

THE EFFECT OF HEAVY VEHICLES ON SATURATION FLOWS AT SIGNALISED INTERSECTIONS

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SUMMARY

A major study of lane saturation flows at signalised intersections in Melbourne has been conducted by Monash University. An integral component of this study is an examination of the influence of various vehicles types on the rate of saturation flow. This paper provides a brief analysis of the magnitudes of through car equivalents and the factors that influence them.

The results have shown that within a heavy vehicle category there is a great range of performance characteristics between the various specific vehicle types and that a four-way classification system may be more appropriate.

The average through car equivalent for heavy vehicles reflects the levels of each type of vehicle in the entire survey. Heavy vehicle equivalents should be used with care because the underlying proportions of each vehicle type in the traffic stream has a significant effect on the magnitude of the heavy vehicle equivalent.

The through car equivalents for heavy vehicles were found to be influenced by the proportion of heavy vehicles in the traffic stream and also by slow moving vehicles at the front of the queue. Contrary to popular belief approach grade did not correlate well with the through car equivalents. The influence of turn radius on the through car equivalents for turning cars was found to follow a model similar to that used by SIDRA.

Analysis of these data is continuing in conjunction with other parameters that have been found to influence saturation flows at signalised intersections.

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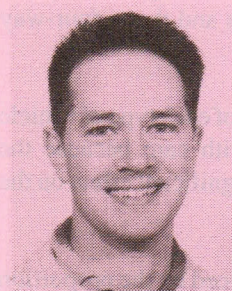
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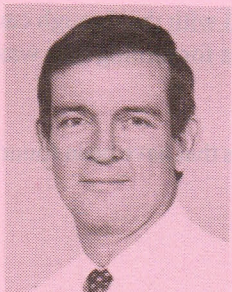
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SUMMARY

A study of the effect of heavy vehicles on saturation flows at signalised intersections is presented. The study was carried out at a signalised intersection in Melbourne, Australia. The results of the study are presented and discussed. The study shows that heavy vehicles have a significant effect on saturation flows at signalised intersections. The effect is more pronounced at intersections with a high proportion of heavy vehicles. The study also shows that the effect of heavy vehicles on saturation flows is more pronounced at intersections with a high proportion of heavy vehicles.



Andrew Cuddon graduated from the University of Melbourne in 1986 with an honours degree in Civil Engineering. He became involved with various transport related projects through part-time work with TTM Consulting Pty Ltd and his interests in traffic engineering continued on to a Masters degree. He has lived in London for 18 months and was employed as a Senior Traffic Engineer by JMP Consultants Ltd. In that role he worked on research projects for TRRL and was involved with the traffic modelling and planning for the London Docklands re-development. Andrew is currently a Ph.D. research student in the Department of Civil Engineering at Monash University where he is continuing his research into saturation flows at signalised intersections.



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INTRODUCTION

1. During the last two years a major study of lane saturation flows at signalised intersections in Melbourne has been conducted by Monash University. The project was initiated by the principal author at the University of Melbourne in March 1987, with a pilot study that concentrated primarily on the development of a suitable technique for the collection of large volumes of saturation flow data (Cuddon 1988; Cuddon and Bennett 1988). A small survey of through-only lane saturation flows was also performed to gain some insight into the variability of the data and the parameters that affect the saturation flows. This study will be referred to as the *pilot study* in this paper.

2. The major saturation flow data collection project was commenced in May 1990 with the principal author's commencement at Monash University. An integral component of this study was an examination of the influence of various vehicle types on the rate of saturation flow at signalised intersections.

OBJECTIVES

3. This paper briefly describes the data collection, analyses and preliminary results of the vehicle classification component of the saturation flow study. The primary objectives were to determine the through car equivalents for a more detailed vehicle classification system than the traditional system distinguishing only light and heavy categories and to investigate the traffic and geometric factors that affect through car equivalents.

VEHICLE CATEGORIES

4. Historically, saturation flow calculations have embodied only two vehicle classes: passenger cars and heavy (or commercial) vehicles. The most common Australian definition of these categories arose from Leong (1964) and Miller (1968) and was also reproduced in ARR 123 (Akçelik 1981) and SIDRA (Akçelik 1990). A heavy vehicle was defined as any vehicle with more than two axles or with dual tyres at the rear.

5. The use of only two vehicle classes for saturation flow studies is becoming increasingly less valid (Brown and Ogden 1988; Kimber, McDonald and Hounsell 1986; Molina 1987). Changes in heavy vehicle operating characteristics, the introduction of many smaller commercial vehicle types, and advancements in intersection layout and lane marking practice have all contributed to this phenomenon. Therefore, in addition to the heavy vehicle equivalents, analyses have been performed on a more detailed classification system.

