801

Turning to commercial vehicles, we can estimate their capacities given a homogeneous stream. In the next table, hypothetical acceleration rates to a terminal velocity of 30 mph are given for automobiles, single-unit trucks, semitrailers, and buses. Also shown are recommended maximum lengths (AASHO) and an estimate of spacing for each of several vehicle types.

Vehicle Type	Acceleration Rate (mph/s)	Maximum Length (ft)	Estimated Spacing (ft)
Auto	3.0	N/A	25
Single-unit truck	1.5	40	45
Semitrailer	1.0	55	60
Other combination	1.0	65	70
Bus	2.5	40	45

By using the table above, we can calculate the capacity coefficients for trucks and buses in the same form as automobiles. The next table gives the capacity coefficients by vehicle type.

Vehicle Type	Terminal Velocity - 30 K	b
Auto	5.50	1.97
Single-unit truck	10.50	2.42
Semitrailer	20.95	2.76
Other combination	20.95	2.99
Bus	10.50	2.42

By assuming that the ratio of green time to cycle length equals 0.5 and that cycle time is 60 s, the hourly capacities shown below are obtained.

	Hourly Capacity		Ratio of Autos to Trucks	
	Cycle Time		Cycle Time	
Vehicle Type	60 s	90 s	60 s	90 s
Auto	746	802	1.00	1.00
Single-unit truck	483	570	1.54	1.41
Semitrailer	197	349	3.78	2.30
Other combination	182	322	4.10	2.49
Bus	483	520	1.54	1.41

The above exercise points up the sensitivity of truck capacity to the assumed acceleration rate, which, of course, varies by truck size, load, and grade. Also, the ratio of auto to truck capacity gives a measure of equivalence ranging from 1.4 to 4.1, depending on truck size, acceleration assumed, and signal length.

Estimating the Capacity for Mixed Autos and Trucks

Weighted Capacities

In the last table above, hourly capacities for each vehicle type and two signal splits are shown. One way to estimate the capacity of a mixed stream would be to weight auto capacity by the proportion of automobiles in the stream and truck capacity by the proportion of trucks in the stream. For example, assuming truck capacity to be six per cycle and 90 percent of the traffic stream, weighted capacity would be 11.4 ($0.1 \times 6 + 0.9 \times 12 = 11.4$).

Converting to Auto Equivalents

Alternatively, since in the example above trucks have only one-half the capacity of autos, we could convert to auto equivalents by multiplying each truck by two. If we continue to assume twelve autos per signal cycle, we can calculate the vehicle capacity for different mixes. For example, a fifty-fifty split of autos and trucks would give eight vehicle equivalents for the four trucks and the four autos, or a vehicle capacity per cycle of eight.

Analysis of Queue Composition

By assuming that trucks are distributed in the traffic stream, the number of autos per truck can be obtained by the ratio of the proportion of autos to the proportion of trucks. Thus, any given proportion of trucks in the traffic stream can be thought of as a queue of vehicles containing one truck and P_A/P_T autos. To assess the impact of the presence of the truck on capacity, we need simply calculate the capacity for that queue for each of the different positions of the truck in the queue; the mean of those capacities is the average capacity for that mix.

For example, assume that the percentage of trucks is 10 percent. Then for every nine autos there will be one truck. If we calculate the capacity of the signal for each of the different positions of the truck in the queue and average these capacities, we will have the average capacity for a traffic stream with 10 percent trucks.

In Table 1 we have calculated the time in seconds for the queue to clear the intersection within 30 s under varying assumptions of the number of trucks in the queue. Note that, with a queue of six vehicles, all will clear even if all six are trucks. For seven vehicles, seven will clear if three or fewer are trucks. For eight vehicles, eight will clear when one vehicle is a truck or all vehicles are autos. For nine or more vehicles up to twelve in the queue, only all-auto queues will clear.

Table 1 has been converted to a capacity chart as shown in Table 2. The probability for any of the conditions in Table 2 can be calculated if the proportion of trucks in the traffic stream is known. For instance, assuming that 10 percent of all vehicles are trucks, the probability of four trucks in the queue of seven vehicles is $P_4 = (7!/4!3!)(0.1^4 \times 0.9^3) = 0.002\ 551\ 5$.

