TRAFFIC NOISE : PREDICTION OF INTERRUPTED FLOW NOISE

A Review & Selection of a Model for use in New Zealand

MALCOLM HUNT
Environmental Engineer, Royds Gardens Ltd, Wellington
and
STEPHEN SAMUELS
Principal Research Scientist, Australian Road Research Board, Melbourne

Transit New Zealand Research Report No. 3

ISBN 0-478-04138-1
ISSN 1170-9405

P O Box 5084, Lambton Quay, Wellington, New Zealand
Telephone (04) 499-6600; Facsimile (04) 496-6666

Hunt, M., Samuels, S. 1991. Traffic noise: prediction of interrupted flow noise. A review and selection of a model for use in New Zealand. *Transit New Zealand Research Report No. 3.*

Keywords: traffic, noise, prediction, interrupted flow, model, roads, Australia, New Zealand

DISCLAIMER

CONTENTS

ABSTRACT

Reliable techniques have been used in a number of countries throughout the world for some years now for the prediction, measurement, assessment and control of road traffic noise. Techniques for the prediction of traffic noise are all based on the assumption that traffic is freely flowing. In many cases when the traffic flow is interrupted, for example in the vicinity of intersections, this assumption is invalid and the established techniques are generally unsuitable. This report concentrates on the generation of traffic noise under interrupted flow conditions.

A comparison of traffic noise from freely flowing traffic conditions and traffic noise produced by interrupted traffic flow conditions identifies the complex nature of interrupted traffic flow noise. This leads to a definition of the important features of a prediction model for interrupted flow. Part of the problem in developing a noise prediction model for these situations is the need to adequately describe the traffic flow characteristics. Models for the prediction of interrupted flow traffic noise can best be developed for use at signalised intersections because of the certainty of data on the timing of traffic flows by observation of signal phasing.

This report reviews in some detail current technology as published in the literature, and recommends the adoption of a suitable model for further trials under New Zealand conditions. Preliminary trials at two intersections in Wellington show the performance of the model is improved by using vehicle source noise levels representative of the New Zealand vehicle fleet because source noise levels relating to Australian conditions where the model was developed are different.

The model is useful in the prediction of noise levels for future situations where signals are to be installed, or where changes in signal phasing are planned. For existing situations, the model is a cost-effective method of determining noise levels at signalised intersections, when compared with manual survey methods. In the longer term it is possible that the model can be used to investigate the optimum phasing of networks of signalised intersections so that the overall noise emission is reduced. Improvements to reduce noise emission may also reduce other emissions from the traffic stream.

1. INTRODUCTION

Road traffic noise may be conveniently defined as the noise produced by traffic operating on the road system. In urban areas, traffic noise represents the major and most pervasive source of community noise (Hunt 1988, Delaney *et al.* 1976, Kugler *et al.* 1976). Unlike many sources of community annoyance, traffic noise can be quantified. Consequently, both the measurement and prediction of it frequently represent important components in the preparation of an Environmental Impact Statement or in a planning study (CRBV 1980, Jameson 1979). Furthermore, the control of traffic noise, either from an existing or a new road facility, tends to involve rather limited options. It is generally recognised that the best long-term solution lies in what is termed 'control at source'. However, this solution is only possible once the source behaviour is understood adequately.

Reliable techniques are being used at present for the prediction, measurement, assessment and control of traffic noise (Hunt 1987, Samuels and Fawcett 1985, Stone and Saunders 1982). However, these are all based on the assumption of freely flowing traffic conditions. In the many cases when traffic flow is interrupted, for example in the vicinity of intersections, this assumption is invalid and the established techniques are generally unsuitable. The present report therefore concentrates on this issue, with particular emphasis on signalised intersections. It is the intention to explore what is currently known about traffic noise generated under such conditions.

This research report also describes the fundamental differences between noise from freely flowing traffic and noise from interrupted flow. It will be seen that these fundamental differences can be related to vehicle operation under the separate flow conditions.

Freely flowing traffic conditions can be described as those occurring on roads where quasi-constant vehicle speed can be maintained with no impediments to traffic flow. Such is the case for "open road" traffic conditions and also for urban conditions where traffic is not constrained by congestion, intersections (signalised, "Give Way", "Stop" signs, etc.) pedestrian crossings or roadworks.

It will be seen that although freely flowing traffic is Gaussian (i.e. "normally" distributed) in nature allowing assumptions to be made regarding noise level distribution over time (leading to prediction methods such as the UK DoE method, based on regression analysis), interrupted flows produced a noise level distribution over time that is less normal (i.e. non-Gaussian). In fact, interrupted flows have the potential to produce a noise level distribution that is close to random, under certain conditions.

The conditions that control the distribution of noise levels relate to the traffic controls placed on vehicles causing interrupted traffic flow.

It is therefore evident that in terms of temporal variations in noise output, free-flow conditions produce traffic noise which will vary with time in a constant manner depending upon total flow, vehicle speed, composition, and road surface. Alternatively, interrupted flow covers a wide range of temporal variation, from that approaching free flowing to that which is approaching purely random.

The key to prediction of any phenomenon is in the identification of prime characteristics of causal factors. In the case of interrupted traffic flow noise, this relates to identification of characteristics of the traffic flow controlling mechanism. In the case of pedestrian crossings this relates to the number of pedestrians wishing to use the crossing and their spatial variation. In the case of unsignalised intersections this relates to the frequency of cross-traffic requiring through-traffic to halt.

The case of signalised intersections represents an ideal situation of model interrupted traffic flow noise. The flow controlling mechanism changes over time with known (indeed programmable) variation while other information required (traffic volume, composition, etc.) is identical to that required for prediction under freely flowing conditions.

This report reviews some methods of predicting interrupted traffic flow noise which do not require information on the temporal characteristics of the traffic flow controlling mechanism. These are therefore based on empirical and mathematical models which, in turn, are based on the relationship of noise level with bulk flow, speed etc. Typically regression analysis has been used to define the relationship. In theory these methods have the advantage of being able to be applied over a wide range of interrupted traffic flow. However, it is surmised that unless the model is applied to conditions similar to those under which the regression data was collected, there is little validity in their use.

There are advantages in a prediction method which is capable of incorporating information on the traffic flow characteristics (i.e. the temporal distribution of traffic flows). This will, however, limit the applicability of the model to situations such as signalised intersections where the data on timing of traffic flows are easily obtained from the signal phasing. It is possible to overcome this limitation in the future if it can be shown that data on traffic flow parameters are obtainable for situations other than signalised intersections.

2. CURRENT TECHNOLOGY

2.1 Preamble

Technical interest in traffic noise at intersections has been increasing in recent years and this is reflected in a growing number of publications on various aspects of the topic. These publications may be conveniently grouped into three subject categories:

* Empirical studies

* Mathematical modelling based on regression analysis

* Simulation studies

Publications within the Empirical Studies category were primarily concerned with reporting the observed magnitudes of interrupted traffic flow noise and comparing these to freely flowing traffic noise levels. Papers in the second category generally presented similar data to those in the first, but then proceeded to quantify their observations using regression analysis techniques. The third category consisted of a series of mathematical simulation treatments of interrupted traffic noise generation, propagation and temporal distribution. A comprehensive listing is given in References of this report and several pertinent works will now be considered in some detail.

2.2 Empirical Studies

In what is essentially a data presentation report, Flynn *et al.* (1980) comprehensively documented the extensive results of a field measurement programme. Their programme involved first, the monitoring of traffic and noise data at seven different sites. Of these, five were at freeways or roadways of different configurations where traffic was freely flowing, and the remaining two were at intersections where the traffic flow was interrupted. The second phase of their programme included a series of controlled tests at an isolated site free of any other traffic.

Vehicle passby noise data were collected for a number of cars and trucks selected on the basis of the current US in-service vehicle population. From there the roadside passby noise produced by various groups of these vehicles was monitored. The vehicle classifications, headways (i.e. distance between successive vehicles) and speeds of these groups were pre-selected for this exercise on the basis of the Kurze (1974) traffic noise theories. The study amounted to an experimental simulation of traffic noise under both free and interrupted flow conditions.

A fundamental property of traffic noise is the manner in which it varies with time. In Fig. 1 two traffic noise time histories are reproduced from Flynn et al. (1980). Both were recorded during their experimental simulation of traffic noise and illustrate clearly the noise level fluctuations associated with both free and interrupted flow situations. As indicated in the free flow case (Fig. 1a), a traffic volume of 660 vehicles (v) per hour was simulated, and this corresponds to 0.18 v/s. The major fluctuations in the Fig. 1a noise signal are observed to occur at about this frequency, thereby illustrating how traffic noise is essentially the summation of the noise produced by the individual vehicles that comprise the traffic.

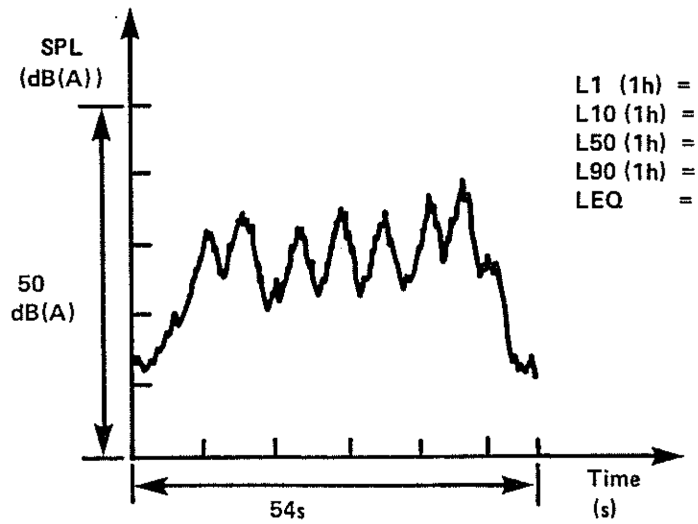


Fig. 1a - Free flow case. 'A'- weighted sound pressure level (SPL in dB(A) in decibels) against time (s) for a simulated multiple traffic event passby of seven automobiles with three gaps (after peaks 2, 3 and 5), at a speed of 56 km/h and a flow rate of 660 v/h, 15 m from microphone (after Flynn *et al.* 1980).

The interrupted flow noise/time history of Fig. 1b presents some distinct differences from the free flow counterpart in Fig. 1a. For the interrupted flow case, the noise level/time curve exhibits somewhat higher peak levels than does the free flow curve. Furthermore, there are fewer major fluctuations and these correspond broadly to the reduced flow rate of 0.09 veh/s. A more fundamental observation is that the overall shapes of the two curves differ considerably. The free flow noise is generally 'continuous' (it does fluctuate in level due to the effects of individual vehicles as discussed previously), throughout the (54s) simulation sample period. The interrupted flow noise only rises significantly above the background for around one third of the (118s) sample period. The interrupted flow noise may therefore be described as 'intermittent' and different in nature to the continuous flow noise. This difference may well contribute to the variation in reported annoyance between free and interrupted flow situations (Brown 1980).

