CHAPTER 5

AN ECONOMIC AND ECONOMETRIC INVESTIGATION OF THE IMPACT OF DIFFERENT VEHICLE TYPES ON CONGESTION

5.1 Introduction

The conventional economic analysis of traffic congestion generally assumes various homogeneous conditions for traffic congestion analysis. These assumptions consist of uniform traffic travelling on a fixed capacity road. In a reality, traffic has complicated characteristics (Walters, 1961 and Verhoef, 1999) and the traffic stream is actually made up of different vehicle types, e.g. trucks, buses and passenger cars. In this regard, it is important to estimate the effect on congestion of different vehicle types using real traffic data. Direct use of speed and flow dat has rarely been used and this chapter shows that the method for its use is more complicated than that suggested by the standard speed flow model.

The conclusion to be drawn from the critical review in Chapter 2 is that the conventional analysis in the derivation of the flow model attempts to find the congestion effects of different types of vehicles in terms of the equivalent number of passenger car vehicles. Unfortunately, the precise definitions of these equivalent effects vary between different studies and, most importantly, it appears that few of the previous studies directly estimate the effects of different vehicles on congestion – most rely to some degree on simulation exercises. It is very common to find the simple, but unsupported assumption, that large or heavy vehicles have an equivalent effect on congestion of two or more passenger cars. This lack of precision and evidence is an important omission in the literature on the economics of congestion.

Hence, our research provides a theoretical model of the marginal external congestion costs of different vehicle types using the speed-flow relationship. This model is then used to estimate such effects on data from the Chalerm Mahanakorn Expressway in Bangkok. The lack of sufficient data limits the generality of the implications of the empirical analysis but suggests that the marginal external time congestion costs of large and heavy vehicles exceed the simple assumption that such vehicles cause twice as much congestion as one passenger car.

5.2 The Theory of the Impact of Different Vehicle Types on Congestion

The present Chapter analyses the marginal external congestion cost using speed-density relationships. To demonstrate the speed-flow relationships of multiple vehicle types, we begin with a simple scenario. Suppose two vehicle types are driving on a finite length of a uniform road. The first type is identical four-wheel passenger cars and the second is identical trucks. This can be explained using Figure 5.2.1, which shows how both the Flow-cars and Flow-trucks affect the speed of vehicles of the first type. Initially, both flows reduce the speed but eventually reach a maximum at different flows and whereupon there is a positive relation between flows and speeds. These relationships differ between the two types of vehicles and the two flows interact in their impacts on the speed of vehicles of the first type.