The probability for each of the outcomes in Table 2 has been calculated assuming that 10 percent of the traffic stream is trucks. These probabilities, when multiplied by the capacity (vehicles clearing the green phase) associated with each probability, yield the weighted average capacity. For Table 2 this is 9.14. Thus the presence of 10 percent trucks in the stream reduces capacity from 12 to 9.14, a reduction of some 24 percent.

Comparison of Methods of Estimating Capacity

The following table reveals that the two shortcut methods (methods 1 and 2 above) seriously understate the impact of trucks on capacity, especially for the higher travel percentages.

	Method of Adjustment		
Proportion of Trucks	Vehicle Equivalents	Weighted Capacities ($P_TC_T + P_AC_A$)	Presence of Truck in Queue
0	12.00	12.00	12.00
0.01	11.88	11.94	11.60
0.05	11.43	11.70	10.28

	Method of Adjustment		
Proportion of Trucks	Vehicle Equivalents	Weighted Capacities ($P_T C_T + P_A C_A$)	Presence of Truck in Queue
0.10	10.91	11.40	9.14
0.25	9.60	10.50	7.54
0.50	8.00	9.00	6.53
1.00	6.00	6.00	6.00

While it is true that, overall, traffic rarely contains 10 percent or more of those vehicles having sizes and acceleration characteristics that match our assumptions, truck routes commonly carry high percentages of heavy trucks. Even when only 5 percent of the traffic is trucks, a reduction of 14 percent in capacity would be expected. Yet, the two alternative techniques show only a 3-5 percent reduction in capacity. Therefore, for any careful analysis of truck impact on capacity, the queue analysis for capacity impact analysis would be recommended.

It would be possible, however, to use an equivalency table to approximate this capacity impact. The number of vehicles in a mixed queue that can clear a given amount of green time can be approximated by knowing the proportion of trucks in the stream, the capacity of autos, and the capacity of trucks. In our example above we can calculate such an equivalency table as mixed capacity = capacity of autos/proportion of autos + proportion of trucks.

Auto Capacity of 12 and Truck Capacity of 6

Proportion of Trucks	Value of K
0.01	4.448
0.05	4.346
0.10	4.129
0.25	3.366
0.50	2.675
1.00	2.000

From the table above for 10 percent trucks, we have $9.14 = 12/(0.9 + 0.1K)$; $K = 4.129$. We have calculated the K values for the truck proportions used in the previous table.

It would be possible to generate a series of tables that give the equivalency as a function of signal green time, auto and truck acceleration and spacing assumptions, and terminal speed. The user would then be able to use the same capacity restraint mechanism he or she now uses but with trucks properly weighted.

Table 1. Time for nth vehicle to clear intersection.

Number of Vehicles in Queue	Number of Trucks in Queue: 0	1	2	3	4	5	6
6	17.8	24.6	25.8	27.0	28.1	29.1	30.0
7	20.0	27.0	28.2	29.3	30.4		
8	22.0	29.4	30.5				
9	24.0	31.75					
10	26.0						
11	28.0						
12	30.0						
13	31.9						

Table 2. Intersection capacity for 30 s with different queue lengths and proportions of trucks.

Number in Queue	Number of Trucks in Queue	Number of Vehicles Able to Clear in 30 s	Probability Assuming 10 Percent Trucks in Traffic
7	4 or more	6	0.003
8	2, 3, or 4	7	0.184
8	1	8	0.383
9	9th vehicle 1st truck	8	0.043
10	10th vehicle 1st truck	9	0.039
11	11th vehicle 1st truck	10	0.035
12	12th vehicle 1st truck	11	0.031
12	0	12	0.282

CONCLUSIONS

These calculations have led to the following conclusions:

1. Separate but concurrent assignment of the truck origin-destination matrix over the highway network and retention of the link truck volumes is desirable for many subregional and neighborhood planning problems;
2. Provision for a truck network designation is desirable so that truck routes or truck prohibitions or both can be considered in the assignment process;
3. As a minimum, trucks should be divided into light or auto-like trucks and heavy trucks;
4. Even a small proportion of trucks in the traffic stream can result in substantial reduction in street capacity (this capacity reduction, however, is not a simple linear reduction proportional to the percentage of trucks in the vehicle stream); and
5. The reduction in capacity from trucks in the traffic stream can be represented by a straightforward algorithm that weights trucks differentially according to their proportion in the traffic stream.

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