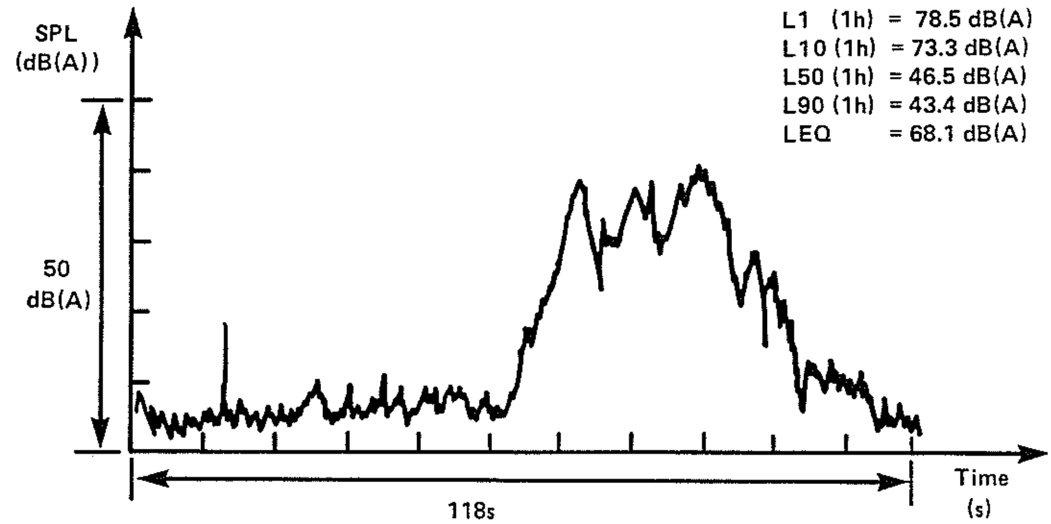


Fig. 1b - Interrupted flow case. 'A'- weighted sound pressure level (SPL) against time (s) for a simulated multiple traffic event, 'stop-and-go' passby of seven automobiles and three trucks, with an initial speed of 56 km/h and flow rate of 300 v/h, 15 m from microphone (after Flynn *et al.* 1980).

Also depicted in Fig. 1a and 1b are the noise indices which, for the interrupted flow case, are considerably higher than those in the free flow example. It is of interest, therefore, to determine to what extent these differences are related to the traffic flow type, given that the two curves were produced under different conditions of both flow and vehicle composition. Several studies such as that of Brown (1980) have shown that a high degree of correlation exists between all the indices listed in Fig. 1. The issue may, therefore, be resolved by an examination of any one of the indices. The L10(1h) index was chosen for this purpose as it is frequently adopted in the USA (Kugler *et al.* 1976), the UK (UK DoE 1975) and Australia (Samuels and Saunders 1982) as a traffic noise descriptor.

Table 1. Comparison of UK and US traffic noise predictions

UK DoE (1975)Prediction

Site	Flow type	Distance (m)	Flow v/hr	% Heavy vehicles	Speed km/hr	Predicted L10(1hr)	Measured L10(1hr)
195	Free	15N 86F	1490N 2110F	11.8N 13.7F	93N 93F	72.8	78.9
355	Int.	20N 50F	1320N 2360F	7.9N 8.3F	64N 64F	68.9	73.9
Difference						3.9	5.0

Note: Metric units, N = Near lane, F = Far lane.

US NCHRP (Kugler *et al.* 1976) Prediction

Site	Flow type	Car+ Truck (v/hr)	Heavy Flow (v/hr)	Car Speed (mph)	Truck Speed (mph)	Distance (ft)	Predicted L10(1hr)	Measured L10(1hr)
195	Free	4649	314	58	58	184	74.8	73.9
355	Int.	5278	112	40	40	120	74.8	78.9
Difference							0	5.0

Note: US units (non-metric).

Predictions were conducted using methods available from both the UK (UK DoE 1975) and the USA (Kugler *et al.* 1976). Although the UK method has not been evaluated under US conditions, the simple nature of the predictions being conducted suggested that the UK method would prove suitable. Also, as it is the comparative, and not the absolute, magnitudes of the predictions that are of interest here, use of the UK DoE method seems appropriate. However, as a further check for any spurious American vehicle or other effects, the US method is also applied. Results of these predictions are given in Table 1 and are also compared to the measured noise levels.

Neither the UK nor US method is applicable to the interrupted flow cases, since both methods are based on freely flowing traffic conditions. Nevertheless, the predictions of Table 1 do suggest that variations in total traffic flow, traffic composition and noise propagation distance are insufficient to explain the observed differences between the interrupted and freely flowing traffic noise levels.

Frequency spectrum analysis is one technique that has application in explaining the variation in response to noise, as just discussed, which are associated with variations in the conditions of the noise generation process. Flynn *et al.* (1980) provide a range of frequency spectra and three of relevance to the present discussion are reproduced in Fig. 2. These are in fact averaged spectra for a set of ten cars and were collected under controlled test conditions. Each car was driven separately past a measuring station under two test conditions and the passby noise monitored. The test conditions conformed to those of Fig. 1 and attempted to simulate typical conditions encountered in both freely flowing and interrupted (stop-and-go) traffic. On subsequent laboratory analysis of this noise, one-third octave band spectra were obtained for each vehicle and then normalised, relative to the overall sound pressure level recorded for that vehicle. The ten normalised spectra were averaged for each test condition and graphed (Fig. 2). While these data originate from individual vehicle passbys, they do have application in the present context because, as discussed previously, traffic noise arises from the summation of the noise generated by individual vehicles that comprise the traffic.

The free flow and interrupted flow spectra shown in Fig.2 differ mainly in the low frequency region below 250 Hz. This difference is greater for the 88 km/h free flow spectrum than for the 56 km/h spectrum. These observations point to the hypothesis that there may be a greater incidence of low frequency noise components associated with interrupted flow noise than with free flow noise. Such a hypothesis would help to explain the earlier observations concerning Fig. 1.

These observations may be enhanced by using some of the in-service data also provided by Flynn *et al.* (1980). It must be emphasised that these data were collected at specific locations chosen to be representative of many in the US.

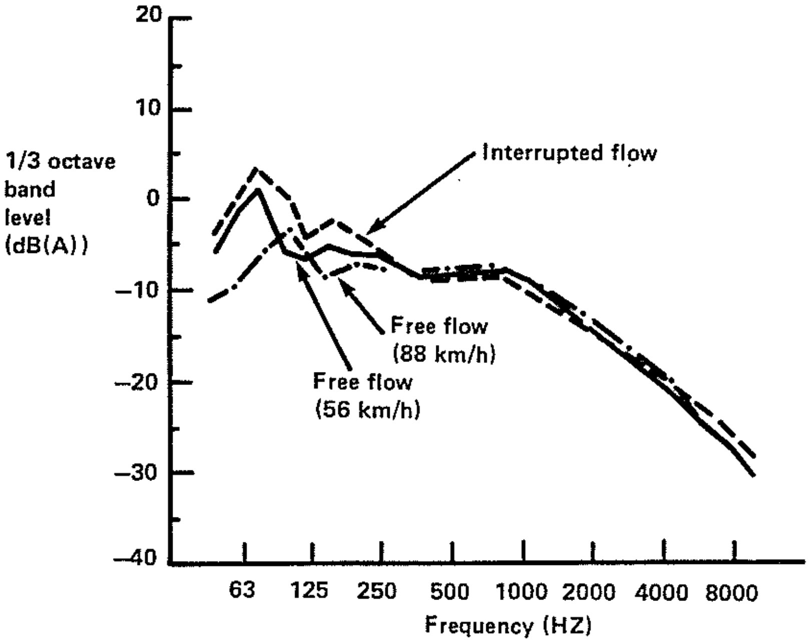


Fig. 2 - Sound exposure level spectrum relative to the A-weighted sound exposure level, at 15m from microphone, for passbys of automobiles (after Flynn *et al.* 1980).

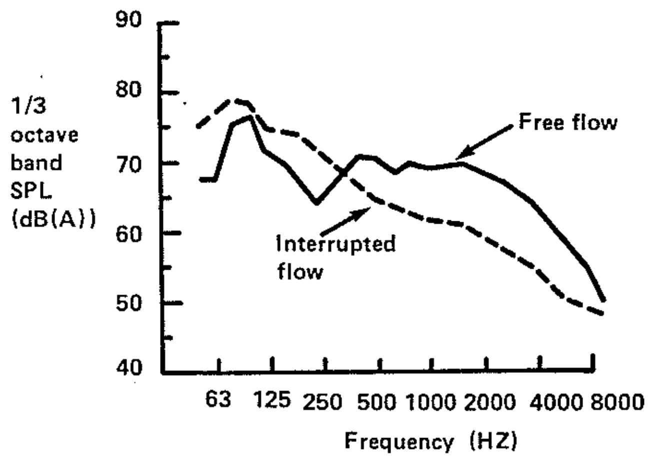


Fig. 3 - Spectra for free and interrupted flow (after Flynn *et al.* 1980).

Relevant one-third octave spectra have been provided by Flynn *et al.* (1980) and two have been reproduced in Fig. 3. Here it is apparent that at frequencies below around 300 Hz the interrupted flow noise spectrum dominates. This observation is consistent with that made earlier concerning the controlled test spectra in Fig. 2. It is obvious in Fig. 3 that the free flow spectrum is the greater of the two for all frequencies above 300 Hz.

The spectral behaviour in Fig. 3 has a possible explanation in terms of the analysis and theories presented in Samuels (1982). He demonstrated that the lower end of spectra, such as those in Fig. 3, are controlled mainly by vehicle engine and related noise sources. Higher frequency components were shown, on the other hand, to result primarily from the various effects of tyre/road interaction. Furthermore, for most vehicles (motorcycles excepted) in a state of reasonable maintenance it is known (Sandberg 1979) that tyre/road interaction noise is the major source of constant speed vehicle noise for all speeds in excess of 30 km/h. These theories suggest that the interrupted traffic flow noise is dominated by engine effects while the freely flowing traffic noise is controlled mainly by tyre/road interaction effects. Such an explanation would seem to reflect the increased incidence of acceleration and braking manoeuvres associated with interrupted traffic flow.

	NEARSIDE LANES						FARSIDE LANES			
	MEAN SPEED	TOTAL TRAFFIC	% CAR	% MT	% HT	TOT. TRAF.	% CAR	% MT	% HT	MEAN SPEED
FREE FLOW	93km/h	1490	88.3	4.5	7.3	2110	86.4	4.0	9.7	93km/h
INTERRUPTED FLOW	64km/h*	1320	92.1	4.3	3.6	2360	91.6	5.6	2.7	64km/h

* Speed limit on approach and departure

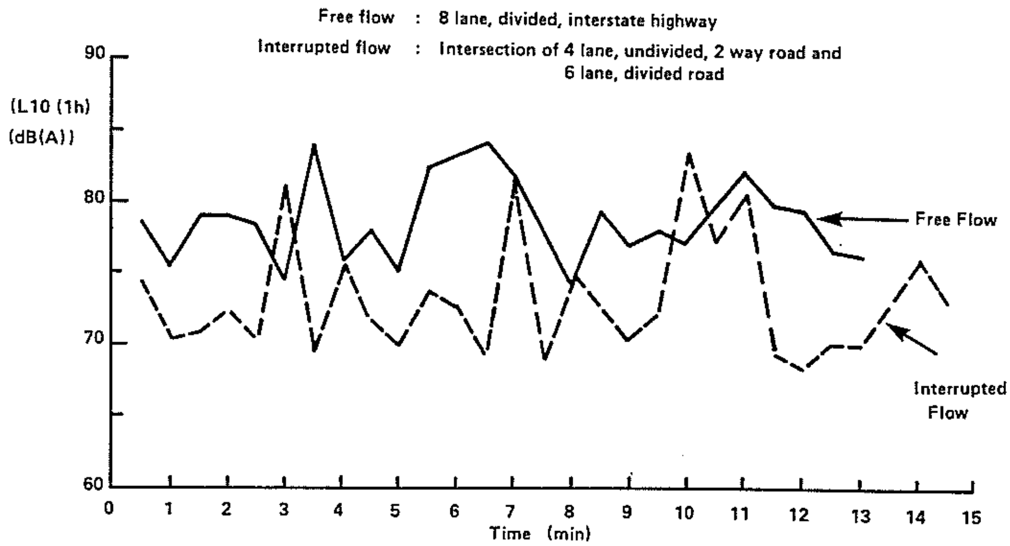


Fig. 4 - Noise/time histories typical of Flynn *et al.* (1980) data for free flow and interrupted flow traffic.
MT = Medium trucks, HT = Heavy trucks.

