HOV LANE EFFECTIVENESS

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It is widely believed that HOV (or "carpool" or "Diamond") lanes will provide more effective use of our overloaded freeways. The idea is that by providing a carpool-restricted lane in which traffic is relatively free flowing, there will be a time saving incentive for drivers to form more carpools; ridesharing will remove cars from the road, person carrying capacity will be increased, and congestion and polluting emissions reduced.

But this simple hypothesis overlooks several potentially more significant adverse effects of the lanes. Surprisingly, with all that has been written about HOV lanes, there has been no proof of their effectiveness. The belief in carpool lanes is driven by intuitive faith *that they will work, not demonstrated or proven performance.*

This report presents a comprehensive carpool lane evaluation based upon actual traffic data for the SR-55 and well established estimates of the elasticity of carpool formation as a function of HOV lane time-saving. The result is the net change in freeway person carrying capacity due to the HOV lane vs unrestricted mixed-flow operation of the lane. We find that for this case, the loss due to necessary lane emptiness far exceeds the gain due to the new carpools formed to take advantage of it. The overall effect is a net capacity loss of 11,000 persons per day or 40% of the potential lane capacity. Extending this result to the planned 1536 lane-mile greater Los Angeles area HOV lane network, the savings by converting that network to mixed flow are estimated equivalent to 614 lane miles of additional freeway capacity, representing a replacement value of $5 billion and generating an annual savings in cost of congestion-lost-time of nearly $1 billion per year.

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PART I: CARPOOL LANE CAUSE AND EFFECT

Choosing to operate a freeway lane as HOV introduces a host of different effects. Some are beneficial to overall traffic, some adverse. These effects extend over not only the carpool lane but the entire freeway and indeed the whole transportation corridor of which the freeway is a part. In order to make a comprehensive assessment of overall *net* benefit it is important first to have a clear understanding of the extent, structure, and relationship of these effects. Much misunderstanding of carpool lane performance has been due to failure to establish such a clear understanding at the outset.

One clear way to sort this out is the *sequential* analysis suggested by Professor Adolph May at ITS Berkeley[1]. In this, the results of changing a lane from regular to carpool-only designation are envisioned as occurring separately in time, so that their effects on capacity can be tracked and accounted for individually. Of course it is not necessary that the events described actually do occur separately as assumed. This is only a *visualization* aid to understanding the differences that *would* occur between the two alternatives. It is a thought experiment, in which we carry out an A-B comparison test by changing A to B, and follow the various effects closely in time. Accordingly we define the following phases:

Phase 1. Pre-carpool lane Baseline: This establishes the regular mixed-flow freeway "baseline" for the experiment. For a specific example we assume the following typical pre-existing (ambient) conditions are determined:

Number of Lanes (per direction):	4
Overall Average Vehicle Occupancy (*AVO*):	1.20
Average Occupancy of High-Occupant Vehicles:	2.2
High-Occupant fraction of Vehicles:	0.166*
Ridesharing Person Fraction:	0.305*
Flow, Vehicles per hour per lane:	1800
Number of vehicles High-Occupant:	1200
Persons per hour per lane:	2160

* Relationships derived in Appendix 1

Congestion is assumed at or slightly past saturation, i.e. level "E" to "F" that is, saturated or worse. (otherwise a carpool lane probably would not have been implemented).

Now, one lane is restricted to carpools only. The carpool threshold, that is, the number of occupants required to qualify, is set as low as possible to afford relative free-flow conditions to the carpool lane, in this case, two or more.

Phase 2. Immediate: Single occupant and multi-occupant *diversion* occurs between lanes and sidestreets. Pre-existing, carpools from other lanes and sidestreets divert to the carpool lane to take advantage of its better speed. Most single occupant vehicles divert from the lane to obey the law. By definition, *no new "benefit" carpools have yet had time to form due to the carpool incentive.*

Three things have now happened all of which are *detrimental* to overall capacity and congestion;

1. The carpool lane is relatively empty, carrying fewer vehicles than was the average lane, pre-carpool.

2. That capacity deficiency is forced on the other lanes. Under the assumed super-saturated conditions this means that both speed and flow in the other lanes are *less* than pre-carpool, phase 1.

3. Weaving of multi-occupant vehicles across the freeway to access the preference lane causes further congestion and loss of capacity.