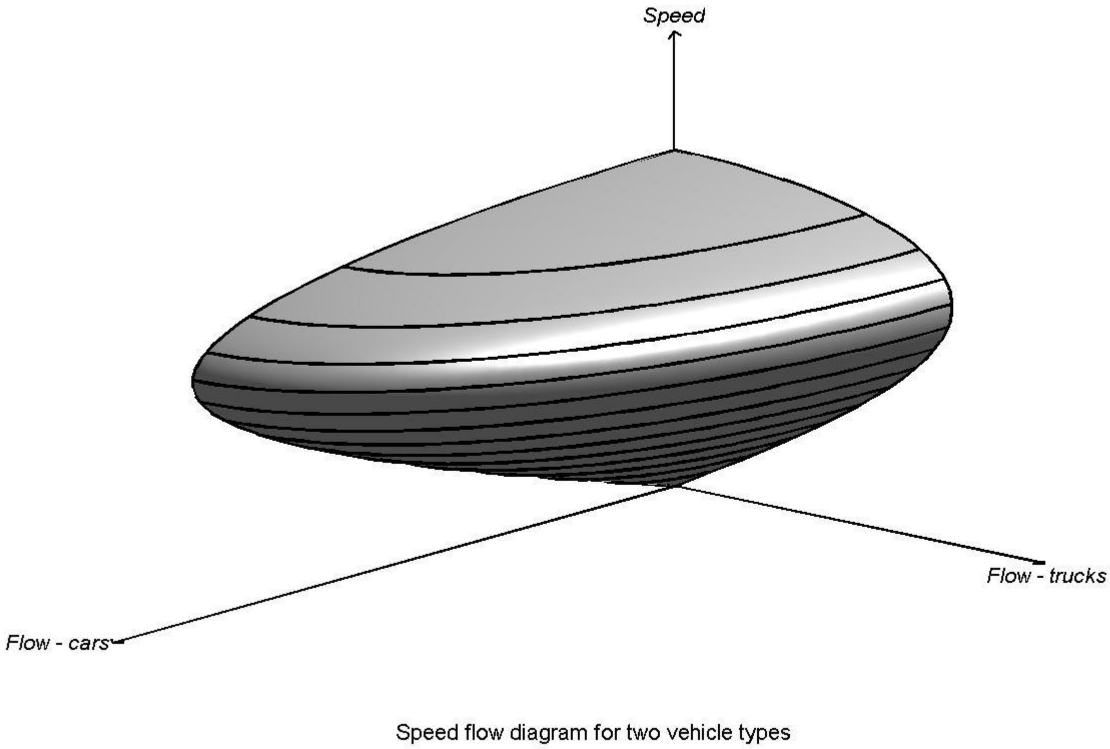

Figure 5.2.1 Speed-Flow Diagram for Two Vehicle Types

There is an identity between each type of flow, density and speed

$$F_i = V_i \; D_i \tag{5.2.1}$$

Traffic density D_i is the number of identical vehicles of type i along a finite length of a uniform road, traffic flow F_i is the flow rate of vehicles of the i^{th} type that pass a given point of the road and V_i is the traffic speed of vehicles of the i^{th} type (by definition the same for all type i vehicles). All variables are measured in continuous time.

The calculation of the marginal external cost is first considered in terms of the traditional speed-flow method. The externality depends on the costs of transport. The average and total cost per vkm[1] for the i^{th} type of vehicle are given by

$$AC_i = a_i + \frac{b_i}{V_i} \tag{5.2.2}$$

$$TC_i = F_i \ AC_i \tag{5.2.3}$$

The traditional presentation of the marginal external costs considers the impact of an additional vkm on speed and consequently total costs. It has not been possible to find in the literature a formal derivation of the analysis given below but this derivation is a simple extension of the analysis for a single homogenous vehicle type, eg see Newberry 1999. The marginal external cost of an additional vkm by an i^{th} vehicle on another j^{th} vehicle is given by the second term of

$$\frac{dTC_j}{dF_i} = AC_j - F_j \ \frac{b_j}{V_j^2} \frac{dV_j}{dF_i} \tag{5.2.4}$$

However, one also needs to consider the impacts on the speed and thus costs of vehicles of all other types. Accordingly, the total marginal external cost of an additional vehicle of the i^{th} type is given by

$$\sum_j \ F_j \ \frac{b_j}{V_j^2} \frac{dV_j}{dF_i} \tag{5.2.5}$$

This method ignores any interaction between the different vehicle types. This is shown to be potentially important in the following analysis and the review in 2.9. As suggested in Chapter 3, this method does not consider that an increase in flow

[1] vkm stands for vehicle-kilometre.

includes a reduction in the distance travelled by vehicles of the same type already on the road and partially offsets the increase in distance travelled by the additional vehicle. To use the flow approach in an appropriate manner, it is helpful to consider a change in congestion costs being caused by the presence of an additional vehicle on the road and not an extra vkm in terms of flow.

Using the analysis developed in Chapter 3, a change in flow F_i can be decomposed into

$$dF_i \;=\; V_i\, dD_i \;+\; D_i\, dV_i \tag{5.2.6}$$

In a very similar manner to the analysis given in Chapter 3, the externality impact of an additional vehicle of the ith type on the speed of jth type vehicles can be examined through the appropriate derivative of speed with respect to density (normalising for the speed)

$$\frac{dV_j}{dD_i}\,\frac{1}{V_i} \tag{5.2.7}$$

Thus, the marginal external congestion time cost of a change in the density of the i^{th} vehicle type on vehicles of the j^{th} type is

$$\frac{D_j}{V_j}\,\frac{dV_j}{V_i\; dD_i} \;=\; \frac{D_j}{V_j}\left(1+\varepsilon_{VD}^{i}\right)\frac{dV_j}{dF_i} \tag{5.2.8}$$

As in Chapter 3, this assumes constant densities, flows and speeds.