In Fig. 4, two noise/time histories, typical of those measured and tabulated by Flynn *et al.* (1980), have been graphed. As shown, the noise/time histories were claimed by Flynn *et al.* *(1980)* to be representative of a freely flowing traffic situation and an interrupted situation at a signalised intersection.

An important observation is that the fluctuations in noise level with time are considerably different for the two cases. The interrupted flow noise/time curve is characterised by several pronounced, short, sharp peaks interposed by longer periods of somewhat lower noise level. On the other hand, the free flow curve exhibits fewer, smaller such fluctuations and appears to be almost random in nature.

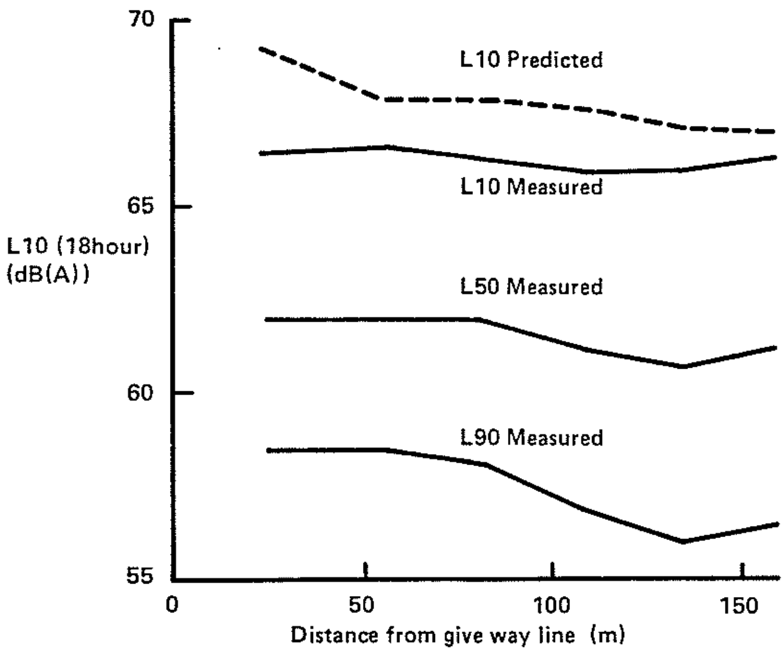


Fig. 5 - Road junction noise levels (after Hothersall and Jones 1976).

Traffic noise levels were measured at three road junctions in the UK by Hothersall and Jones (1976). Two of these junctions were signalised intersections, the third being a roundabout. Noise data were monitored at several locations alongside the major road leading into each intersection and plots of measured L10(18h) and other levels against distance from the intersection were made. Predicted L10(18h) levels, obtained from UK DoE (1975) using an estimated constant speed of 50 km/h, were plotted in the same fashion. An example is given in Fig. 5. At a number of separate locations around the intersections, L10(1h) noise levels were also measured and predicted.

Generally, Hothersall and Jones (1976) concluded that all their measured traffic noise levels decreased with increasing distance from each intersection, with this particular distance being measured alongside the major road into the intersection. Their predicted L10(18h) levels were consistently in excess of the measured levels, and Fig. 5 is typical of this. However the reverse was the case for their L10(1h) predictions. On the basis of these results, Hothersall and Jones claimed that the performance of the UK DoE prediction method (UK DoE 1975) was reasonable for interrupted traffic flow situations. However they did note that they were not able to ascertain whether this was caused by the intrinsic nature of the method, the traffic conditions encountered at their three sites, or to some known or unknown complex site parameters.

Hothersall and Jones (1976) reported without explanation that their measured levels tended to exceed their predicted levels at locations adjacent to lanes in which the traffic was accelerating. The reverse situation occurred at observer positions adjacent to lanes where the traffic was decelerating. These observations reflect prediction errors associated with the constant speed and free flow assumptions that were made in order to apply the UK DoE method to interrupted flow situations. Errors of this type were considered previously using the Flynn *et al.* (1980) data.

2.3 Regression-based Modelling

Gilbert *et al.* (1980) attempted to develop an L10(1h) prediction model for interrupted traffic flow conditions and to relate it, where possible, to the UK DoE (1975) prediction method. Their associated objectives were to determine the effects of flow, speed, propagation and reflection factors on interrupted traffic flow noise, and to create an interrupted flow parameter suitable for traffic noise prediction purposes.

Gilbert *et al.* (1980) were unsuccessful, however, in determining an interrupted flow parameter. Their main effort here (see Gilbert 1977) concerned what they termed an Index of Dispersion (T) which was defined as the ratio of the variance to the mean of the number of vehicles arriving in each ten-second interval. Traffic exhibiting a T value in the range 0.85 to 1.15 was considered to have a random or near-random distribution pattern. When traffic was approaching uniform flow, T would be less than 0.85, while for traffic approaching "platoon" flow T would exceed 1.15. Platoon flow occurs where traffic travels in linear groupings with small gaps between each vehicle and larger gaps between successive groups. The regression equation which incorporated this parameter was as follows:

$$L10(1h) = 55.2+9.18\log Q(1+0.09H)+4.2\log VY+2.3T \qquad (1)$$

Where Q = Traffic Volume (v/hour)
H = Proportion of vehicles exceeding a mass of 1.5 tonnes (%)
V = Mean speed of traffic (km/h)
Y = Carriage width (m)
T = Index of Dispersion

This equation was found to reasonably predict noise levels with a Coefficient of Determination (R^2) of 0.67. The standard deviation of the errors of predictions using the equation, determined earlier by Gilbert (1977) using measurements at 190 sites where the flow was less than 1000 vehicles/hour, was 2.7 dB(A). It appears that the Index of Dispersion parameter (T) would be of little or no value for future interrupted flow traffic noise predictions since, according to Gilbert *et al.* (1980), it cannot be estimated with any reasonable degree of accuracy. On the basis of their subsequent measurement programme, Gilbert *et al.* (1980) produced an updated regression equation which is reproduced as Equation (Eqn)(2):

$$L10(1h) = 43.5+11.2\log(L+9M+13H)+0.42Y+10\log A+4.6\log B \qquad (2)$$

Where L = Light vehicle flow (v/h)
M = Medium vehicle flow (v/h)
H = Heavy vehicle flow (v/h)
Y = Carriage width (m)
A, B = Mathematical terms incorporating propagation and reflection parameters.

The propagation and reflection parameters used included the distance from kerb to nearside building facade, the distance from kerb to receiver, proportion of soft ground between kerb and receiver, and the proportion of soft ground between receiver and any facade present. This equation had a coefficient of determination of 0.88 and a validation study revealed that the mean and standard deviations of the prediction differences (Predicted Value - Measured Value) associated with Eqn (2) were -0.6 dB(A) and 1.3 dB(A) respectively.

Although Eqn (2) represents, in purely statistical terms, an improvement over Eqn (1), it still remains an equation which quantifies a series of measurements made in Greater London. Perhaps the major shortcoming of the Gilbert *et al.* (1980) results, as culminated in Eqn (2), is that it does not include a measure of interrupted traffic flow. Dispersion index and vehicle speed were excluded from Eqn (2) on the basis of future usefulness and of the significance determined by regression analyses.

In considering noise at roundabouts, both L10 (1h) and Leq were regressed against traffic flow and the percentage of heavy vehicles in the traffic by Lewis and James (1980). Their regression equation for the noise alongside both approach/departure roads to the roundabouts was of the form given in Eqn (3):

$$L10(1h) = A + B \log Q + CP \qquad (3)$$

Where A,B,C = Regression Coefficients
Q = Total vehicle flow (v/h)
P = Proportion of heavy vehicles (%)

This equation produced a standard error of the L10(1h) estimate of 1.5 dB(A). Again the results of Lewis and James (1980) must be seen as site specific and, therefore, of limited application. That Lewis and James (1980) considered this problem might suggest, however, that noise from roundabouts represents an area of future research in Australia and New Zealand.

2.4 Simulation Studies

Favre (1978) considered the noise produced by traffic approaching a signalised intersection. The traffic parameters adopted were based on both current traffic theory and observations. For example, the desired speed for each vehicle in the simulation was determined by using a Gaussian-truncated distribution, with the average and the standard deviation based on observations of typical traffic in France (the country in which the simulation was conducted). Further, vehicles were deemed to move in accordance with an empirically derived pursuit law that related the displacement of successive vehicles, categorised as either heavy or light. The model also responded to signal phasing. By assigning a noise/time profile to each vehicle, the noise/time history of the total traffic noise could be simulated for any particular traffic (flow, speed, composition, etc.) situation, given a set of propagation and road geometry parameters. From there, the various noise indices were calculated.

The performance of Favre's simulation model was studied using measurements at one location where the traffic flow predominated in one direction. Reasonable results, as exemplified by Fig. 6, were obtained. The model appeared to overpredict by several dB(A).

In what could be described as a useful simulation exercise, Favre (1978) demonstrated that it may well be possible to simulate successfully the noise produced by traffic whose flow is interrupted. Favre's model is constrained severely by its limited range of traffic, vehicle and propagation parameters. Indeed, Favre himself concluded that his model was of limited dependability and is not therefore suitable for all urban traffic noise situations.

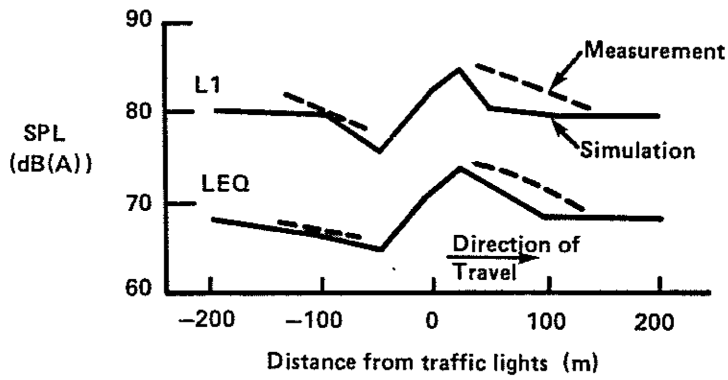


Fig. 6 - Measured and predicted levels. 700 v/h, 5% heavy vehicles. 50 to 70 km/h. Light cycle: 50s green, 5s amber, 45s red (after Favre 1978).

Sparkes and Large (1980) considered the simulation of the noise produced by vehicles accelerating across a signalised intersection. They commenced by establishing two vehicle categories (heavy and light) and then proceeded to use information published previously to obtain simulations of what amounted to the average acceleration characteristics of these two categories. Both noise/speed information and traffic flow behaviour at intersections were subsequently combined with these acceleration specifications to simulate the average noise produced by a vehicle from each category passing through the intersection. By specifying the particular vehicle queue composition (distribution), the noise profile produced by that queue was simulated by an appropriate summation of the noise associated with individual vehicles in that queue. Validation of the model was attempted using measurements at one observer location at one signalised intersection in the UK.

The results published by Sparkes and Large (1980) are typified by that reproduced in Fig. 7 and showed that for particular queues, the simulated noise profiles were of similar form to those measured. Of additional interest here are the similarities between these Fig. 7 curves and those for the controlled test data given in Fig. 1b. The Fig. 7 curves tend, therefore, to add weight to the previous arguments concerning noise generation that were advanced on the basis of Fig. 1b. There are some discrepancies in the Fig. 7 data, with the prediction difference magnitudes typically being in the order of 2 to 3 dB(A).