Each of these effects represent real loss of *capacity* (see Appendix 2). By definition of the phase, no new carpools have had time to be formed so there are no offsetting benefits. So the net effect is a loss of overall vehicle capacity and increased overall congestion. Further, since no new carpools have yet been formed, the Average Vehicle Occupancy is unchanged,

> *Therefor, the person capacity is adversely effected in exactly the same adverse ratio as the vehicle capacity.*

At this stage almost all of the assumed 17% multi-occupant vehicles will have diverted to the carpool lane. Under the preexisting conditions assumed above, the carpool lane is now carrying 1200 vph and 2640 persons per hour while the mixed flow lanes are carrying only 2000 persons per hour. Thus it is possible accurately to report that,

> *"The carpool lane is now carrying more than 1.8 times as many people as a mixed flow lane"*

even though the *freeway as a whole has significantly less person and vehicle capacity, and is more congested* than pre-carpool. This is no contradiction and occurs because the occupancy *enrichment* of the carpool lane, is offset by an even larger occupancy *depletion* of the mixed flow lanes. The fact that all the high occupant vehicles have been induced into the same lane, and that the lane is now carrying more persons is not only irrelevant, but counter-indicative of what is happening to the freeway or corridor as a whole.

Yet, the above statement (with insignificant number variations), ignoring the adverse effects on the other lanes, is generally put forth as the principal simplistic "proof" of the effectiveness of carpool lanes and the main foundation of carpool lane acceptance. The Institute of Transportation Engineers has in fact published a special report on the subject of "The Effectiveness of High Occupancy Vehicle Facilities"[2] in which this misleading statement is the *only* effectiveness "proof" offered. To think that this observation in any way proves or even implies HOV effectiveness is a serious logical error.

Phase 3. Long Term: Eventually (with time measured in months) more new, *"benefit"* carpools are formed to take advantage of the time saving incentive. Under the above listed baseline assumptions, on the average, every 2.2 such new ridesharrers form a carpool, ride in 1 car instead of 2.2 and thus remove 1.2 cars from the road. The reduced vehicle capacity remains unchanged but, there is now increased person-carrying capacity and reduced congestion as compared to Phase 2.

> *If, and only if, the additional capacity made available by these new `benefit' carpools exceeds that lost in Phase 2, person-carrying capacity will have increased , congestion, fuel usage, and pollution reduced, and the carpool lane can be called beneficial.*

The remainder of this report is devoted to the quantification and reduction of these factors to comparable terms so that the *net* ultimate effect on person capacity and congestion can be determined. Of the three adverse effects identified in Phase 2 only the "emptiness" effect can be evaluated at this time. The other two adverse effects will be ignored, thus biasing the estimates *in favor* of carpool lane performance, i.e., providing only an upper limit on carpool lane benefits (or a lower limit on their loss).

PART II:
ANALYSIS OF CAPACITY GAIN (LOSS)

CALIFORNIA SR-55 PERFORMANCE DATA (Phase 1)

The following analysis is illustrated with actual data for the northbound SR-55 Freeway on November 17,1989 . The California Department of Transportation (CALTRANS) chose the day and provided the vehicle counts and speed data.

Total vehicles per hour (VPH) flow, for the freeway, is graphed in *Figure 1*. Over the full congested period of the day, the average mixed-flow lane carried 21,131 vehicles vs. 11,167 for the carpool lane, a loss of 9,964 *vehicles* or 47% of a regular lane capacity. Note that the mixed-flow lanes are near saturation (flat-topped) congestion all day while the carpool lanes are relatively empty during the morning.