Accounting for the congestion cost imposed on all vehicle types gives the marginal external congestion time cost as

$$\sum_j \frac{D_j}{V_j} \frac{dV_j}{V_i \; dD_i} = \sum_j \frac{D_j}{V_j} \left(1+\varepsilon_{VD}^i\right) \frac{dV_j}{dF_i}$$
$$= \sum_j \left(1+\varepsilon_{VD}^i\right) \frac{dV_j}{dF_i} \frac{D_j}{V_j} \qquad (5.2.9)$$

In order to consider the interaction of different vehicles and the infinite regress idea developed in Chapter 3, it is necessary to consider the matrix form of equation (5.2.9). The impacts on journeys times of changes in the distances travelled by different vehicles types, represented by $V_i \; dD_i$, can be modelled by (assuming three different vehicle types and fixed speeds)

$$\begin{bmatrix} \frac{D_1}{V_1}\frac{dV_1}{V_1\ dD_1} & \frac{D_1}{V_1}\frac{dV_1}{V_2\ dD_2} & \frac{D_1}{V_1}\frac{dV_1}{V_3\ dD_3} \\ \frac{D_2}{V_2}\frac{dV_2}{V_1\ dD_1} & \frac{D_2}{V_2}\frac{dV_2}{V_2\ dD_2} & \frac{D_2}{V_2}\frac{dV_2}{V_3\ dD_3} \\ \frac{D_3}{V_3}\frac{dV_3}{V_1\ dD_1} & \frac{D_3}{V_3}\frac{dV_3}{V_2\ dD_2} & \frac{D_3}{V_3}\frac{dV_3}{V_3\ dD_3} \end{bmatrix} \begin{pmatrix} V_1\, dD_1 \\ V_2\, dD_2 \\ V_3\, dD_3 \end{pmatrix}$$

$$= \begin{bmatrix} \frac{D_1}{V_1}\left(1+\varepsilon_{VD}^1\right)\frac{dV_1}{V_1\ dF_1} & \frac{D_1}{V_1}\left(1+\varepsilon_{VD}^2\right)\frac{dV_1}{V_2\ dF_2} & \frac{D_1}{V_1}\left(1+\varepsilon_{VD}^3\right)\frac{dV_1}{V_3\ dF_3} \\ \frac{D_2}{V_2}\left(1+\varepsilon_{VD}^1\right)\frac{dV_2}{V_1\ dF_1} & \frac{D_2}{V_2}\left(1+\varepsilon_{VD}^2\right)\frac{dV_2}{V_2\ dF_2} & \frac{D_2}{V_2}\left(1+\varepsilon_{VD}^3\right)\frac{dV_2}{V_3\ dF_3} \\ \frac{D_3}{V_3}\left(1+\varepsilon_{VD}^1\right)\frac{dV_3}{V_1\ dF_1} & \frac{D_3}{V_3}\left(1+\varepsilon_{VD}^2\right)\frac{dV_3}{V_2\ dF_2} & \frac{D_3}{V_3}\left(1+\varepsilon_{VD}^3\right)\frac{dV_3}{V_3\ dF_3} \end{bmatrix} \begin{pmatrix} V_1\, dD_1 \\ V_2\, dD_2 \\ V_3\, dD_3 \end{pmatrix}$$

$$= \mathrm{A} \begin{pmatrix} V_1\, dD_1 \\ V_2\, dD_2 \\ V_3\, dD_3 \end{pmatrix}$$

(5.2.10)

As in Chapter 3, it is important to recognise that the additional journey time (5.2.10) in turn causes additional congestion that is part of the congestion externality. These additional journey times lead to further congestion in an infinite regress with the matrix relationship, at each stage of the regress, between the additional density for a period of time and the lost distance travelled caused by the increase in density been given by the elasticities of speed with respect to density. The total additional journey times travelled by the three types of vehicle caused by the initial additional vehicle journeys are given by

$$\left[A + A^2 + A^3 + A^4 \; ...... \right] \begin{pmatrix} V_1 \, dD_1 \\ V_2 \, dD_2 \\ V_3 \, dD_3 \end{pmatrix} = \mathrm{A} \left[I - A \right]^{-1} \begin{pmatrix} V_1 \, dD_1 \\ V_2 \, dD_2 \\ V_3 \, dD_3 \end{pmatrix} \qquad (5.2.11)$$

The aggregate cost of an additional vehicle kilometre by the first vehicle type is given by summing the individual elements of the vector

$$b \;\; A \left[I - A \right]^{-1} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad (5.2.12)$$