6. Throughout the pilot study surveys it was acknowledged that the number of axles or wheels on a vehicle does not necessarily provide a good indication of its performance at a signalised intersection. A simple axle or wheel specification for vehicle classification is not definitive and some exceptions to the general rules were developed. The most important exception that has been introduced for this study is that light vans, whether they had single or dual tyres on the rear axle were considered as cars. In addition, the relatively small samples of motorcycles and buses required that they were incorporated

within the other vehicle categories. Motorcycles, when travelling within a lane (not between lanes), were grouped with passenger cars. Buses and coaches were grouped with rigid trucks. Based on all the considerations above the vehicle classification system shown in Table I was adopted.

7. All saturation headways have been classified according to vehicle and turn type involved. (Saturation headways were all headways after the fourth vehicle in the queue until the last queued vehicle crossed the stop line or the end of the green period was reached.) The example shown below is the set of headway types for a lane with a dual classification system consisting of CARs and type X vehicles (any vehicle/turn type other than CAR). A wider classification system, consisting of more vehicle types, will have a greater number of different headway types between vehicles and manoeuvres of each type.

C_C = CAR followed by a CAR

X_X = type X vehicle followed by a type X vehicle

C_X = CAR followed by a type X vehicle

X_C = Type X vehicle followed by a CAR

Table I

Vehicle Categories

CAR (Car)
Passenger Cars
Motorcycles
Light Vans (≤ 6 wheels)
LCV (Light Commercial Vehicle)
Light Trucks
Mini Buses
CARs towing a trailer
RIG (Rigid Truck)
Single Unit Rigid Trucks
Buses and Coaches
ART (Articulated Truck)
Semi Trailers
Truck towing a trailer
LTCAR (Left Turning CAR)
RTCAR (Right Turning CAR)
HV (Heavy Vehicle)
HV = LCV + RIG + ART

THROUGH CAR EQUIVALENTS

8. A vehicle category is essentially defined according to the number of passenger cars to which it is equivalent. Allowance must therefore be made for both the vehicle type and manoeuvre that is performed. This associates each vehicle making a given manoeuvre with a number of through car units (tcu) corresponding to an equivalent number of cars travelling straight through the intersection. Through car equivalents are employed in traffic signal analyses to enable saturation flow to be considered totally independent of the composition of the traffic stream. This ensures that a saturation flow value can be stated for a particular intersection geometry and environment without prior knowledge of the traffic composition.

9. Through car equivalents may be illustrated using the following formulae. For a traffic stream consisting of a number of vehicle and turn types a *traffic composition factor* is used to convert the saturation flow in through car units to vehicle units using eqn (1) below. The calculation of the traffic composition factor itself is shown in eqn (2).

$$S_{veh} = f_c S_{tcu} \quad (1)$$

$$f_c = 1.0 / \sum_{i=1}^{i=N} \rho_i e_i \quad (2)$$

where:

f_c	=	traffic composition factor;
e_i	=	through car equivalent for vehicle/turn type i (tcu/veh);
N	=	number of vehicle\turn categories in the traffic stream;
ρ_i	=	proportion of vehicles of type\turn i in the traffic;
S_{veh}	=	saturation flow in vehicle units (veh/h); and
S_{tcu}	=	saturation flow in through car units (tcu/h).

THE CALCULATION OF THROUGH CAR EQUIVALENTS

10. Through car equivalents may be calculated by a number of methods. However, the most common of these, the *headway ratio method*, as used by Scraggs(1964), Miller (1968) and Brown and Ogden (1988), was used for this study.

11. This procedure commences by examining the condition that Scraggs describes as the '*necessary and sufficient condition for the effect of a heavy vehicle to be independent of the type of vehicle preceding it and following it*'. This condition should be true if through car equivalents are to be calculated by the headway ratio method. It involves a comparison of the two sides of eqn (3) below where \bar{h}_{c_x} represents the average headway of a CAR followed by a type X vehicle. For those headway samples that do not exactly fulfil the independence condition a least squares technique is used to adjust the average headways on the basis of their relative sample sizes. Scraggs (1964) and Brown and Ogden (1988) explain these analyses in detail.

$$\bar{h}_{c_c} + \bar{h}_{x_x} = \bar{h}_{c_x} + \bar{h}_{x_c} \quad (3)$$

12. The through car equivalents are calculated from eqn (4), below. This is the *headway ratio method*. When there are more than two classes in the traffic stream the headways involving cars dominate so that eqn (4) can be used for each class of vehicle separately. The calculation of vehicle equivalents for each vehicle and turn type is performed by replacing the data for X_X headways by the average headway for any vehicle/turn type followed by a vehicle of the same type. Note that through car equivalents always compare the headways for a given vehicle type with cars travelling straight through the intersection.

$$e_x = \frac{\bar{h}_{x_x}}{\bar{h}_{c_c}} \quad (4)$$

where: e_x = through car equivalent for vehicle of type X;
 \bar{h}_{x_x} = average X_X headway; and
 \bar{h}_{c_c} = average C_C headway.