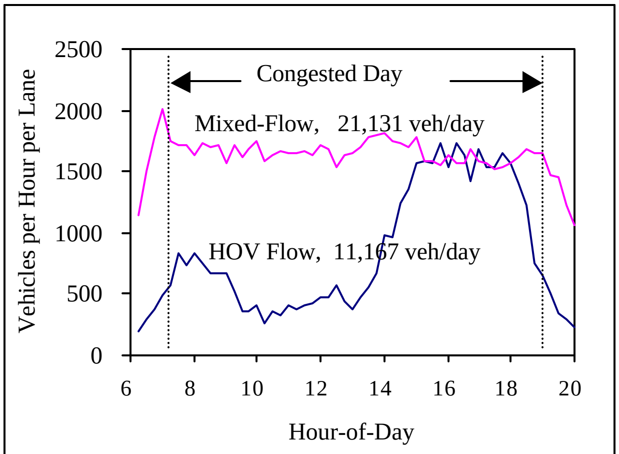
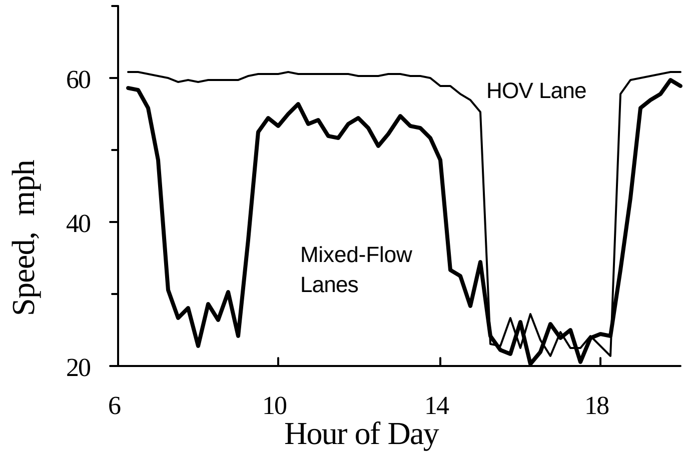


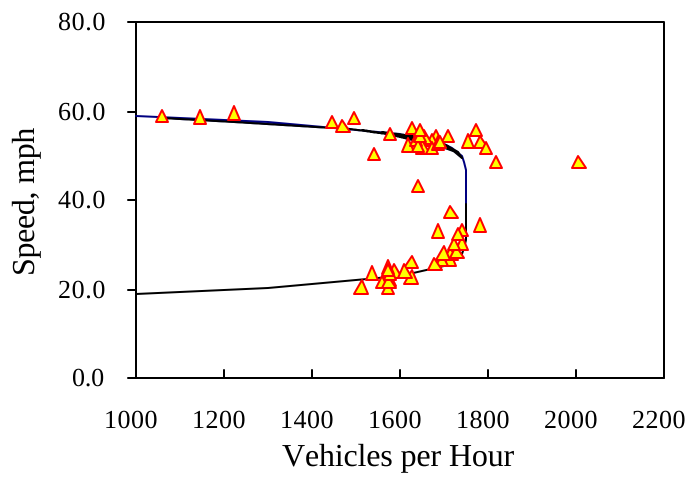
Figure 1. HOV vs MIXED Flow per Lane

Figure 2 graphs the speed versus hour of the day, given directly for the mixed-flow lane, and inferred from the traffic flow for the carpool lane. Note that mixed-flow lane speed approached free flow during midday but never quite reached it. That indicates sporadic, spontaneous, slow-down events typical of level of service (LOS) E or F, defined by CALTRANS as "unstable flow, maneuverability extremely limited, and some momentary stoppages". In the afternoon hours the carpool lane becomes as congested as the mixed flow lanes and the speeds are essentially the same.



<u>Figure 2. HOV & Mixed-Flow Speed</u>

In Figure 3, each 15 minute SR-55 traffic period was used to plot a point on the speed-flow scatter plot. The curve's unique shape depends on the overflow *versus* speed characteristics of the surrounding streets traffic, not just the freeway traffic. This relationship is used to project carpool lane velocities from flow, since, unfortunately, they were not measured directly.



<u>Figure 3. Speed vs Flow</u>

MEASURING THE LOSS DUE TO LANE EMPTINESS (Phase 2)

The first part of the carpool lane gain/loss balance sheet is given directly by the traffic count data. Over the entire congested day, 7am to 7 pm, the carpool lane, in this particular day, carried 9,964 fewer vehicles than the average mixed flow lane. Since the pre-carpool lane or overall Average Vehicle Occupancy is very nearly 1.26 persons, this corresponds to an initial person capacity loss, prior to new carpooling, of (1.26 x 9,964 =) 12,554 persons per day. This is the person capacity loss through Phase 2 of the sequential analysis outlined in Part 1 above. Now we have to take into account the effect of benefit carpooling.