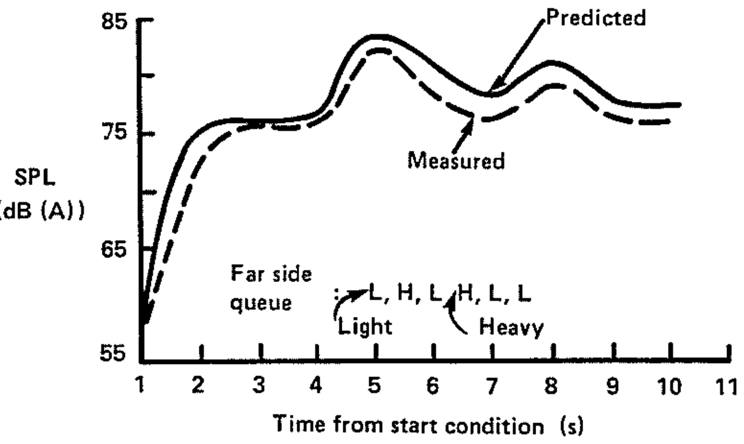


Fig. 7 - Noise from accelerating queue of vehicles (after Sparkes and Large 1980).

The techniques of Sparkes and Large (1980) are useful and of interest since they attempted a logical progression from the noise source to the receiver. The literature on which they drew to derive their simulation tends to deal with heavy vehicle noise and it is likely, therefore, that their model is biased towards this type of noise. By adopting only two vehicle categories, they have probably imposed too severe a restriction on the application of their model. This could readily be overcome by extending the range of categories.

Furthermore, Sparkes and Large made broad assumptions concerning vehicle noise generation and operating characteristics. For example, their acceleration noise data were determined from laboratory studies of (constant speed) engine noise. Their model may be summarised, therefore, as one of essentially restricted application. It does however suggest that it is possible to simulate the combination of the noise generated by individual vehicles in an accelerating queue of vehicles to produce the total roadside noise.

Bowlby *et al.* (1989) developed an interrupted flow traffic noise prediction method for incorporation in the free flow traffic noise computer prediction programme STAMINA, developed from the US FHWA Highway Traffic Noise Prediction Model. By assigning "zones of influence" as areas where there were marked changes in vehicle speed (acceleration or deceleration), the resultant level of traffic noise is predicted by adjusting the free flow model by an equivalent constant speed that will produce the desired level differences relative to the freely flowing situation. Acceleration/deceleration is modelled by one or two zones of influence. The length of the zones was determined by field evaluation, and a series of equivalent constant speeds was developed for each vehicle type for each zone of influence. Validation showed good correlation with measured levels at signalised, unsignalised intersections (stop signs) and slip ramps (where initial and final speeds were non-zero).

In assessing the usefulness of this recent development it is necessary to consider:

(1) The extent to which the US FHWA prediction method for free flowing traffic can be adapted to suit traffic conditions in other countries.

(2) Owing to different vehicle fleet characteristics, it would be necessary to derive new parameters for the zones of influence, equivalent constant speeds, and possibly review the vehicle classification categories, if the interrupted flow-adjusted STAMINA computer program were to be applied outside the US.

(3) The appropriateness of the fundamental philosophy of adjusting traffic flow speeds to obtain equivalent noise levels under interrupted flow conditions.

Generally, the Bowlby *et al.* (1989) model is a specific development of the FHWA model and, unless the entire free flow/interrupted flow model were used, the usefulness provided by the interrupted flow amendment is not evident. It is considered that, until such time as the FHWA free flow model is evaluated for use in this country, it will not be possible to evaluate the interrupted flow portion of the model. This evaluation would have to consider vehicle classification categories and source strength factors in order to predict noise levels with sufficient accuracy under free flow conditions.

Wang (1975) developed a model which commenced with a treatment of the noise from a moving vehicle. By assuming the vehicle to be a point noise source, Wang postulated that the instantaneous sound field surrounding the vehicle could be treated mathematically as a conoid, the major axis of which rises vertically from the point source (located at ground level) to a magnitude equal to the source level of the vehicle under a particular operating condition. The passby noise/time profile of that vehicle as monitored at a roadside observer location could be determined by taking a vertical plane through the conoid, parallel to the direction of motion of the vehicle, at the observer location. Roadside noise measurements were simultaneously collected at varying distances up to 18 m from the road of individual vehicles in freely flowing traffic. These were used to determine empirically both the source levels and conoid shapes associated with three vehicle categories (motorcycles, cars and trucks) at speeds of 60, 80 and 100 km/h. After subsequent experience with the model it was modified slightly to account for observed directivity effects associated with vehicle noise.

Wang (1975) then applied his conoid noise model to the prediction of freely flowing traffic noise. For a given traffic situation the roadside noise/time history was simulated as the sum of the noise, predicted by the conoid model, produced by individual vehicles in the traffic. Traffic composition and directional split were selected using random number generators. Validation of the model was attempted by collecting data at five sites of freely flowing traffic. Wang's data are insufficient for a rigorous evaluation, but using these the initial results indicated that the model predicted L10, L50 and L90 generally within 3 dB(A). Thus, although the model is not yet adequately validated, early indications are that it appears promising and should be investigated further as it seems to be based on a reasonable application of basic acoustic theory.

Wang considered extending the model to include interrupted traffic flow situations. He argued that by adding acceleration and deceleration terms and by applying a random number approach to predicting vehicle arrivals at, say, a pedestrian crossing, the model could be adapted to suit interrupted flow conditions.

Wang (1975) demonstrated the feasibility of this approach by producing a computer program that incorporated a simplified expression for the noise generated by accelerating and decelerating vehicles (obtained from Hothersall and Jones 1976) and a formulation of his concepts of random number descriptors of vehicle arrivals and departures. Five measurement samples of interrupted traffic noise at a signalised pedestrian crossing indicated that, for cars only, the concept/theory was promising.

Generally the work of Wang (1975) can be described as providing a useful initial step towards the formulation of a robust theory and model of interrupted traffic flow noise. This model concerned freely flowing traffic and obviously has not yet been adequately validated. This model does, however, rely heavily on several assumptions concerning vehicle noise generation and propagation. It is not surprising, for example, that it was found necessary to adapt the noise conoid to allow for vehicle noise directivity effects (Samuels 1982). Further, he did not include any noise propagation parameters, as these were essentially catered for in the empirically determined noise decay envelopes which were mapped by the conoids.

In extending the conoid model to include interrupted flow situations, Wang (1975) did little more than to suggest that this is possible. His treatment of this topic was in essence both brief and rather inconclusive. The indications are, however, that the model could be developed and modified suitably to incorporate interrupted flow conditions. Such a process would also involve widening the range of parameters such as propagation distance and associated parameters, traffic speed and vehicle category covered by the model.

A model developed by the Australian Road Research Board (ARRB) (Samuels 1988) is based on aggregating the noise from individual vehicles passing through the intersection. The model commences with Vehicle Behaviour descriptors, which map the progress of each vehicle through the intersection. From there, Source-Receiver Geometry functions are created to determine the instantaneous distances between each observer location and every vehicle as the vehicles proceed through the intersection. At the same time, Noise-Source Relationships are formulated to quantify the noise output of each vehicle at all times during the intersection traverse. A schematic representation of the model is presented in Fig. 8.

The three primary model components of Source-Receiver Geometry, Vehicle Behaviour and Noise-Source Relationships are combined mathematically to calculate, at each observer location, the noise produced by a platoon of vehicles passing through one arm of the intersection. Superposition techniques are then applied to total the noise originating from both arms. By repeating these calculations over time, the noise history around the intersection may be obtained. Histories may be provided in both the frequency and the time domains, the latter allowing subsequent calculation of the conventional traffic noise indices such as L10(1h) and Leq (Samuels 1988).

Predictions of traffic noise levels at simple signalised intersections may be undertaken using the commercially available package ITFNS - Interrupted Traffic Flow Noise Simulation. The ARRB package comprises an interactive, personal computer version of a suite of programs that incorporate the algorithms and procedures of the model.

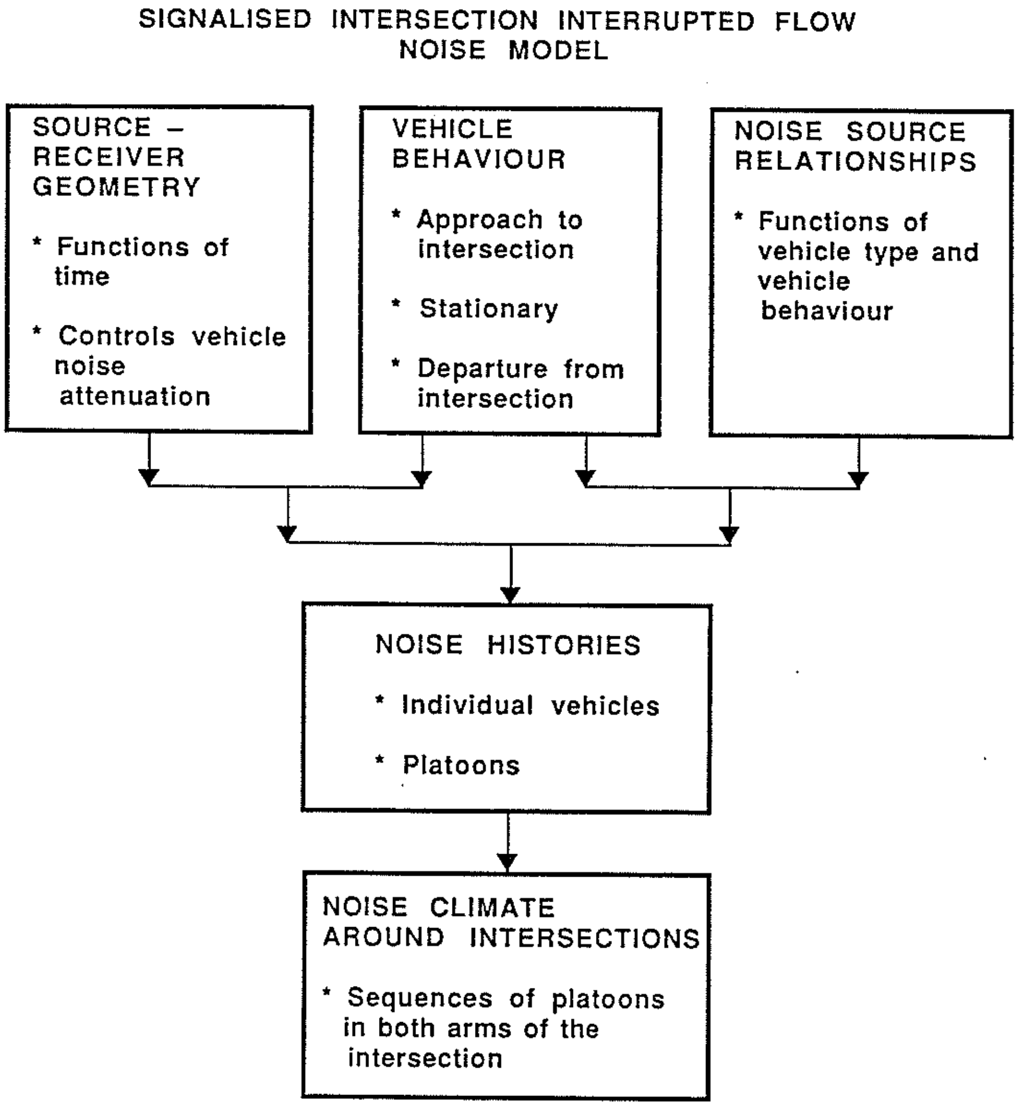


Fig. 8 - Interrupted Traffic Flow Noise Simulation (ITFNS)
Basic components and their relationships.

In general terms, the user must undertake the following six steps to conduct a prediction:

1. Define the intersection (dimensions)

2. Quantify the traffic volumes through the intersection

3. Specify the traffic signal sequences

4. Nominate an observer position

5. Specify the traffic flow characteristics (which may be random over time or otherwise specified as required)

6. Run ITFNS, responding to the requests for data, to predict either A-weighted or linear (unweighted) traffic noise levels.

2.5 Modelling Overview

Generally, modelling is based on individual vehicle noise levels which are aggregated in accordance with the various modelling equations. Usually the vehicle noise data had been obtained empirically from either controlled tests or from in-service data collection. In either case these data were generally collected under constant speed conditions, although this was certainly not always the case.