DATA COLLECTION

13. The saturation flow project has involved the collection of generic real-time data for each vehicle as it crosses the stop line, the traffic signal changes, and the end of the saturated portion of each green period. The choice of data collection technique was based on the results of the pilot study (Cuddon 1988; Cuddon and Bennett 1988). That study concentrated primarily on the development of a suitable technique for the measurement of large volumes of saturation flow data. The chosen measurement technique for the current project has incorporated a laptop personal computer to assist data collection by a single surveyor. Computer software, called SATFLOW, was developed to control real-time data input and to perform the saturation flow and headway analyses.

14. SATFLOW (Cuddon 1991) is **SAT**uration **FLOW** data collection and analysis software that assists and coordinates real-time data input and performs preliminary data checks and saturation flow/headway analyses. The software package was specifically written for this research project. However, it also has the potential for use outside this field because it collects generic real-time vehicle data that may be used to calculate many other traffic flow parameters.

15. Using this software, data were recorded by pressing a key on the laptop computer keyboard each time the rear-most axle of a vehicle crossed the stop line. This provided a headway definition that was consistent with other recent saturation flow studies and ensured that those vehicles at the head of the queue that stopped with their front wheels past the stop line were recorded during the green period in which they actually passes through the intersection. SATFLOW enabled vehicles to be classified and signal changes to be identified according to the key that was pressed. Data input was highly regulated so that most invalid keystrokes were not accepted as legitimate data.

16. Upon completion of data collection the SATFLOW analysis module was used to divide the raw data into individual green periods and to calculate the average saturation flow. The program also provided statistics on the headways classified by vehicle type, vehicle equivalents and saturation flow profiles by calculating the saturation flow in successive 5-second intervals during the green period.

RESULTS

PREAMBLE

17. Over a period of 18 months data were collected by the principal author for a total of 163 lanes at 71 sites throughout the Melbourne metropolitan area. The survey data comprised over 5000 green periods and resulted in the collection of in excess of 40,000 saturation headways.

18. Through car equivalent analyses were conducted for each of the vehicle types shown in Table I. Each vehicle type has been analysed for progression in the following lane types:

- (a) through-only lanes (TH);
- (b) exclusive left turn lanes (LT);
- (c) exclusive right turn lanes (RT);
- (d) combined through and left turn lanes (TL); and
- (e) combined through and right turn lanes (TR);

RAW HEADWAYS

19. Table II shows a summary of the raw (unadjusted) headways. These are the average of the lane values for those samples with at least two X_X headways. (The criterion of at least two X_X headways was to enable headway adjustment). Note that the number of lanes used to calculate each value varies significantly and in two cases only one lane of data was available.

Table II

Raw (unadjusted) headways

LANE TYPE	VEH TYPE	C_C	X_X	C_X	X_C	No. of LANES
TH	LCV	1.68	2.59	1.94	1.77	2
	RIG	1.72	3.08	3.17	1.95	11
	ART	1.63	3.88	4.83	1.91	3
	HV	1.70	3.42	3.29	1.88	17
LT	RIG	2.27	3.35	3.14	2.57	2
	HV	2.17	3.59	3.34	2.35	3
RT	RIG	1.90	3.41	2.91	2.03	1
	ART	2.07	4.81	5.24	1.93	1
	HV	1.82	2.93	3.13	1.89	7
TL	LTCAR	1.82	2.31	2.44	1.96	11
TR	RTCAR	1.83	2.16	2.25	1.95	4

Notes:

1. All headway units are s/veh.
2. Headways for LT and RT lanes involve turning cars (LTCAR, RTCAR) rather than through CARs.
3. When calculating averages equal weight was given to each lane.
4. CAR followed by CAR (C_C) headways vary between each lane and vehicle type because each value is the average of a different sample of lanes.

TESTING LHS/RHS EQUIVALENCE

20. To determine whether the difference between the two sides of the independence equation, eqn (3), was significant three hypothesis tests were performed. The three tests, performed at the 5% level of significance (LHS = left hand side, RHS = right hand side of eqn (3)) were to check:

Test 1: LHS = RHS; Test 2: LHS < RHS; and Test 3: LHS > RHS.

21. Overall, just slightly less than half (46%) of lanes passed Test 1 indicating that the independence condition is not always true. However, 46% of lanes passed test 2 also, indicating that for a majority of lanes it could not be concluded that the LHS was significantly less than the RHS. Test 3 was failed by almost all lanes (83%) indicating that on rare occasions only was the LHS greater than the RHS of the independence equation.