ESTIMATING BENEFIT CARPOOLING

Estimating the amount of new carpooling attributable to the lane, that is "*benefit*" carpooling is a more subtle problem. New carpooling occurs all the time whether or not there is a carpool lane. Under steady state conditions, carpooling is an equilibrium process with old carpools dissolving and new carpools replacing them at about the same rate irrespective of the HOV lane incentive. These, along with the pre-existing carpools may be called the "ambient carpools". Their carpooling is in no way attributable to the HOV lane. It is a common mistake of carpool lane analyses to implicitly attribute all new or ambient carpools to the carpool lane and thus vastly overestimate its benefits. The extent of new "benefit" carpooling attributable to the lane incentive has been determined directly in only two cases of which we are aware. One of these is the work of Giuliano [6] which happens to have been done on the California SR-55 but several years earlier, and the other for the Katy freeway in Houston. Giuliano's work was based on extensive and carefully controlled driver questionnaires but may be of questionable applicability because of differences in time saving in the two-year span.. The Houston study was for an entirely incomparable type of HOV facility and did nothing to control for highly probable self-serving bias on the part of the respondents.

The best basis for estimating the benefit carpooling in this case appears to be the body of knowledge incorporated in several mathematical models [Refs.1,3,4] of modal choice. These are empirical models, derived from extensive empirical data bases, predicting the modal split, that is the fraction of commuters who will choose various transportation modes such as drive alone, carpool, train, bus, etc, as functions of a number of explanatory variables including: travel time, automobile ownership, availability of alternate travel modes, distance to work, income level, etc. For the most part, these models used the "multi-nominal logistic" equation as a general mathematical format. This is an expression of the form:

$$P_i = \frac{\exp\left[\sum_j C_{i,j}\ Q_{i,j}\right]}{\sum_k \exp\left[\sum_j C_{k,j}\ Q_{i,j}\right]} \qquad (1)$$

In this equation,

P_i = the fraction of travelers choosing mode, i (e.g. carpooling, driving alone, etc.)

$Q_{i,j}$ = various explanatory variables such as travel time, income, number of cars owned, fare, tolls, etc. for mode i.

$C_{i,j}$ = coefficients, determined by appropriate fitting procedures based upon extensive empirical databases involving all these quantities.

For changes, say ΔT, in just one of the $Q_{i,j}$, due to carpool lane travel time saving for a carpooler (i = "c"), this complex equation simplifies to

$$P_c^1 = \frac{P_c^0 \exp(C_{c,t}\Delta T)}{1 + P_c^0\left(\exp(C_{c,t}\Delta T) - 1\right)} \quad (2)$$

Further, for small changes (which will usually be the case), to adequate accuracy, this can be approximated by the first term in a Taylor's series expansion in ΔT:

$$\Delta P_c = P_c^0 (1 - P_c^0)\, C_{c,t}\, \Delta T + \cdots \quad (3)$$

where

P_c^0 = the pre carpool-lane ridesharer fraction (about 0.3)

P_c^1 = the post carpool-lane ridesharer fraction

ΔT = the time saving by using the carpool-lane, minutes,

$C_{c,t}$ = the empirically determined coefficient of carpooling utility with respect to time savings.

Three determinations of $C_{c,t}$ are available:

Author	$C_{c,t}$	$K=P_c^0(1-P_c^0)C_{c,t}$ assuming P_c^o=0.30	
May [1]	0.023/min	0.0048/min	(used in FREQPn)
Cambridge [3]	0.015/min	0.0032/min	(used in LARTS)
Harvey [4]	0.024/min	0.0050/min	

This is remarkable agreement, considering these coefficients were derived from independent databases.

We will use a $C_{c,t}$ coefficient of 0.021/min and corresponding K = 0.0045 as an average. This means that a ten-minute savings would be expected to produce a total ridesharer increase of 4.5% of the persons on the road. At least one other study confirms this: In 1988 when the SR-55 carpool lane was providing a ten-minute time savings over its 11 mile length at peak traffic hour [5], Giuliano [6] found the carpoolers attributable to the carpool lane during the peak hour to be 4% of the total travelers.

The time saving, ΔT for equation 2 is then given by:

$$\Delta T_{hr} = \frac{D}{S_{hov}} - \frac{D}{S_{mf}} \quad (4)$$

with the speeds for the carpool and Mixed-Flow lanes, S_{hov} and S_{mf} as shown in Figure 2. Here, the distance, D, should be taken as the smaller of either the carpool lane length or average freeway commute distance. For the case of the 55 freeway, these are both about the same; we use D =11 miles. In applying equations 2 and 3 we assume that the commuter carpooling candidates normally travel the freeway at about the same hour every day and are therefor influenced and motivated by the time savings at that particular hour. This means we can do an hour-by-hour benefit carpool assessment.