Significantly, these data were collected for a number of vehicles and then averaged values were employed to represent the noise from particular vehicle categories. Either two or three vehicle categories were generally adopted. These covered cars and light trucks, 'medium' sized trucks and heavy trucks. It was noted that both the selection and composition of these categories varied with the country of origin of the model. As with most free flow models, weight of vehicle was used as a surrogate classifier of vehicle noise output.

There are obvious limitations in applying constant speed noise data to an interrupted flow situation where acceleration and deceleration occur. Both the form and the peak magnitude of a vehicle noise profile monitored under constant speed conditions will usually differ from that under interrupted flow conditions. (See pp.8-9 for Flynn *et al.* (1980) data). Also, the character of the noise, as reflected in the instantaneous frequency spectra at various times throughout the profiles will be considerably different for the two flow conditions.

However, having obtained the constant speed vehicle noise information, modellers (e.g. Bowlby *et al.* 1989, Wang 1975, Sparks and Large 1980, and Favre 1978) would then consider various characteristics of the traffic under study. This was done by reference to traffic engineering literature or by assumption or, in some cases, empirically. Vehicle arrival patterns at an intersection, for example, tended to be described as random or as given by various statistical distributions. When traffic flow alone was incorporated in the models, a similar situation arose, with, say, vehicle headways usually being described by some form of exponential distribution. A desired speed parameter of one form or another was often employed and was usually based on a truncated normal distribution with specified mean and variance.

All models then required some treatment of acceleration and deceleration behaviour. Typically this would also involve assumptions concerning exactly where the acceleration/deceleration manoeuvre occurred. The vehicle categories were used here and some averaged acceleration and deceleration relationships were employed. Then, by applying both the other traffic information and the constant speed vehicle noise data, a simulation of the traffic noise source levels was obtained.

At this point propagation parameters were introduced and there appeared to be a wide variety of approaches to dealing with this issue. A common technique was to assume a uniform rate of attenuation of about 6 dB(A) for each doubling of distance. Empirical data were sometimes used and these were often site-specific. In some cases the earlier measurements of vehicle noise source levels were conducted at varying distances from the vehicle trajectories and these data were employed in such a fashion as to incorporate propagation effects. Additional propagation parameters were not, therefore, adopted in these cases and this approach appears reasonable.

Once the noise propagation factors had been applied to the traffic noise source levels, simulation of the traffic noise at the roadside was achieved. This noise varies with time and a common modelling approach was to simulate the noise/time history and from there to derive predictions of indices such as L1, L10, L50, L90 and Leq over nominated time periods. All predictions were provided in sound pressure, dB(A), levels. There was little or no discussion if these indices and units were appropriate for interrupted flow or indeed free flow traffic situations. The unstated assumption seemed to be that since these indices and units had been widely adopted when dealing with freely flowing traffic noise, then they would be suitable for interrupted flow traffic noise. Indeed there is good argument for retaining a consistent set of units to deal with another aspect of traffic noise.

The performance of the models was generally variable and, in most cases, inadequately determined. For the most part insufficient data were applied to this task.

An assessment of the performance of existing free flow traffic noise models when applied to interrupted flow situations involved the US NCHRP and the UK DoE prediction methods being applied to some of the Flynn *et al.* (1980) interrupted flow noise data. Both models performed inadequately and some of the difficulties that arise when attempting to apply a free flow model to an interrupted flow case were determined.

Generally such problems occur because the two kinds of flow are not comparable and are associated with selecting appropriate parameter values to use in the model. The parameter of speed is a good example. Free flow models are based on constant speeds, yet speed is one parameter that is not constant during interrupted traffic flow. Selection of a suitable speed is left to the discretion of the user of the model and this might typically involve some means of averaging or even weighted averaging. However since no statistical information on the effects of this selection are available, predictions made on this basis must be regarded as little more than guess-work. Furthermore the inherent problems associated with the differences in vehicle noise output at constant speed compared with those during acceleration or deceleration also came into effect. Similar problems to these arise when attempting to select values of most other parameters such as traffic flows, vehicle mix, and propagation distances.

3. MODEL SELECTION

On the basis that this review has included all relevant prediction procedures for traffic noise under interrupted traffic flow conditions, the assessment and final selection of one model for further investigation was based on the following conditions:

(1) In the absence of any evidence to the contrary, it is worth using the same noise descriptors for interrupted traffic flows as for free flowing traffic. The available methods of centile levels (e.g. L10) and equivalent continuous level (Leq) for quantification of traffic noise have established methods for both the measurement of noise and for the assessment of community response.

(2) The performance of the model with regard to comparisons with measured levels (predicted versus measured) is an important aspect in assessing performance. Most models have not undergone rigorous testing, although two examples (Samuels 1988 and Bowlby *et al.* 1989) have been subjected to reasonably thorough testing at a number of sites.

(3) The model must be flexible for use under conditions other than those under which it was developed. For example, vehicle source noise levels are known to vary between countries. Having provisions in the model to use source levels representative of New Zealand conditions overcomes this.

(4) The model should be relatively easy to use. A computer program (or the possibility of development into a computer program) is a useful way to reduce calculation time, errors, and to store output data.

(5) The model should handle data typical of New Zealand traffic situations where interrupted traffic flows occur. As a minimum, it should handle signalised intersections and should preferably be capable of being developed into a model that can predict traffic noise under most interrupted flow conditions.

4. THE ARRB MODEL

4.1 Overview

ARRB has developed an interrupted flow model, known as ITFNS (Interrupted Traffic Flow Noise Simulation), for signalised intersections in Australia (Samuels 1988). The model provides roadside noise histories generated by traffic at a simple, signalised intersection and also by traffic on a straight road under free flow conditions. Model predictions have demonstrated the complexity of the noise generation process at an intersection and how the various components interact to produce the intersection noise histories. The noise generation characteristics of individual vehicles, platoons of vehicles and sequences of platoons in one and in both roads of the intersection have been identified and the effects of other relevant factors, such as roadside observer location, have also been demonstrated. By evaluation against a variety of empirical data the model was found to be a good predictor of roadside noise histories generated under both interrupted and free flow conditions.

From there, a procedure has been developed for the prediction of traffic noise at a simple, signalised intersection by means of an interactive computer package. This package was developed following evaluation of the model. It provides several outputs which include noise/time histories and histograms, along with the conventional indices such as L10 and Leq. This package is fully documented in Samuels and Shepherd (1989). An example of the package outputs is presented in Fig. 9 where a noise history and noise histogram are presented for a particular intersection. Also shown in this example are the conventional indices L10, L50(1h) and L90(1h). The model will conduct such predictions over each hour so that, over one day, indices such as the L10(18h) may also be determined. Information of the type in Fig. 9 which constitutes the primary output of the commercially available computer package. ITFNS has been designed to run on any IBM-compatible PC with a hard disk. To install the software the user will require 1Mb of hard disk memory. An additional minimum of 2Mb will be required for output files.

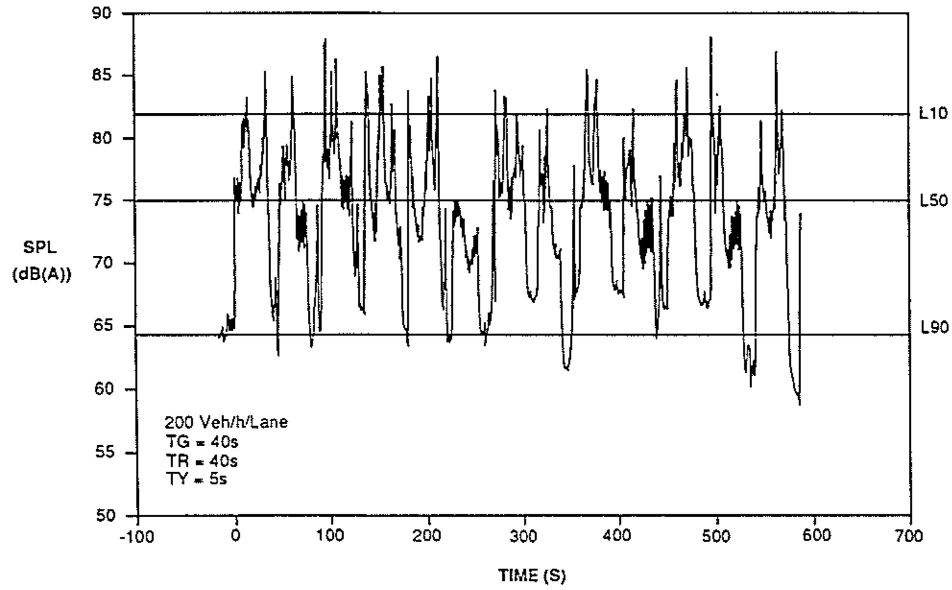


Fig. 9a - Model output - Noise history. TG = Duration of Green Signal (TR & TY have similar meanings for Red and Yellow signals).

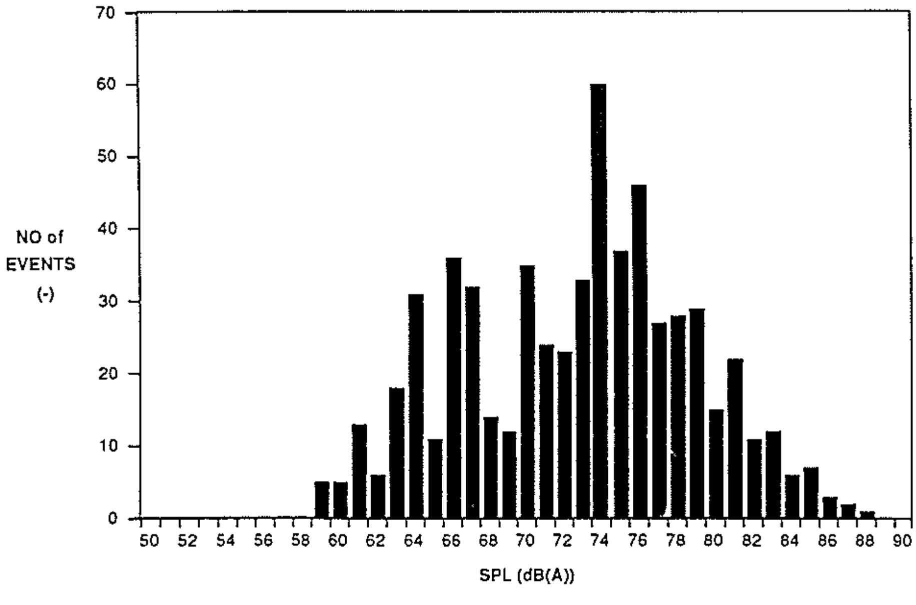


Fig. 9b - Model Output - Noise histogram.

4.2 Evaluation of the Model

Evaluation of the model involved assessing its performance against measured traffic noise data. For this purpose relevant data available from both the US and the UK were adopted initially. In addition, noise, traffic, and site data were collected at two Australian intersections specifically for the model evaluation so that model predictions could be assessed directly against measured levels. Some free flow data was also collected for further evaluation of this aspect of the model. The evaluation is fully documented in Samuels (1988).

The overall approach of the evaluation has been to investigate the model in terms of its noise history outputs. This is because the model is directed at quantifying and assessing noise generation. Consequently a programme of investigating specific aspects of the model components (Fig. 8) was not undertaken as these may simply be regarded as internal to the model and do not affect the final outputs. Furthermore, it is essential that the model provides accurate noise-time histories. In this way the noise indices, which are merely descriptors of these histories, will be both accurate and valid.