This analysis and the expression (5.2.12) have similarities to those given in Chapters 3 and 4 but is framed in a more complex matrix form. However, as in these Chapters, the expression (5.2.12) is not the exactly correct statement of the true marginal external congestion cost. The true external effect has also to take account of the possibility of changes in the behaviour of road users consequent on the greater costs following the initial addition time spent on the road by all users. The term γ_{ji} represents the response of vehicles of the jth type to an increase of one vkm by vehicles of the ith type. Thus

$$\begin{bmatrix} \varepsilon_{FT}^{1}\ D_1\ \dfrac{dV_1}{V_1\ dD_1} & \varepsilon_{FT}^{1}\ D_1\ \dfrac{dV_1}{V_2\ dD_2} & \varepsilon_{FT}^{1}\ D_1\ \dfrac{dV_1}{V_3\ dD_3} \\ \varepsilon_{FT}^{2}\ D_2\ \dfrac{dV_2}{V_1\ dD_1} & \varepsilon_{FT}^{2}\ D_2\ \dfrac{dV_2}{V_2\ dD_2} & \varepsilon_{FT}^{2}\ D_2\ \dfrac{dV_2}{V_3\ dD_3} \\ \varepsilon_{FT}^{3}\ D_3\ \dfrac{dV_3}{V_1\ dD_1} & \varepsilon_{FT}^{3}\ D_3\ \dfrac{dV_3}{V_2\ dD_2} & \varepsilon_{FT}^{3}\ D_3\ \dfrac{dV_3}{V_3\ dD_3} \end{bmatrix} [I-A]^{-1} \begin{pmatrix} 1-\gamma_{11} \\ \gamma_{12} \\ \gamma_{13} \end{pmatrix} = \begin{pmatrix} \gamma_{11} \\ \gamma_{12} \\ \gamma_{13} \end{pmatrix} \qquad (5.2.13)$$

Such equations as (5.2.13) can be solved for all γ_{ji} . Thus, the equations of the type (5.2.12) and (5.2.13) can be used to solve for the marginal external congestion costs. It is clear that this brief outline of the approximate procedure requires the collection of more information than is usually available from traffic surveys and implementation of the approximate procedure is not considered further. However, at the end of this chapter a rough approximation is examined that sheds some light on the relative marginal external costs.

Thus, estimation of the marginal external congestion costs of different vehicles requires the measurement of the speeds and flows of all types of vehicles and consideration of the interaction between different vehicles and possible non-linear effect in their own flows. It is unlikely that there exist many data sets which measure all these necessary speeds and flows.

5.3 Empirical Investigation of The Impact of Different Vehicle Types on Congestion on The Chalerm Mahanakorn Expressway Bangkok

5.3.1 Data Description

We investigate car speed-flow relationships of three vehicle types on the Chalerm Mahanakorn Expressway, Bangkok. Details of the data are given in Chapter 4.4.1 and Appendix A4.2. The only additions to this description are when the data usage is different. Traffic flow in this study were observed from the total number of toll passes sold in every hour for different vehicle types collected at tollbooths. There were three vehicles types: four-wheel passenger cars, large and exempt vehicles. We used prices of toll passes to classify type of vehicles because four-wheel passenger cars and large vehicles are charged differently. There was no charge for exempt vehicles. Large vehicles in this study included buses and those vehicles used for transporting goods; i.e. vehicles with 6-wheels, 8-wheels, 10-wheels, and more than-10-wheels. Exempt vehicles included ambulances, fire engines, police cars, diplomatic and official cars, rescue cars and those with parades.

The scatter diagram in Figure 5.3.1 shows the speed-flow relationship by using a factor of 2 PCE[2] to convert the number of large vehicles and exempt vehicles into a standard unit. These flows are then added to the corresponding flows of four-wheel passenger cars. These observations show both ordinary and hypercongestion. A clear distinction between ordinary congestion and hypercongestion is at approximately 40 km/h[3]. Speeds higher than 40 km/h represent approximately 81% of the total observations. The present empirical analysis is concerned only with ordinary congestion. Therefore, observations with speeds less than 40 km/h are removed.

[2] PCE is a factor which is commonly recommended for converting the impact of a heavy vehicle as an impact of two passenger cars, see review in Section 2.9, Chapter 2.

[3] km/h stands for kilometres per hour.