PERSON CAPACITY RESULTS

Figure 4 plots the hour-by-hour person capacity gain due to new benefit carpooling (equations 2 and 3) above and loss due to emptiness below the zero line. Over the full day, the benefit carpooling due to carpool time-saving incentive is estimated to have induced a 1,318 vehicle or 1,702 person gain due to benefit carpooling, to be netted against the loss of 9,964 vehicles or 12,455 persons found above due to lane emptiness. The net loss is about 40% of lane capacity whether measured in persons or vehicles. Person capacity gain here is the *new* AVO times the vehicle capacity gain, all evaluated as explained in Appendix 1.

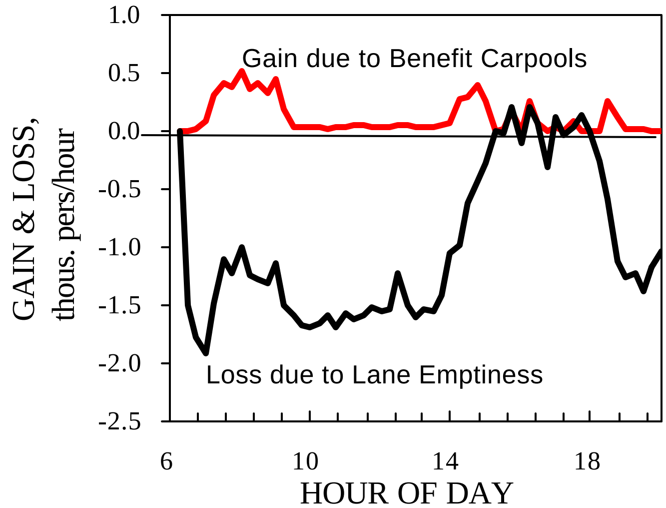


Figure 4. HOV GAIN & LOSS

The hourly pattern is interesting. This consists of two small peaks, one in the morning peak hour and one at the beginning of the afternoon peak hour. As the afternoon peak jam develops, however, the carpool lane also becomes saturated and offers no time saving advantage over the mixed-flow lanes. Commuters travelling in these hours are offered no time savings. There is essentially no carpooling incentive, and correspondingly, by equation 2, no benefit carpooling. Notice that on the day-round basis, the loss due to lane emptiness, is almost ten times greater than the gain due to cars removed from the road by the benefit carpools.

Finally, Figure 5 plots the hour-by-hour ***net*** person Gain(Loss), which is simply the difference of the two curves in Figure 4. Over the congested 12-hour day, the net result of the carpool lane is a loss of 10,753 persons per day or 40% of potential lane capacity.

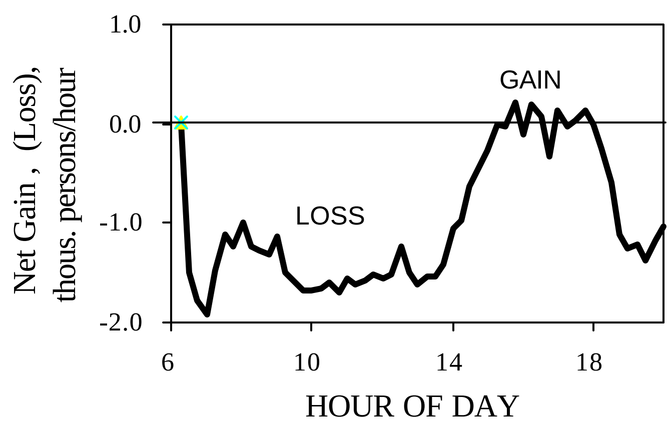


Figure 5. HOV Net Gain by Hour

PART III.
THE COST OF WASTED CAPACITY

Having found the net effect of the northbound 55 carpool lane to be a capacity loss of about 40% of a freeway lane, the question naturally arises, "What does this mean? How important is it? Is this significant or inconsequential?" We need to attach a *cost* to this presently wasted capacity. Fortunately a relevant means exists for doing so.