FACTORS AFFECTING INDEPENDENCE

22. The above tests indicate that the two sides of the independence equation can be considered equivalent. However, there are a number of situations where the condition is seriously breached and it would be interesting to know the circumstances under which the independence condition becomes violated.

23. Simple linear regressions have been performed with a number of traffic and geometric parameters against the error between the two sides of the independence equation to determine the factors that have an affect on the independence assumption.

24. It is evident that the size and performance of a vehicle affects the independence condition. A vehicle with a large effect on the capacity of the lane (in comparison with a passenger car) seriously breaches the independence assumption whereas a vehicle with a small effect on capacity is more likely to satisfy the independence condition.

25. A measure of a vehicle's effect on capacity is its through car equivalent. A simple linear regression between the percentage error between the two sides of the independence equation and the through car equivalent for heavy vehicles (e_{HV}) revealed an R^2 of only 0.4, however, the model trend was significant at the 1% level. The model produced by the regression analysis was:

$$\%ERROR = 41.7 - 20.6 e_{HV} \quad (5)$$

26. Most of the other combinations of vehicle and lane type also produced similar relationships between the percentage error and the through car equivalent, however, they displayed greater dispersion and less significant regression coefficients.

27. Numerous other parameters, such as the percentage of heavy vehicles and degree of saturation, were also regressed against the percentage LHS/RHS error. Although most of the models did not produce high R^2 values because of data scatter, the trends in the data were significant. In all cases there was an *ideal* parameter value at which the two sides of the independence equation were equal and any deviation from this ideal value caused the independence condition to become increasingly less valid.

28. For example, in a through lane with a proportion of heavy vehicles (%HV) of about 7.5% the independence condition was close to being true, however, proportions greater than this value forced the LHS to be less than the RHS and proportions less than the ideal value forced the LHS to be greater than the RHS. Therefore, for low concentrations of heavy vehicles the number of consecutive heavy vehicles is small and consequently the ability of consecutive heavy vehicles to reduce their overall effect is reduced. For consecutive heavy vehicles to have significantly less effect than isolated ones there is a

minimum proportion of heavy vehicles in the traffic stream: below this value the effect of heavy vehicles, compared to isolated ones, becomes very small.

29. These models imply that there is a set of optimum conditions under which the independence assumption is valid and any deviation from these conditions results in violation of the independence condition.

ADJUSTED HEADWAYS

30. Given that the independence condition is often violated the raw headways must be adjusted before through car equivalents can be calculated by the headway ratio method. Fig. 1 shows a plot of the adjusted against the unadjusted through car equivalent for each lane with at least two X_X headways. The difference between the unadjusted and the adjusted values varies significantly with the various vehicle and lane types. The size of the error also appears to be a function of the number of lanes of data used to calculate the through car equivalents. The greater the number of lanes of data the lower the magnitude of the error between the two through car equivalents. This was expected because with a greater number of lanes the unadjusted headways would be more accurate and representative of the population of headways and, if the independence condition is true for the underlying headway population, the difference between the adjusted and unadjusted through car equivalents should be less.

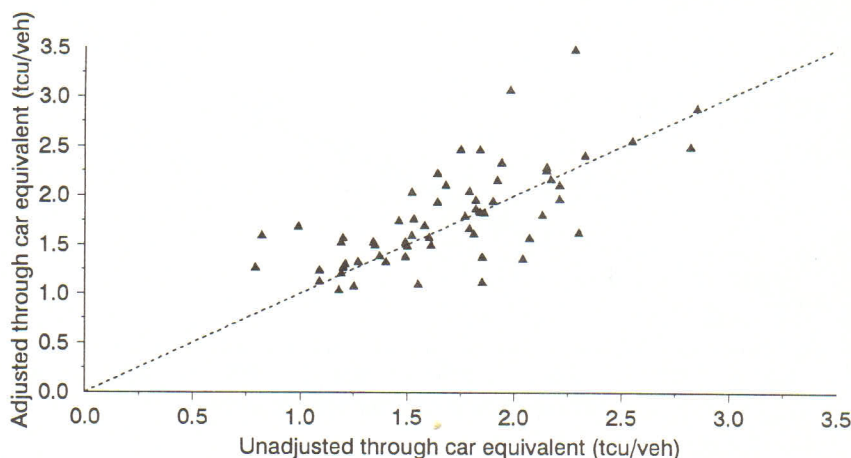


Fig. 1 Adjusted against unadjusted through car equivalents

INFERRED THROUGH CAR EQUIVALENTS

31. The average difference between the adjusted and unadjusted through car equivalents for the lanes with at least two X_X headways amounted to only 0.08 tcu/veh or 6.5%. This implies that adjusting the headways had only a minor effect on the calculated through

car equivalents. Therefore, if the independence condition is assumed to be true, and unadjusted rather than adjusted headways are used, the error is minimal.