A speed-flow scatter diagram for ordinary congestion is shown in Figure 5.3.2. The diagram clearly suggests negative speed-flow relationships. In the next section, we use the previous theoretical model to attempt estimation of the marginal external congestion time costs for the three different vehicle types on cars' speed. It should be emphasised this is not a complete empirical analysis of the impacts of different vehicles on congestion.

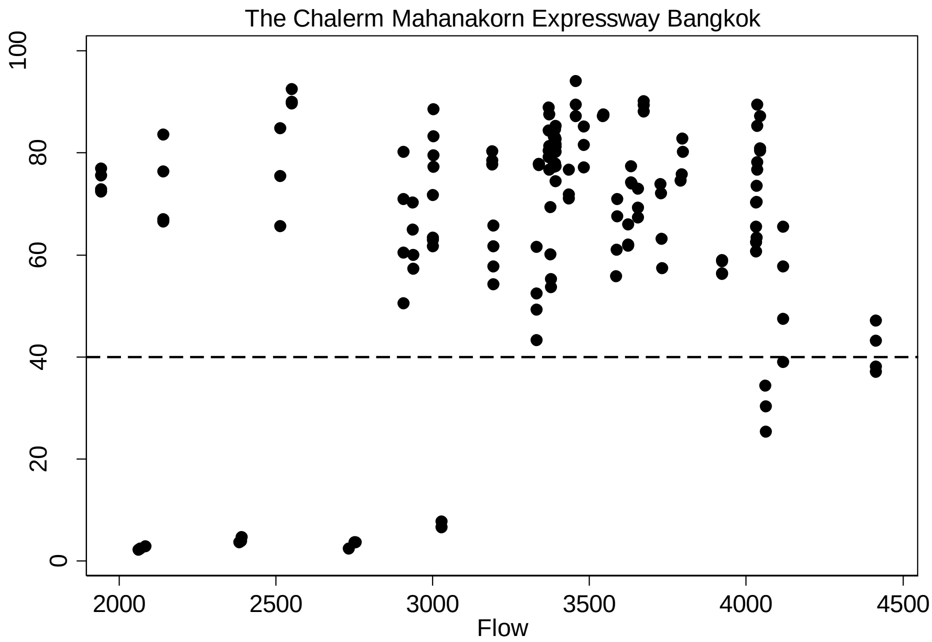

Figure 5.3.1 Speed-Flow Relationship on the Chalerm Mahanakorn Expressway Bangkok (all observerations)

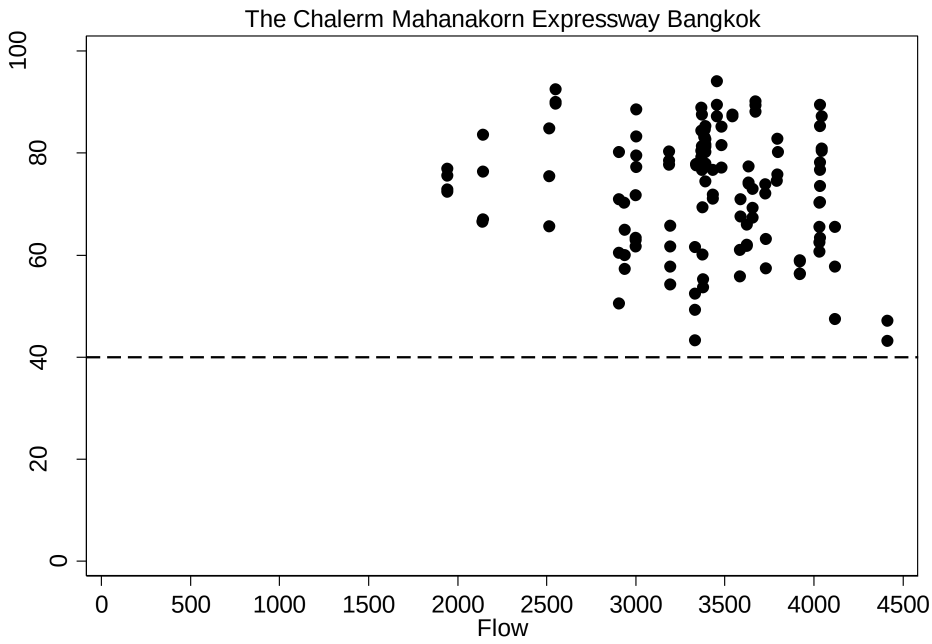

Figure 5.3.2 Ordinary Congestion Speed-Flow on the Chalerm Mahanakorn Expressway in Bangkok