Based on the Texas Transportation data and pioneering investigations, [7, 8] reference [9] derives a congestion index, MCI, basically a regional volume to capacity ratio, V/C which can be calibrated to yield a usefully accurate estimate of regional congestion delay and cost. This calibration is shown in Figure 6. The data support a simple linear approximation for congestion time-delay (minutes per mile) as a function of MCI, the regression line shown, the equation for which is :

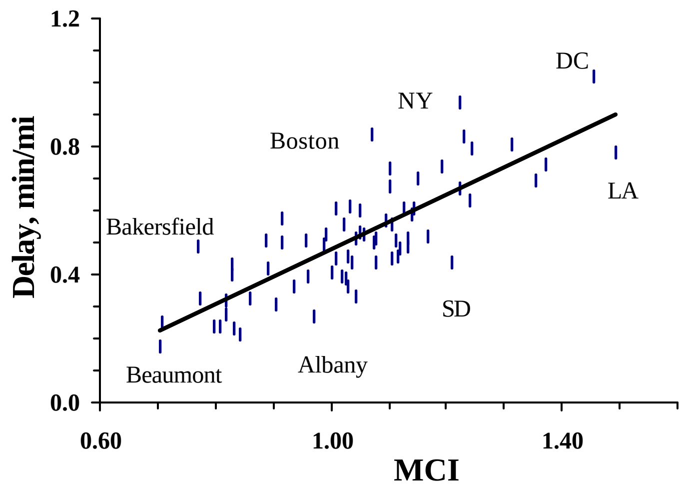


Figure 6. Congestion Delay vs MCI

$$D_{min/mi} = 0.86\ MCI - 0.38 \qquad (5)$$

where

$$MCI = V/C \qquad (6)$$

V = total regional traffic volume imposed on congesting roads, person-miles/day

C = total regional capacity, person-miles/day
= 13,000 AVO FLM + Other Terms for arterials, toll roads, etc., irrelevant to the present study.

FLM = Freeway Lane-miles

AVO = Average Vehicle Occupancy persons/vehicle

Then given a value of time, VOT, $/person-hour the total annual regional cost of congestion time-delay, RC, is

$$RC = V \quad VOT \quad AVO \quad D \quad 250/60 \ (\$/yr) \qquad (7)$$

(TTI data [8] uses 250 working days per year)

Finally, given a relatively small increment of freeway lane-miles, ΔFLM , the corresponding savings of regional cost of congestion is

$$\Delta RC \quad = 250/60 \quad V \quad VOT \quad AVO \quad \frac{d\,D}{d\,FLM} \quad \Delta FLM \tag{8}$$

$$\Delta RC \quad = -(0.86 \;\; 13{,}000 \;\; 250/60) \quad VOT \quad AVO \quad MCI^2 \quad \Delta FLM \tag{9}$$

Following TTI [8] we assume VOT = $12.00 per person-hour, and AVO = 1.25, then

$$\Delta RC \;=\; -\,\$699{,}000 \quad MCI^2 \quad \Delta FLM. \tag{10}$$

For the Los Angeles urbanized area (1996), MCI = 1.49, each added lane mile of effective freeway capacity produces an average congestion time-delay savings of $1.6 million per year. The SCAG (Southern California Association of Governments) year 2020 plan for this area (which includes Orange County) calls for 1536 lane miles of HOV [Ref. 11]. If for the sake of this example we assume that the average capacity loss due to the HOV lane is the same 40% found for the Orange County example treated earlier, then by converting those lanes to regular, unrestricted mixed-flow we would recover some 614 lane miles of effective freeway capacity, having a replacement cost of about $5 billion, and producing an estimated annual saving in cost of congestion of

ΔRC = $952 million per year.

Assuming 3.5% real interest (relative to inflation) and 40-year lifetime, the capitalization or present value of that revenue stream would be worth $20.3 billion (constant 1996 dollars).

This is the estimated value in terms of potential travel-time savings of presently wasted HOV lane capacity, which could be recovered at negligible cost by simply converting the entire Los Angeles HOV lane system to mixed flow.

PART IV
CONCLUSIONS and RECOMMENDATIONS

CAPACITY

1. A comprehensive methodology has been developed for calculating the net person and vehicle capacity gain(loss) attributable to a carpool lane. This methodology takes into account both the initial loss of capacity (vehicle and person) that occurs just due to the traffic diversion, and the subsequent recovery of person capacity as new carpools are formed to take advantage of the time savings offered by the lane.