32. Headway adjustment is, therefore, not of paramount importance and the stipulation of a minimum of two X_X headways can be removed. This enabled through car equivalents to be calculated for samples that, by chance, did not contain any X_X headways. This formula (eqn (6)) is derived from the headway ratio formula (eqn. (4)) and amounts to assuming that the independence condition (eqn (3)) is true. The values calculated from eqn (6) have been named *inferred* through car equivalents because they do not use X_X headways directly.

$$e_x = \frac{\bar{h}_{C_X} + \bar{h}_{X_C} - \bar{h}_{C_C}}{\bar{h}_{C_C}} \quad (6)$$

33. Fig. 2 below shows a plot of the adjusted against the inferred through car equivalents. The close relationship between the adjusted and inferred parameters enables the calculation of through car equivalents for many more lanes because the stipulation of a minimum sample of two X_X headways can be eased.

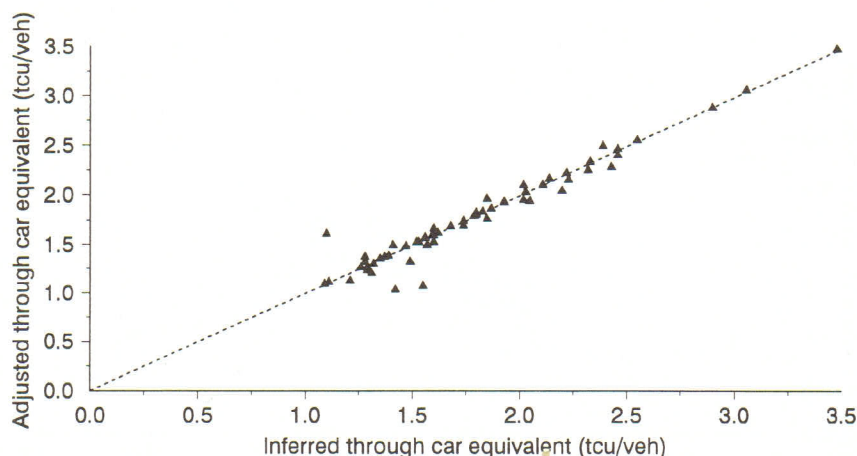


Fig. 2 Adjusted against inferred through car equivalents

RESULTING THROUGH CAR EQUIVALENTS

34. Table III shows summary statistics for the average through car equivalents for each vehicle/manoeuvre type. The data for lane samples with at least two X_X headways are adjusted through car equivalents and other lanes are inferred values if C_C, C_X and X_C headways were available.

35. There is significant variation in the through car equivalents for the vehicles that comprise the heavy vehicle category, with the values for articulated trucks being more than double those for light commercials and 50% greater than those for rigid trucks. i.e. For all lane types increased vehicle size and reduced performance characteristics (LCV→RIG→ART) resulted in higher through car equivalents.

36. The heavy vehicle category in the table combines light commercials, rigid trucks and articulated trucks into a single group. The through car equivalent for through heavy vehicles (1.65 tcu/veh) is significantly lower than the value of 2.00 that is often assumed. However, the new value is closer to the 1.85 tcu/veh that Miller (1968) originally calculated (but for simplicity he used 2.00 tcu/veh) and the value of 1.75 determined by Webster and Cobbe (1966) and 1.63 by Carstens (1971). If light commercial vehicles are included in the CAR category rather than in the HV class the value of the through car equivalent for heavy vehicles travelling straight ahead increases to 1.99 tcu/veh.

Table III

Summary statistics for lane by lane through car equivalents

LANE TYPE	VEH TYPE	No. of LANES	MAX	MIN	MEAN	STD DEV
TH	LCV	65	2.26	0.74	1.26	0.32
	RIG	66	2.88	0.67	1.77	0.45
	ART	14	4.82	2.52	3.22	0.60
	HV	85	2.55	0.72	1.65	0.42
LT	LCV	3	1.67	1.43	1.52	0.13
	RIG	4	2.04	1.37	1.79	0.32
	ART	2	2.86	2.44	2.65	0.30
	HV	5	2.01	1.52	1.79	0.20
RT	LCV	22	1.91	0.84	1.28	0.25
	RIG	20	3.74	1.08	1.81	0.53
	ART	10	3.18	2.40	2.75	0.22
	HV	29	2.46	0.95	1.70	0.32
TL	LCV	6	1.59	1.02	1.24	0.22
	RIG	5	2.51	1.36	1.81	0.43
	HV	8	2.33	1.08	1.51	0.43
	LTCAR	13	1.76	1.03	1.38	0.20
TR	RTCAR	5	1.26	1.07	1.16	0.08

Notes:

1. Units for TH, TL and TR lanes are tcu/veh.
2. Equivalents for LT and RT lanes are relative to turning cars (LTCAR, RTCAR) rather than through CARs. These values must be multiplied by the equivalents for left turning and right turning cars respectively to convert them to through car units.
3. The equivalents for LCV, RIG, ART & HV in combined TL and TR lanes are for through vehicles travelling in these lanes.
4. When calculating averages equal weight was given to each lane.
5. Lane samples with at least 2 X_X headways are *adjusted* values. Others are *inferred* through car equivalents.