The performance of the model in predicting the noise generated by a platoon of vehicles was assessed initially by using the data that was carefully collected under controlled conditions and well documented by Flynn *et al.* (1980). In addition, limited data provided by Sparkes and Large (1980) of the noise produced by platoons in one arm of an intersection also assisted the assessment of the performance of the model. These evaluations were fully discussed in Samuels (1988) where it was shown that the model performed very well in predicting the measured noise histories. As an example of model performance, the match with the Flynn *et al.* (1980) data for the US is reproduced in Fig. 10.

A more detailed evaluation, which both complemented and extended the comparisons conducted thus far, was based on data specifically collected in Australia for the purpose. Noise and accompanying traffic data were monitored simultaneously at each of three sites in outer suburban Melbourne. Two of the sites were signalised intersections (interrupted flow conditions), while the third was an isolated, straight road where traffic flowed freely. Once again the objective of this part of the evaluation was to assess the performance of the model in predicting measured roadside noise histories under both interrupted- and free-flowing traffic conditions. Again, refer to Samuels (1988) for full details.

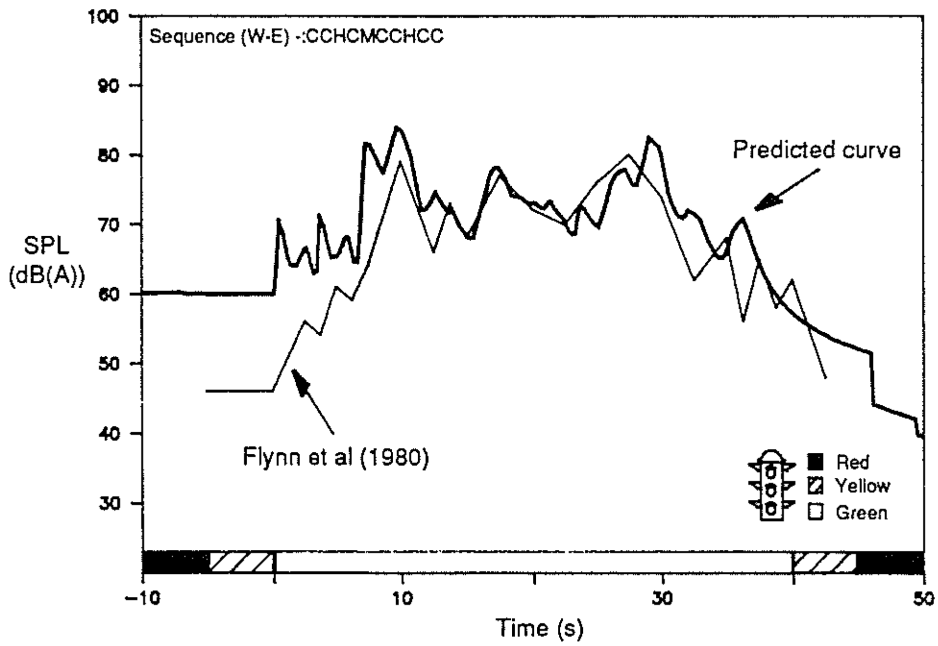


Fig. 10 - Predicted and measured data for the noise histories of an accelerating platoon of vehicles (after Samuels 1988).
C = car, M = medium truck, H = heavy truck.

Typical of these evaluation results are the three samples of noise histories of Fig. 11. In all cases there is generally very good agreement between the measured and the predicted histories. Both the temporal and level fluctuations of the predicted curves match well those of the measured histories. Some minor discrepancies are evident, and these no doubt reflect variations in both noise source levels and operating conditions during passage through the intersection of individual vehicles in the observed traffic. Such variations might reasonably be expected as a result of the representative nature of the vehicle noise source and performance characteristics embodied in the model. However these variations are generally small. The approach of using representative vehicles is suggested to have been successful (Samuels 1988). Similarly good results were also obtained at the other sites, including the free flow condition site. On this basis it may be concluded that the model has been found to be a good predictor of the noise histories generated by a variety of traffic operating under both interrupted flow conditions and free flowing conditions. The model therefore, has provided a means by which the noise generation processes can be understood and quantified.

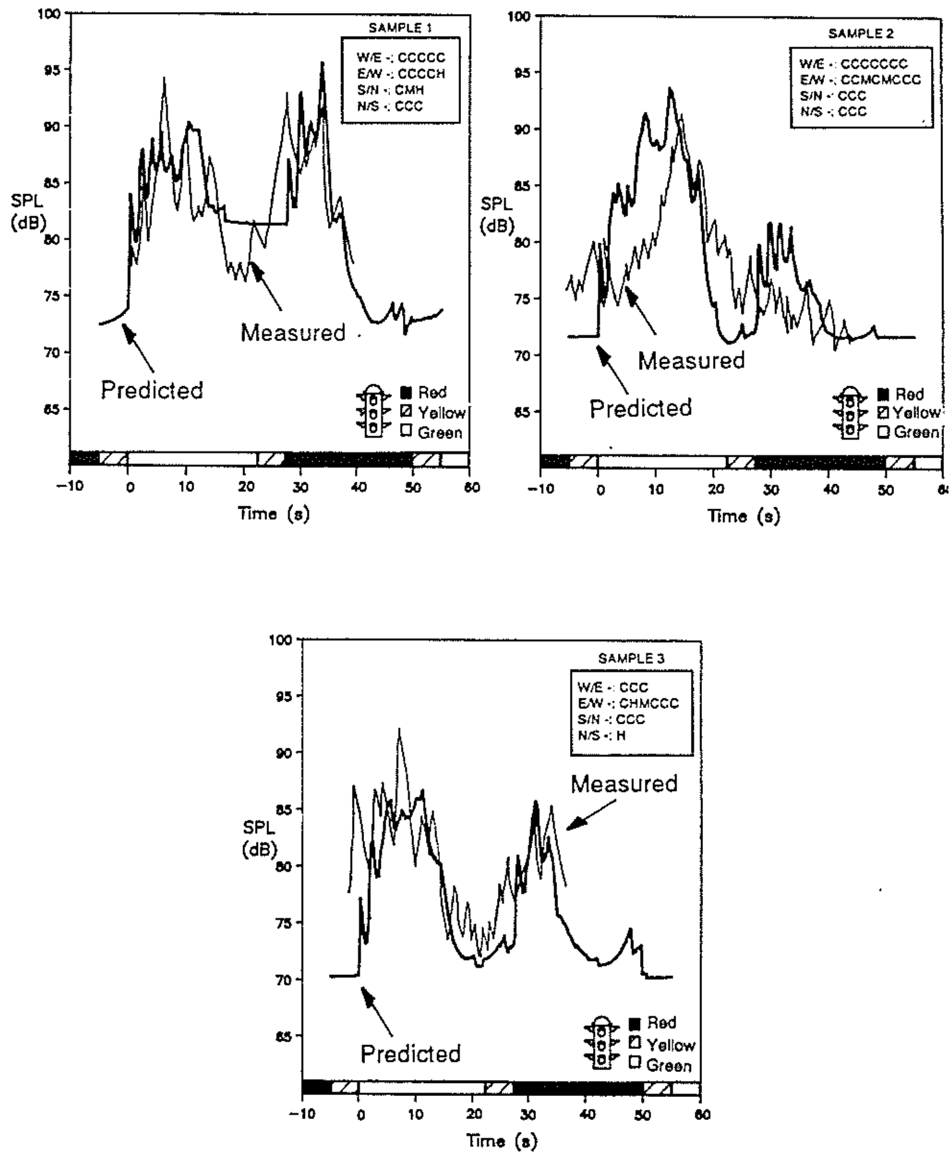


Fig. 11 - Predicted and measured noise histories for Australian data on one site. Platoons are shown for each direction (W/E = West East, etc.). Platoon compositions are C: Car, M: Medium Truck and H: Heavy Truck.

4.3 Sensitivity Analysis of the Model

A sensitivity analysis of the model has been undertaken to illustrate both its performance and some salient features of traffic noise at signalised intersections. Several relevant parameters were varied for the analysis and were chosen to investigate fundamental effects in the three major components of the model, namely the source-receiver geometry, the vehicle behaviour and the noise-source relationships (Fig. 8). The parameters are as follows:

Observer location
Platoon composition in all directions
Platoon composition in each direction
Platoon sequences
Vehicle headway
Vehicle noise source strengths

The analysis was conducted for the intersection depicted in Fig. 12, with lane dimensions W=L=5 m, cycle sequence tg = 40 s and ty = 5 s. Predictions were made of the intersection aggregate noise level at Observer O1 (x = y = 15). To conduct the analysis, the model was run as appropriate for each parameter set, the ranges of which are listed in Table 2. Results of the analyses are summarised here, as follows:

1. Observer location (Table 2, Fig. 13)

The three runs show a clear trend of decreasing noise level with increasing distance from the source, although complexities are caused by the variable nature and locations of the sources. Moving from Observer O1, away from the intersection, parallel to the NS/SN road as shown in Run 1, Fig. 13, a reduction in the peak of the noise history caused by the passage of the EW/WE traffic has occurred. The maximum peaks have reduced by some 7dB. Simultaneously some complex changes may be observed in that part of the history due to the NS/SN traffic (these peaks occur during the red phase in Fig. 13). Both increases and decreases have taken place and these correspond to the position of the observer relative to the various vehicle manoeuvres. For instance, the second of the two prominent peaks in the NS/SN traffic component of the noise history relates to the acceleration manoeuvre of the platoon moving from North to South. This peak may be seen to increase as the Observer distance is increased (to the South). But in so moving the Observer is merely being positioned closer to the point of maximum acceleration noise output and this explains the observed peak increase, which is in the order of 3dB.

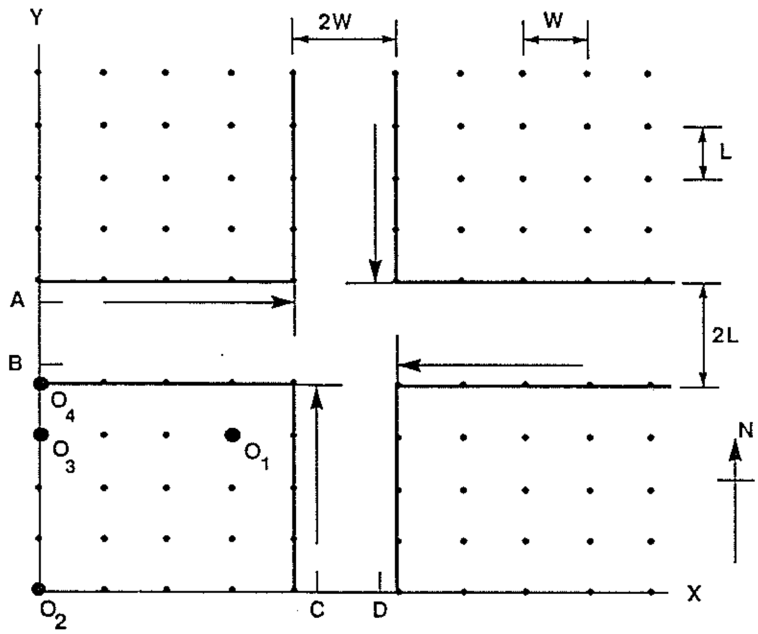


Fig. 12 - Signalised intersection showing traffic flow directions and array of observer locations (O1 - O4). The observer array may be extended as required. L = length; W = width; A,B,C,D = lanes.

The same trends, but in the reverse direction, were found for Run 2 (Fig. 13) when the Observer moved away from the intersection parallel to the EW/WE road. In the third case (Run 3, Fig. 13) the Observer moved diagonally away from the intersection and this induced a general reduction in all levels. At the most distant observer location, the levels had reduced by 5 to 6 dB which is consistent with the increased propagation distance involved.

Generally, therefore, the effect of increasing distance from the intersection depends on the direction by which the distance is increased. Overall the noise levels decrease with increasing distance, but this trend is by no means clear cut. Since the model illustrates that the traffic noise generation varies both in magnitude and temporally along the roads forming the intersection, moving 'away' from the intersection can mean in some cases moving closer to a location of higher noise output. In so doing the increased noise attenuation from increased distance can be offset by the increased source levels at the new observer location.