2. The methodology is illustrated with available traffic count data for the northbound SR-55 freeway carpool lane on November 17, 1989. Over the full daily congested period, the estimated net effect of the carpool lane is a ***loss*** of capacity equivalent to 40% of the potential lane capacity, whether measured in persons or vehicles.

3. The results do not take into account two other identifiable losses of capacity due to the HOV lane, the added congestion due to forced weaving to access the lane and the further loss

of capacity that results from imposing further traffic demand on the already super-saturated mixed-flow lanes. Thus the estimates of overall loss of capacity and cost of congestion due to the lane can only be stated as lower limits.

4. Overall, and except for a very brief transient effects during peak congestion, these results indicate that this carpool lane is strongly counterproductive to the aims of increased person carrying capacity, reduced congestion, fuel usage, and air pollution.

ECONOMIC CONSEQUENCES

5. The Texas Transportation Institute study [7, 8] provides a sound basis for estimating the economic benefit of incremental increases of freeway capacity, including not only the lost time saved on the freeway, but the indirect effects on sidestreets, accident rates, and insurance costs.

6. For the Los Angeles urbanized area, each added or recovered lane-mile of freeway produces a congestion-time-delay saving worth $1.6 million per year.

7. If the average HOV lanes inefficiency in Los Angeles is similar to that found in the Orange County example, converting the greater Los Angles planned 1536 HOV network to unrestricted mixed-flow would yield an effective additional capacity equivalent to about 614 lane-miles of freeway, having a replacement cost $5 billion and yielding an annual congestion-time-delay saving worth $1 billion per year.

RELATION TO OTHER FINDINGS

8. These results agree generally with two earlier AJM analyses [9,10] one of which was for a different freeway system (Katy, Houston) and the other for the 55 freeway two years earlier. Both earlier studies used different data and different methodology for determining the gain in person-capacity due to the carpool lane induced modal shift to carpooling. Both also took into account the negative factor, the loss due to lane emptiness. In this latter respect, all three of these reports appear to be unique.

9. How can these results be reconciled with the widespread belief of the transportation community that carpool lanes do work? Believe it or not, these results are not contradicted by, nor comparable to ***any*** other published carpool lane performance analysis results. To the best of my fairly complete knowledge of such publications,

> *no other published real data performance analysis results nationally, has addressed, much less evaluated, the overall **net** gain (or loss) of person or vehicle capacity or the net effect on congestion or pollution due to the carpool lane, taking into account the loss of person capacity due to the necessary emptiness of the lane.*

10. All of the many success claims that have been published with respect to carpool lane actual performance appear to be based upon just four prototype half truth "plausibility indicators" or “pseudo-proofs” that do not prove or even directly claim to prove its effectiveness, but simply, superficially, and misleadingly imply it. These four misleading "plausibility indicators" are discussed and analyzed in Reference [10].

11. An alternative complete approach to HOV effectiveness analysis is through theoretical traffic modeling. Reference [10] summarizes all eight known (to this author) cases where these modeling methodologies have directly or indirectly addressed the HOV effectiveness issue. With but one partial exception the findings are that HOV lanes are less effective than unrestricted lanes in terms of total travel-time, congestion, emissions, and energy consumption. An unweighted average of all these benefit measures over all the subject reports provides an HOV effectiveness factor of 0.31 relative to unrestricted mixed-flow lanes.

RECOMMENDATIONS

12. The results of this study and those of reference 9 strongly suggest that the present presumption that HOV lanes are more effective than unrestricted freeway lanes is almost always wrong. At the very least that default presumption as it exists in present law and regulation should be reversed. Unrestricted operation should be required unless a competent study shows otherwise in particular circumstances.

13 As has been shown herein, the economic consequences of wrong law and policy in this regard, while in the form of largely hidden cost-of-congestion, are nevertheless measurable in the *billions* of dollars. Further serious study of HOV lane effectiveness is warranted and essential. The essential outlines of such serious study have been put before the legislature in Assemblyman McClintock's AB2140 (1998) and AB44 (1999).

14. The principal requirements for the performer of such a study include

- The independence to be able to report findings sharply contrary to the transportation community orthodoxy and to federal funding policy.
- The technical competence to resolve an operations analysis problem of some subtlety.
- The authority to command attention to results that may sharply contradict present law and policy.