37. Table IV shows a comparison between the new through car equivalents for the detailed classification system compared with those determined by Brown and Ogden (1988). On average the new through car equivalents are 12% greater than the 1988 values. The difference for cars and rigid trucks is small (less than 10%) but the new through car equivalents for light commercials and articulated trucks are significantly larger (difference is 48% for right turning light commercials). The discrepancy appears to be dependent on the reliability of each estimate. The mean through car equivalents for light commercials and articulated trucks were subject to more variation in both studies because of their relatively small sample sizes compared with those for cars and rigid trucks.

38. The discrepancy between the results for the two studies may also be a reflection of the differing traffic and geometric characteristics of the sites at which data were collected or the slight inconsistency in vehicle classification. In the Brown and Ogden study small vans were considered as light commercials whereas in the current study they were included in the CAR category.

39. Table V compares the through car equivalents for heavy vehicles in the current study with those used in SIDRA and those calculated by Brown and Ogden. Again the difference in the heavy vehicle equivalents between the two studies may be a reflection of the inconsistent classification systems, but is more likely due to differing levels of each vehicle type that makes up the heavy vehicle definition. For example, the Brown and Ogden value for through heavy vehicles may be greater than that for the current study because the proportion of articulated trucks for the former may be greater.

40. The SIDRA default values of through car equivalents provided in Table V assume that the left turns are *restricted* and the right turns are *normal*. The new through car equivalents for left and right turning cars are greater than the default values used by SIDRA, however, the new values for heavy vehicles are significantly less than the SIDRA defaults. Again, the difference may reflect the underlying traffic and geometric conditions for each data set. The following paragraphs discuss some of the parameters that have been found to influence the through car equivalents.

FACTORS AFFECTING THROUGH CAR EQUIVALENTS

41. Numerous simple linear models have been performed to determine the factors that influence through car equivalents.

Congestion and Traffic Conditions

42. Signal timing parameters such as green time and cycle time showed little correlation with the through car equivalents. Parameters such as degree of saturation and saturation flow, describing the traffic flow and congestion conditions, exhibited slightly better correlations but few were significant at the 10% level.

Table IV

Comparison of detailed through car equivalents with Brown and Ogden (1988)

	Brown & Ogden	Current Study
Through Lanes		
CAR	1.00	1.00
LCV	1.39	1.27
RIG	1.79	1.79
ART	2.46	3.21
Exclusive Left Turn Lanes		
CAR	1.27	1.38
LCV	1.43	1.78
RIG	2.13	2.30
ART	2.67	3.66
Exclusive Right Turn Lanes		
CAR	1.11	1.16
LCV	1.00	1.48
RIG	2.16	2.10
ART	2.87	3.19

All values are through car units

Table V

Comparison of heavy vehicle through car equivalents with other Australian data

	SIDRA	Brown & Ogden	Current Study
Through lanes			
CAR	1.00	1.00	1.00
HV	2.00	2.08	1.68
Exclusive Left Turn Lanes			
CAR	1.30	1.27	1.38
HV	2.60	2.44	2.22
Exclusive Right Turn Lanes			
CAR	1.00	1.11	1.16
HV	2.00	2.47	1.97

Notes:

1. All values are through car units.
2. The SIDRA values assume that left turns are *restricted* and right turns are *normal*.
3. Source: Akçelik (1990); Brown & Ogden (1988).

Vehicle Types

43. Interestingly, the best correlation for through car equivalents was obtained with the standard deviation of the headways in each sample. It has been shown that the variance of the headways is affected by percentage of heavy vehicles in the traffic stream (Cuddon 1988) and it appears that the through car equivalents, themselves, are correlated with the headway variance. This implies that the through car equivalents may be influenced by the proportion of heavy vehicles in the traffic stream. To examine this behaviour the percentage of each vehicle type in the traffic stream (neglecting the first four vehicles in each green period) was modelled with the its corresponding through car equivalent.

(a) Light Commercial vehicles, Rigid Trucks and Articulated trucks

44. The percentage of light commercial vehicles was not a significant factor for light commercial through car equivalents nor for heavy vehicle equivalents. The percentage of rigid trucks correlated well with the heavy vehicle equivalents but not the rigid truck data. Similarly the percentage of articulated trucks correlated well with the heavy vehicle equivalents and not the articulated truck values.