5.3.2 Analysis and Results

In this section, we estimate the car speed-flow relationships of three different vehicle types**.** These are four-wheel passenger cars, large vehicles (i.e. trucks and buses) and exempt vehicles. Firstly, the estimation uses a simple linear model (5.3.1). This specification is chosen to show a simple comparison between the congestive impacts of different vehicle types.

$$V = \alpha + \beta\, 4w + \gamma\, la + \delta\, ex + \varepsilon \qquad (5.3.1)$$

where *V* represents passenger car speeds, and *4w*, *la* and *ex* represent flows of four-wheel passenger cars, large vehicles and exempt vehicles, respectively.

Table 5.3.1 reports the estimation of this speed-flow relationship and diagnostic tests. Every slope coefficient is negative as expected. However, only the slope coefficient of car speed with respect to flow of large vehicles is statistically different from zero at 99% confidence level. In addition, this regression fails in the Heteroscedasticity and White tests and the reported standard errors are adjusted. The more major misspecificaton RESET and Normality Jarque-Bera tests are passed.

Hence, the interaction and non-linearity suggested by the theory of Section 5.2 demand a further estimation with a more general specification. Therefore, we carry out the next estimation using the equation

$$V = \xi + \pi\, 4w + \eta\, la + \varphi\, ex + \psi\, (4w)^2 + \phi\, (la)^2 + \chi\, (ex)^2 + \phi\, 4w\_la + \theta\, 4w\_ex + \Omega\, la\_ex + \mu \qquad (5.3.2)$$

The coefficients of this regression and its diagnostic tests are reported in Table 5.3.2. Surprisingly, all linear flow terms are statistically insignificant, but one of the curvature coefficients and all the interactions terms are statistically significant. That these latter coefficients are significant suggests that one should not drop the simple linear variables for m the specification. The results of the diagnostic tests are similar to the simple linear model in Table 5.3.1 in that the Heteroscedasticity and White tests are failed but the RESET and Normality tests are passed – the latter only just.

In order to correct the failed White test, the results shown in Tables 5.3.1 and 5.3.2 are already adjusted with Heteroscedasticity-consistent standard errors.

Table 5.3.1 Ordinary Congestion Speed-Flow Model: Dependent Variable *V*

Variables	Coefficients
4w	-3.91×10^{-4}
	(0.13)
la	-5.29×10^{-2}***
	(-3.08)
ex	-1.35×10^{-1}
	(-0.60)
Diagnostics	
Observations	108
F-Statistics	8.98
Adjusted R^2	0.229
Heteroscedasticity :Chi-Squared	9.94
	(1.6×10^{-3})
White Test:Chi-Squared	14.98
	(5.6×10^{-4})
RESET:F-Statistic	1.85
	(0.14)
Normality:Chi-Squared	3.81
	(0.14)

Notes:

1. *** indicates the parameters that are significantly different from zero at 1 percent; ** at 5 per cent, and * at 10 per cent.
2. Figures in parentheses under the coefficients are t-statistics and under the diagnostic tests are ‘p-values’.

Table 5.3.2 Ordinary Congestion Speed-Flow Model: Dependent Variable *V*

Variables	Coefficients
4w	-1.01×10^{-1}
	(-0.97)
la	-4.19×10^{-3}
	(-0.01)
ex	-2.99
	(-1.19)
$(4w)^2$	7.45×10^{-6}
	(0.45)
$(la)^2$	8.51×10^{-4}***
	(-3.00)
$(ex)^2$	-4.36×10^{-2}
	(-0.85)
4w_la	1.42×10^{-4}*
	(1.76)
4w_ex	2.11×10^{-3}***
	(3.05)
la_ex	-1.87×10^{-2}**
	(-2.57)
Diagnostic Statistics	
Observations	108
F-Statistics	5.48
Adjusted R^2	0.295
Heteroscedasticity :Chi-Squared	6.66
	(9.8×10^{-3})
White Test:Chi-Squared	9.25
	(9.8×10^{-3})
RESET:F-Statistic	1.59
	(0.19)
Normality:Chi-Squared	0.61
	(0.73)

Notes:
1. *** indicates the parameters that are significantly different from zero at 1 percent; ** at 5 per cent, and * at 10 per cent.
2. Figures in parentheses under the coefficients are t-statistics and under the diagnostic tests are ‘p-values’.