Table 2 - Sensitivity Analysis Parameters

1. Observer Location

RUN 1		RUN 2		RUN 3		Comments
X	Y	X	Y	X	Y	
15	15	15	15	15	15	See Figure 13
15	10	15	5	15	0	

2. Platoon Composition - All Directions

	RUN 4				RUN 5		
C	M	H	Total	C	M	H	Total
17	1	1	19	19	0	0	19
8	1	1	10	10	0	0	10
4	1	0	5	5	0	0	5

3. Platoon (P) Composition - Each Direction

Platoon Composition

Platoon	C	M	H	Total
P1	17	1	1	19
P2	8	1	1	10
P3	10	0	0	10
P4	5	0	0	5

Platoon Splits

Run No.	EW	WE	NS	SN
6	P1	P1	P1	P1
	P1	P1	P2	P2
	P1	P1	P3	P3
	P1	P1	P4	P4
7	P1	P1	P1	P1
	P2	P2	P2	P2
	P3	P3	P3	P3
	P4	P4	P4	P4
8	P1	P1	P1	P1
	P1	P4	P4	P4
	P1	P4	P1	P4
	P4	P1	P4	P1

Table 2 (Continued)

4. Platoon Sequence

Run No.	Cycle	Platoon Split EW	WE	NS	SN	Comments
9	1	P1	P1	P1	P1	Using P1 as a reference platoons in two directions are varied over successive sets of signal cycles.
	2	P2	P1	P1	P1	
	3	P3	P1	P1	P1	
	4	P4	P1	P1	P1	
10	1	P1	P1	P1	P1	
	2	P1	P1	P2	P1	
	3	P1	P1	P3	P1	
	4	P1	P1	P4	P1	

5. Vehicle Headway

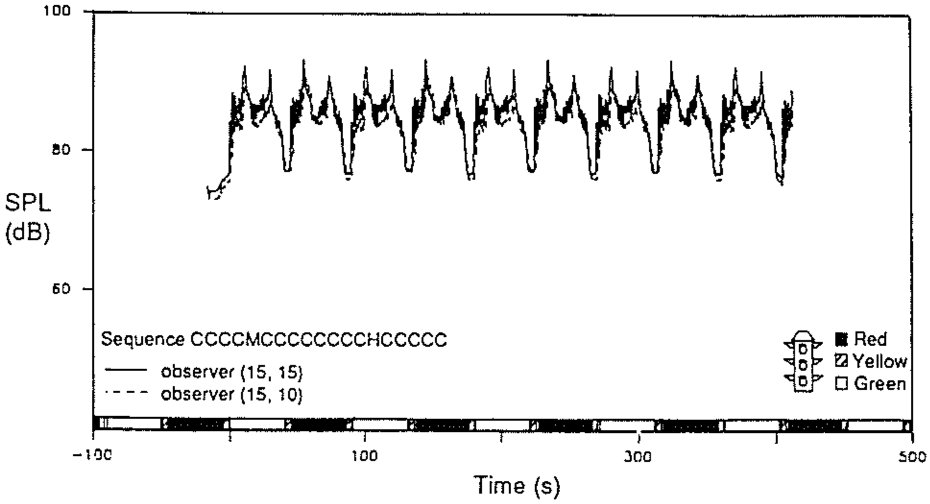
Run No.	Relative Headway EW	WE	NS	SN	Comments
11	1.00	1.00	1.00	1.00	Using P1 as a reference the headways are varied for each direction. P1 operates repeatedly in all directions.
	0.50	0.50	1.00	1.00	
	1.00	1.00	0.50	0.50	
	0.25	0.25	1.00	1.00	
	1.25	1.25	1.00	1.00	
	1.50	1.50	1.25	1.25	
	1.50	1.50	1.00	1.00	

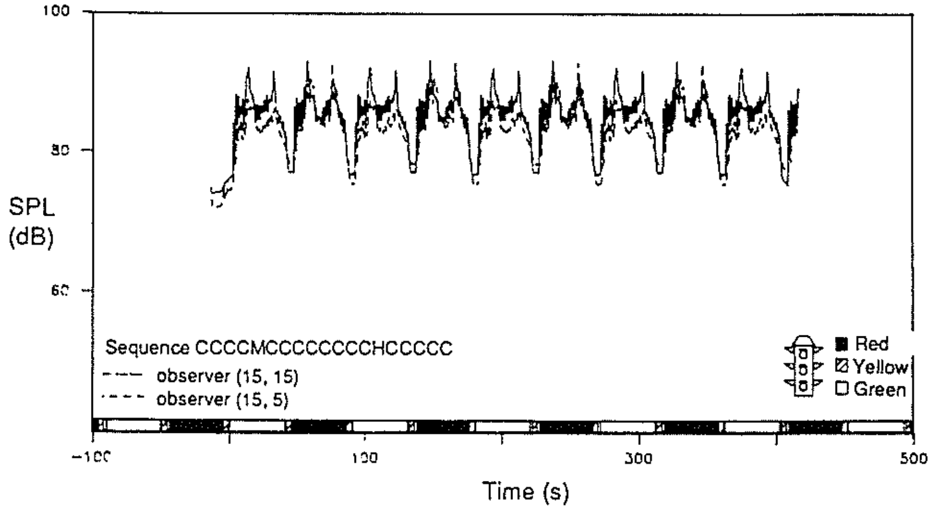
6. Vehicle Noise-Source Strengths

Run No.	Source	C dB(A)	M dB(A)	H dB(A)	Comments
12	Deceleration	61.2	80.6	81.6	Using P1 as a reference, source strengths are varied + or - 10 dB(A) for each vehicle. P1 operates repeatedly in all directions
		71.2	90.6	91.6	
		51.2	70.6	71.6	
13	Stationary	60.0	75.0	75.0	
		70.0	85.0	85.0	
		50.0	65.0	65.0	
14	Acceleration	original	original	original	
		O + 10	O + 10	O +10	
		O - 10	O - 10	O - 10	
15	Constant Speed	75.0	84.5	84.5	
		80.5	94.5	94.5	
		60.5	74.5	74.5	

2. Platoon Composition - All Directions (Table 2, Fig. 14)

Results of Run 4, reducing the 19-vehicle platoon to platoons of 10 and 5 vehicles, are given in Fig. 14. The immediate and expected observation is that the noise peaks become narrower (in time) as the platoon size decreases. This induces longer periods of lower noise level, which tends to emphasise slightly the noise generated by each platoon on approach to the intersection. The same observations were made for Run 5 where the platoons comprised only cars.





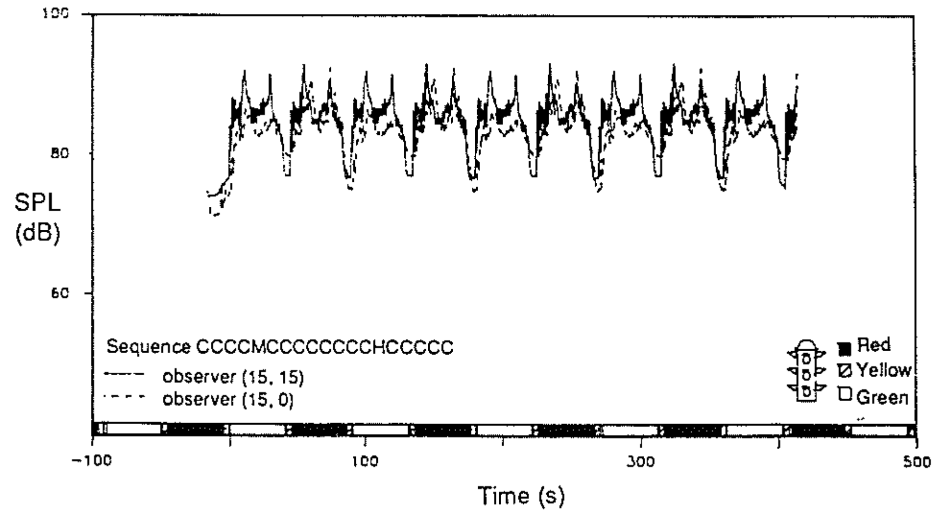


Fig. 13 - Noise level variations with observer location.

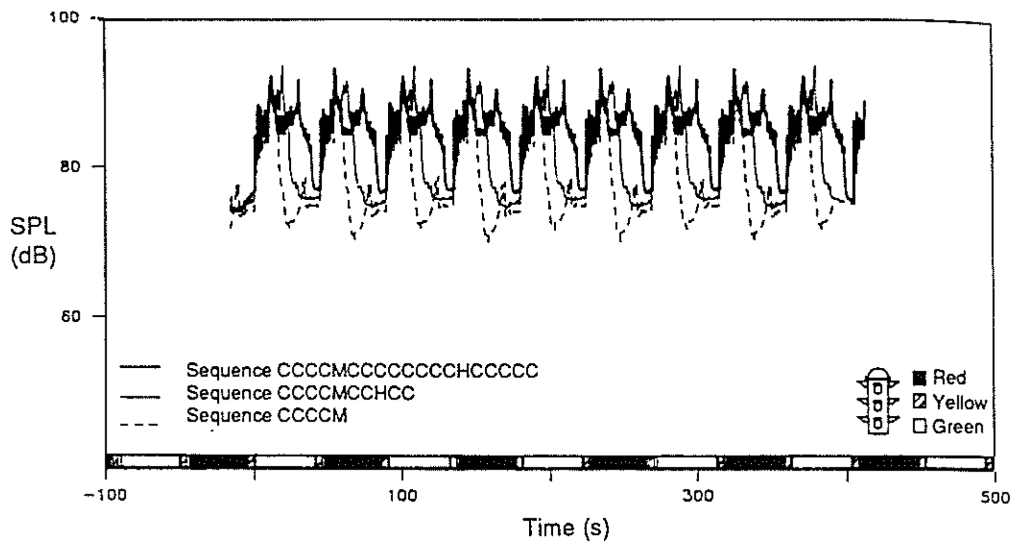


Fig. 14 - Noise level variations with platoon composition varied uniformly in all directions, for Run 4 (Table 2).

The importance of trucks in the generation of interrupted flow noise is apparent in Fig. 14. For any platoon, the peaks associated with the trucks at 95 to 97dB are around 10 dB above those due to the cars. (This observation was also supported by Run 5 where the levels were uniformly in the 85 to 87 dB range.) It may be observed that the first part of the noise histories of each platoon are similar since the first five vehicles in each are the same. Later in the cycle noise histories vary in width (time) with subsequent prominent peaks being associated with a heavy vehicle in the first two cases.

The nature and results of this example have suggested that some of the conventional wisdom concerning traffic volume and composition (e.g. UK DoE 1975, Kugler *et al.* 1976) for free flow conditions is somewhat related to interrupted flow noise generation. While increasing flow and truck content in the traffic lead to increased noise levels, the detailed effects of these parameters are more complex for interrupted flow. Flow appears to control the duration of the interrupted flow noise peaks while truck content seems to have a major influence on the absolute magnitudes of these peaks. In addition, the acceleration noise components of all vehicles are important as these also make a substantial contribution to the peak levels of the noise histories (Fig. 14).

3. Platoon Composition - Each Direction (Table 2 (3), Fig. 13, 14)

So far consideration of the model has involved the simplifying condition that identical platoons operate repeatedly in all directions through the intersection. Although a little artificial, this technique has allowed ready identification of noise generation behaviour. Relaxing the condition has involved the consideration of alternative platoons and for simplicity the four shown in Part 3 of Table 2 were adopted. These platoons were run through the intersection to explore the effects of platoon composition in each direction. Relatively simple cases were selected here so that the important primary effects were not lost in excessive detail. The aim (as with all parts of the present Sensitivity Analysis) was to investigate trends and representative behaviour by means of suitable parameter selection, rather than to consider every conceivable possibility.