(b) Heavy vehicles

45. The percentage of heavy vehicles in the traffic stream produced a good correlation with the through car equivalents for heavy vehicles. The resulting model between the percentage of heavy vehicles (%HV) and the through car equivalent for heavy vehicles (e_{HV}) was:

$$e_{HV} = 1.52 + 0.03 \%HV \quad (7)$$

where both regression parameters were significant at the 0.1% level but the R^2 was only 0.11.

46. It was interesting that the percentages of rigid trucks and articulated trucks in the traffic stream affected the magnitude of the through car equivalent for heavy vehicles but not for rigid and articulated trucks respectively. In addition, the percentage of light commercials had little effect on any of the through car equivalents. The percentage of heavy vehicles in the traffic stream produced a significant correlation with heavy vehicle equivalents and the correlation was increased when the percentage of heavy vehicles discounted light commercials.

Heavy Vehicles at the Front of the Queue

47. During the saturation flow surveys it was observed that a heavy vehicle at or close to the front of the queue affected the flow of vehicles further along the queue because the slow accelerating vehicle disrupted the flow conditions immediately downstream of the intersection.

48. The best model describing this behaviour involved the percentage of heavy vehicles during the first 10 seconds of the green period. That is, the number of heavy vehicles to cross the stop line during the first 10 seconds divided by the total number of vehicles to cross the stop line during the green period. The percentage of heavy vehicles during the first 10 seconds of green (%HV10) produced a model with an R^2 of only 0.09, however the trend was significant at better than 0.1%. The resulting model is shown in eqn. 8.

49. Although these models show that through car equivalents are affected by slow vehicles at the front of the queue they are unlikely to be useful unless the distribution of heavy vehicles along the queue is known.

$$e_{HV} = 1.55 + 0.07 \%HV10 \quad (8)$$

Geometric Conditions

(a) Lane width and approach grade

50. Lane width was not a significant parameter when modelled with any of the through car equivalents. This is logical since lane width may influence passenger cars also and would, therefore, not affect the through car equivalents. It is often thought that approach

gradient affects heavy vehicles more than cars. However, the data displayed significant scatter and little correlation with the average percentage approach grade (between a point 50 m upstream of the stop line and the stop line itself.)

(b) Turn radius

51. A number of regression models were formulated to determine the relationship between the through car equivalent for turning cars (LTCAR, RTCAR) and the turn radius for each lane. These models were of the form used in SIDRA where:

$$e_{TURNCAR} = a + \frac{b}{r^c} \quad (9)$$

and,

$e_{TURNCAR}$ = through car equivalent for turning cars (LTCAR+RTCAR);
 a, b, c = regression parameters; and
 r = turn radius (along the swept path of the centre of the vehicle).

52. Because there was a large variation in the sample sizes used to calculate the through car equivalents the analyses were weighted by the number of C_X headways for each sample. This was chosen as the weighting variable because the through car equivalents were found to be very closely related to the average C_X headway. See Fig. 3.

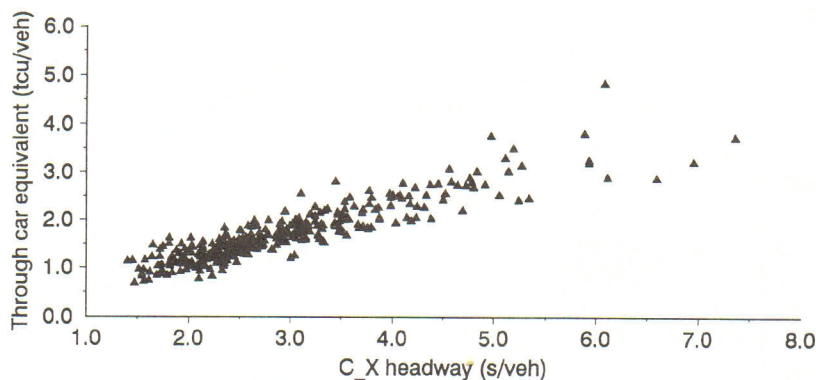


Fig. 3 Through car equivalents against average C_X headway

53. The 3 parameter non-linear model, eqn (9) (Model 1), was difficult to fit because the three coefficients were difficult to derive from a sample of only 18 data points so the value of coefficient 'c' was set at 3.0, the SIDRA default (Model 2). An additional model set the value of the parameter 'a' to 1.0 (Model 3) because it was expected that for large turn radii the through car equivalent for a turning car would approach that of a through car (1.0).