PART V: APPENDICES

APPENDIX 1. CARPOOLING ARITHMETIC

Let

NP = Number of Persons using freeway

NV = Number of Vehicles using freeway

NR = Number of Ridesharers (i.e. multi-occupant vehicle occupants)

NV = Number of Vehicles

$NMOV$ = Number of Multi-Occupant Vehicles

AVO = Average Vehicle Occupancy = NP/NV

$AVOM$ = Average Occupancy of Multi-Occupant Vehicles = $NR/NMOV$

$RSPF$ = Ridesharers Fraction of Persons = NR/NP

$MOVF$ = Multi-Occupant Vehicles Fraction of Vehicles = $NMOV/NV$

These are related as follows:

$$NR = NV\ MOVF\ AVOM$$

$$AVO = 1 + (AVOM - 1)\ MOVF$$

$$RSPF = (AVOM\ MOVF\ NV)/NP = (AVOM\ MOVF)/AVO$$

For Typical Numerical Example:

$$MOVF = .2$$

$$AVOM = 2.3$$

then

$$AVO = 1.260$$

$$RSPF = 0.365$$

If ridesharing is increased to RSPF + ΔRSPF, with the average occupancy of each multi-occupant vehicle, AVOM remaining constant, then

$$\Delta NR = NP\ \Delta RSPF$$

$$NMOV' = NMOV + \Delta NR/AVOM$$

$$NSOV' = NSOV - \Delta NR$$

$$NV' = NV - \Delta NR\ (1 - 1/AVOM)$$

$$= NV - NP\ \Delta RSPF\ (1 - 1/AVOM)$$

$$= \quad NV \{1 - AVO\ (1 - 1/AVOM)\ \Delta RSPF\}$$

$$AVO' = NP/NV' = NP/(NV - NP\ \Delta RSPF\ (1 - 1/AVOM))$$
$$= \quad AVO/(1 - \Delta RSPF\ (1 - 1/AVOM))$$

$$MOVF' = NMOV'/NV'$$
$$= (NMOV + NP\ \Delta RSPF/AVOM) / (NV - NP\ \Delta RSPF\ (1 - 1/AVOM))$$
$$= (MOVF + AVO/AVOM\ \Delta RSPF) / (1 - AVO\ (1 - 1/AVOM)\ \Delta RSPF)$$

The effect of the change in ridership may be expressed as a change in *either* vehicle or person capacity. The increase in vehicle capacity is just the reduction in vehicles on the road, that is

$$\Delta VC = NV-NV'$$
$$= NV\ AVO\ (1 - 1/AVOM)\ \Delta RSPF$$

For example, with the above baseline numbers, a 4.5% (0.045) increase in ridership fraction, RSPF, would yield a 3.20% increase in vehicle capacity. Alternatively, if that available capacity were filled at the new AVO', the corresponding increase in person capacity would be

$$\Delta PC = \Delta VC\ AVO'$$
$$= NP\ AVO\ (1 - 1/AVOM)\ \Delta RSPF / \{1 - (1 - 1/AVOM)\ \Delta RSPF\ \}$$

For the example this yields a 3.28% increase in person capacity. These relations are used in the text to calculate the effect of ridership increase.

APPENDIX 2 DEFINITION OF CAPACITY

The term "capacity" is used herein exactly as defined in the Transportation Research Board, "Highway Capacity Manual":

> "The *capacity* of a facility is defined as the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway <u>under prevailing roadway, traffic, and control conditions</u>" (emphasis added).

Note that *control conditions* are a part of this definition. If you impose a control condition restricting a lane to, say, purple cars, you restrict its *capacity* as defined. Similarly an HOV restriction that results in reduction of lane volume is a reduction in lane vehicular capacity. If under prevailing conditions a lane is supersaturated and carrying fewer vehicles than if it were not, then its *capacity* is likewise reduced. The reduction in flow resulting from all these effects reduces the roadway capacity in the defined sense as well as practically. In this paper we denote the *theoretical maximum* capacity under unrestricted conditions as "potential" capacity.

PART VI: REFERENCES

1. May, A., Okitsu, and Roden, "FREQP7 - A Freeway Corridor Simulation Model", pps. 85-94, ITS Berkeley, June 1980.

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