Nevertheless, this non-linear regression cannot directly predict the impact of each type of flow on cars' speed. We use parameters in Table 5.3.2 to calculate the impact of each type of vehicles' flow on the decreased speed and display them with the results from Tables 5.3.1 and 5.3.2 in Table 5.3.3. It is important to note that elasticities of speed with respect to flow are not observed for large and exempt vehicles. The omission of these effects overestimates the associated marginal external congestion time costs (METCs).

Table 5.3.3 suggests that the impact of additional flow of large vehicles on cars' speed may be approximately between 10 to 1000 times the impact of four-wheels passenger vehicles using the simple linear and the non-linear model respectively. However, notice should be taken of the lack of statistical significance of the results in Tables 5.3.1 and 5.3.2. It should be noted that the non-linear regression indicates the importance quantitatively and statistically significance of interactive effects and is probably the preferred regression. Similarly, the impact of the additional flow of exempt vehicles on cars' speed compared to the four-wheels passenger vehicles is much larger, being between 300 to 100 times larger using the simple linear and the non-linear model respectively. Anecdotal evidence suggest that traffic stops for the passage of exempt vehicles. These estimates are greatly in excess of the commonly used factor of two PCEs for the relative congestive impact of large vehicles. However, it should be noted that the empirical evidence is often not statistically significant and the interaction terms suggest strong interactive effects.

Table 5.3.3 Effect of vehicle type flows on cars' speed

	Linear Model	Non-Linear Model
Four Wheel Vehicles	-0.0004	-0.0050
Large Vehicles	-0.0529	-0.0658
Exempt Vehicles	-0.135	-0.5090

Finally, we estimate the "marginal external congestion time cost (METC)" ignoring the matrix analysis of the earlier part of this Chapter and the impact of deterred demand. These calculations use the estimated parameters in Table 5.3.3. The calculated "METCs" are presented in Table 5.3.4. Unfortunately, speeds of large and exempt vehicles were not observed in this research, thus the $\left(1+\varepsilon_{VD}^{i}\right)$ of large and exempt vehicles cannot be estimated. The calculations for large and exempt vehicles in Table 5.3.4 were made without $\left(1+\varepsilon_{VD}^{i}\right)$. Whereas the marginal external congestion time cost for four-wheels passenger cars were appropriately calculated. It should again be emphasised that these calculations are made without following the matrix related and deterred demand theoretically correct analysis.

Table 5.3.4 "Marginal External Congestion Time Cost on Cars" [min/vkm]

	Linear Model	Non-Linear Model
Four Wheel Vehicles	0.01	0.16
Large Vehicles	1.67	2.07
Exempt Vehicles	4.25	1.60

5.4 Conclusions

The marginal external congestion time cost of a car on other cars is estimated with a large degree of error at between 0.01 to 0.1 min per vkm, which is only of slight importance. The biased estimates for large and exempt vehicles METCs on cars are of the order of magnitude extending to perhaps a few minutes per vkm.

The theoretical analysis presented in this Chapter for the congestion effects of different types of vehicles suggest that the theoretically correct procedure for estimate the marginal external congestion costs is complex, involves the interaction of different vehicle effects and can only be analysed correctly with matix algebra. The simple econometric analysis conducted here is subject to a large degree of error but also suggests the importance of interaction effects and perhaps non-linear effects. The empirical results reported here indicate, but do not prove, that there are more serious congestion externalities generated by large and exempt vehicles in ordinary congestion than may have previously been thought. A more thorough analysis requires collection of data on speeds and flows of all types of vehicles. This is likely to be expensive to achieve.

With regard to future research, the empirical results presented are only indicative as the number of observations is too small and more importantly the speeds of the large and exempt vehicles are not observed. This means that the elasticity of speed with respect to flow of such vehicles cannot be estimated and this elasticity is an important part of the prediction of the impact of such vehicles on the congestion of other vehicles. In order to estimate such elasticities, a complete investigation requires data on the speeds and flows of all vehicle types. Additionally, a correct analysis of all vehicle externalities requires the use of matrix algebra and may only be achievable through simulation exercises.