54. Table VI provides the resulting regression parameters along with the residual sum of squares (RSS) and the multiple correlation coefficient R^2 . The R^2 values were inflated because the weighting parameter replicated each data point by the number of C_X headways.

Table VI

Regression models for the effect of turn radius on cars

Model	a	b	c	RSS	R^2
1	1.11	53.91	2.58	12.27	0.98
2	1.12	120.03	(3.00)	12.32	0.98
3	(1.00)	178.86	(3.00)	15.11	0.97

Notes:

1. Values in brackets were fixed.
2. R^2 values are inflated because of weighting variable.

55. There was little difference in the residual sum of squares for models 1 and 2 so setting the value of 'c' to 3.0 appears to be reasonable. Fixing the value of 'a' to 1.0 (Model 3) had a greater effect on the model fit because for larger turn radii the data asymptototed to a through car equivalent greater than 1.0. Even so this model was an adequate fit to the data. The regression parameter 'b' was, however, 20 % higher than the SIDRA default of 150, but the difference may have been due to the small number of data points used.

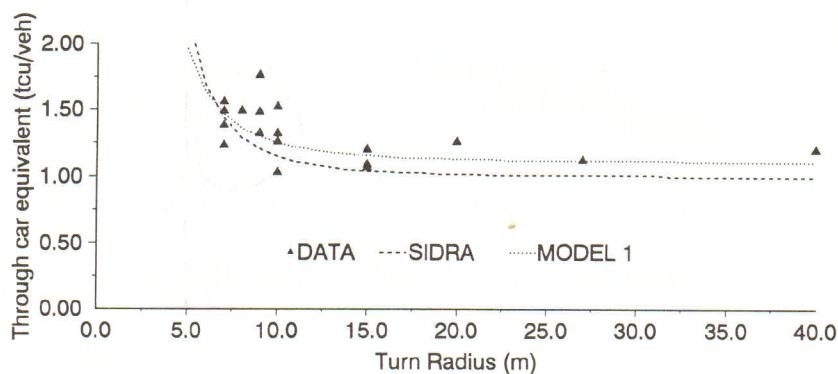


Fig. 4 Through car equivalent for turning cars against turn radius

56. The data clearly show that the influence of turn radius on turning cars follows the form of the model used in SIDRA. Note that the models show significant variation for small turn radii so the models should not be used for turn radii below about 6 m. In

addition, these models have been formulated on a limited number of lanes of data and no sensitivity analyses for the model parameters have been performed. Fig. 4 shows a plot of the through car equivalents for turning cars against turn radius with model 1 and the SIDRA default model also shown.

57. Data were not collected for turning heavy vehicles so the influence of turn radius on these vehicles could not be examined.

CONCLUSIONS

58. The independence condition that is a requirement for the calculation of through car equivalents by the headway ratio method is not always valid for raw headways. The error between the two sides of the independence equation was found to be a function of the proportion of heavy vehicles in the traffic stream and also the through car equivalents themselves. This implies that the size and performance characteristics of a vehicle affect the independence condition: a vehicle with a large effect on capacity may seriously breach the independence condition whereas a vehicle with a small effect on capacity is more likely to satisfy the condition.

59. Adjusting the raw headways to ensure that the independence condition is true has only a minor effect on the resulting through car equivalents. Headway adjustment is not, therefore, of paramount importance. This enables through car equivalents to be inferred from samples that, by chance, do not contain any X_X headways. These inferred through car equivalents are more closely related to the adjusted values than their unadjusted counterparts because most of the information for the through car equivalents comes from the C_X (CAR followed by type X vehicle) headways. In fact the relationship between the average C_X headway for a sample and the resulting through car equivalent is very close to linear.

60. This study has found that there is a need to distinguish between the different truck types that comprise the heavy vehicle category. There is significant variation in the through car equivalents for the vehicles that comprise the heavy vehicle category, with the values for articulated trucks being more than double those for light commercials and 50% greater than those for rigid trucks. The average through car equivalent for heavy vehicles reflects the levels of each type of vehicle in the entire survey. Heavy vehicle equivalents should be used with care because the underlying proportions of each vehicle type in the traffic stream has a significant affect on the magnitude of the heavy vehicle equivalent.

61. The through car equivalents for heavy vehicles were found to be influenced by the proportion of heavy vehicles in the traffic stream and also by heavy vehicles at the front of the queue. Contrary to popular belief approach grade did not correlate well with the through car equivalents. This implies that approach grade has a similar affect on all vehicle types. Turn radius had a significant affect on turning vehicles. The influence of turn radius on the through car equivalents for turning cars was found to follow a model of the form used by SIDRA.

62. This paper has provided a brief analysis of the magnitudes of through car equivalents and the factors that influence them. Analysis of these data is continuing in conjunction

with other parameters that have been found to influence saturation flows at signalised intersections.

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