Platoon P1 was used as a reference and various combinations of the four platoons were run repeatedly using Runs 6 to 8 in each direction. The output for Run 6 (Fig. 15) is typical of the three. The first curve is a repeat of the first in Fig. 13 and 14. Note that in all three curves, Platoon P1 is maintained in the EW and WE directions. As the platoons contract in the other directions, the duration and level of the noise peaks associated with these directions also reduce, in line with the previous observations. These changes appear to have no influence on the EW/WE components of the noise history. Similar trends were noticed in the Run 7 and 8 outputs, with the noise history components for each direction reducing successively and independently in both level and duration as the platoon size and composition were contracted.

The noise generation behaviour demonstrated by this case is one of independent source arrays operating in each direction through the intersection. This would be expected from the configuration of the model and might also suggest that the condition of repeated equivalent platoons in a given direction is a reasonable first approximation as far as modelling noise generation is concerned.

4. Platoon Sequence (Table 2 (4), Fig. 16)

To consider the effects of repeating identical platoons through the intersection, platoon composition was varied sequentially as shown in Part 4 of Table 2. The results for Run 9 where the platoons proceeding in the EW direction are varied in sequence progressively over four successive signal cycles are shown in Fig. 16. Again Platoon P1 sets the reference condition and it is the noise produced during the green phase of Fig. 16 that is affected by variations in the EW platoons.

It is apparent that progressively reducing the size of the EW platoon (from P1 to P4) produces a corresponding reduction in the noise history components produced by that road. These noise components are comprised of two prominent sets of peaks, the first of which is produced by the WE-moving platoon and the second is from the EW platoon. The latter peaks, as expected, experience the major change. This effect is a gradual reduction such that the P4 condition is some 5 to 6 dB(A) below the P1 condition and results from the contraction of the platoon. Accompanying this is a 2 to 3 dB reduction in the peaks associated with the WE platoon and this ensues from the aggregation of the levels from each (WE and EW) platoon to produce the total noise for the road. It is also apparent that the noise history components caused by the NS/SN platoons are not affected by these EW platoon changes.

The overall effect in this case is a systematic reduction in noise levels corresponding to a systematic contraction in platoon size and composition. The same effect was observed for the NS/SN noise components in Run 10. These observations are consistent with those made earlier in the Sensitivity Analysis. They indicate the strong influence of traffic composition on roadside noise under interrupted flow conditions. For random traffic, platoon composition would be varying continuously in all directions and fluctuations of the type systematically occurring in Fig. 16 would be experienced (randomly) in all components of the roadside noise history.

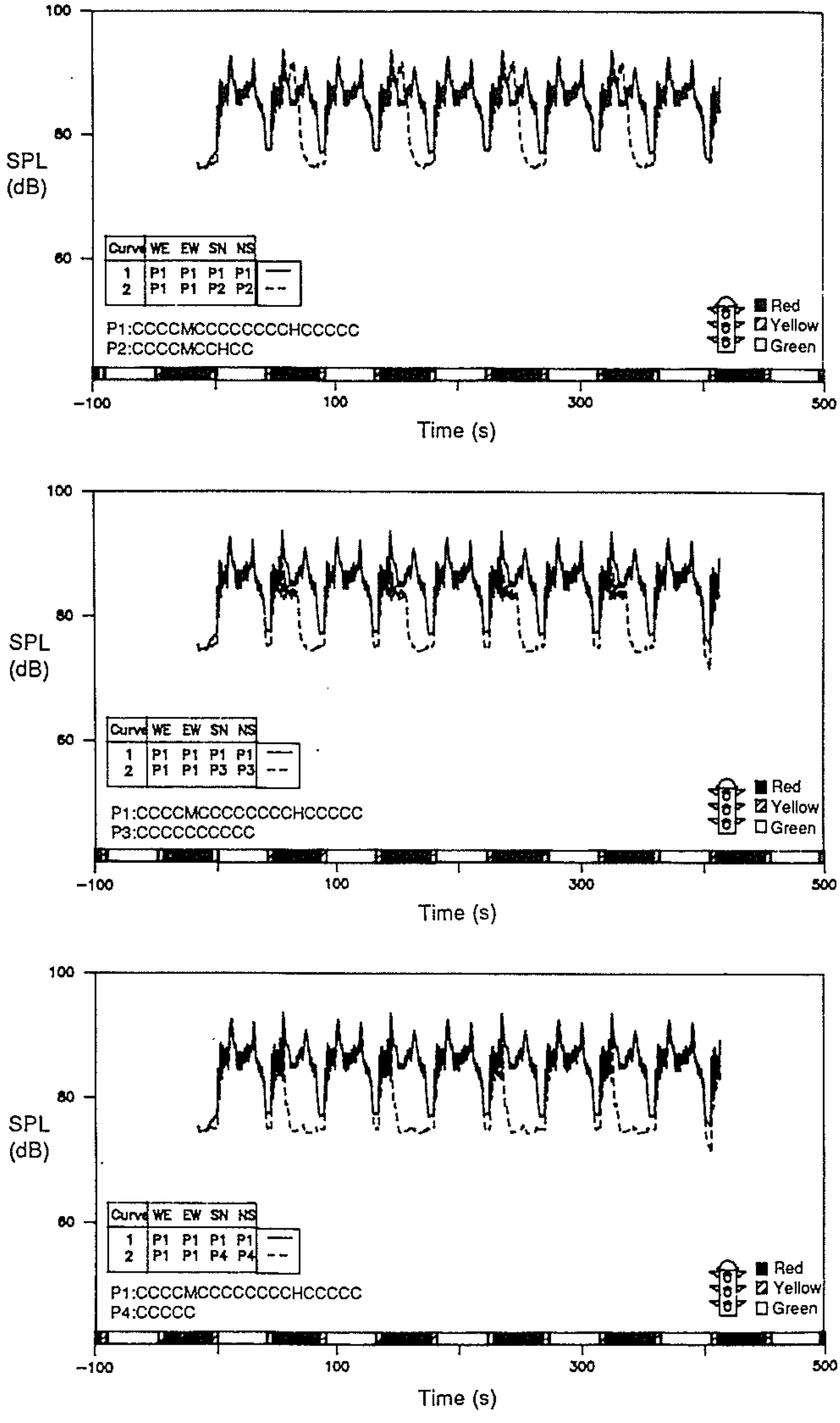


Fig. 15 - Noise level variations with platoon composition varied selectively in each direction (Table 2).

5. Vehicle Headway (Table 2 (5), Fig. 17)

The model assigns what is termed "headways" (i.e. the time between vehicles) to vehicles departing the intersection. The headway separates departures of successive vehicles in a given platoon. Since the noise history of a platoon is determined by aggregating the noise outputs of all vehicles in the platoon, both the magnitude and shape of the history will depend on the relative positions of the vehicles. These positions depend initially on the headway and consequently it was of interest to investigate such headway effects. To do this, Platoon P1 was again used as a reference condition and the headway varied between ±10% as listed in Part 5 of Table 2.

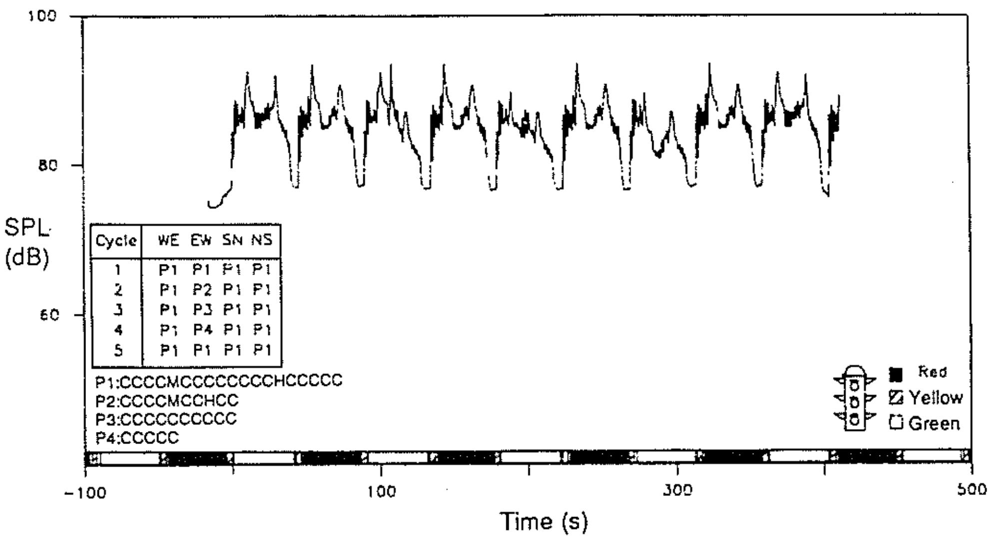


Fig. 16 - Noise level variations with platoon sequence (Table 2).

Clearly shown in Fig. 17 is that the effect of headway primarily controls the duration of the noise history of a given platoon. The duration is directly related to headway and increases proportionately with headway increase. As observed previously, such changes in the noise history of one road do not influence the history from the other road of the intersection. It is interesting to note that the peak levels of Fig. 17 are not changed appreciably by varying headway. As headway reduces there appears to result a more sustained, slightly more uniform, period of near-peak level noise. Conversely, by reducing the noise history duration, increased periods of lower roadside noise level will result. Manipulating headway by, say, traffic management techniques, may prove to be a useful traffic noise control strategy.

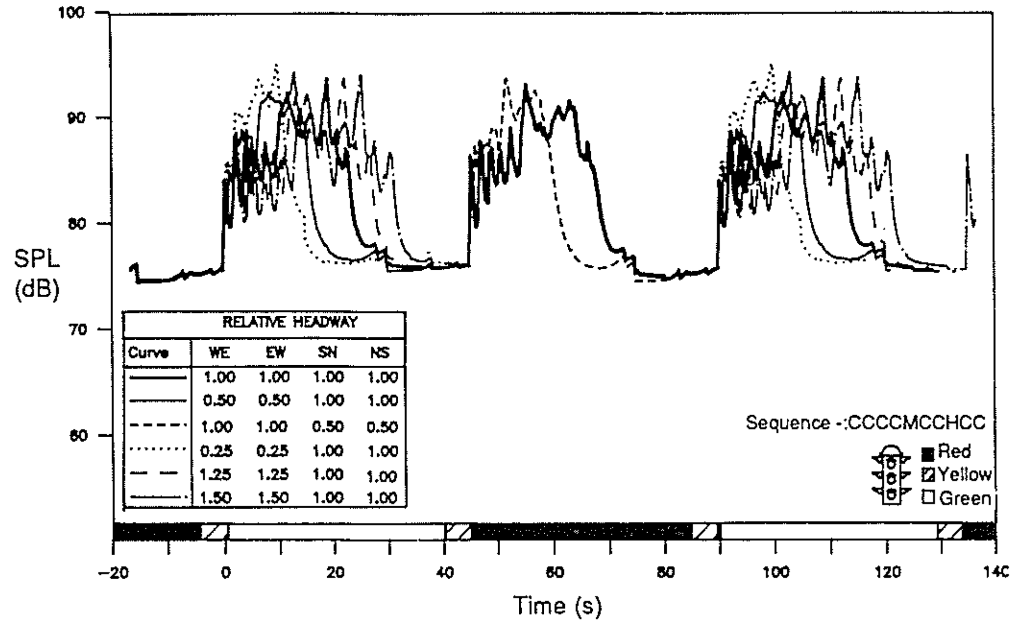


Fig. 17 - Noise level variations with vehicle headway.
(Table 2).

6. Vehicle Noise Source Strengths (Table 2 (6), Fig. 18)

A fundamental factor in the generation of all traffic noise is the strength of the vehicle noise sources. Much detail is given in Samuels (1988) of how this factor is incorporated in the model. Effects of the factor were investigated by independently varying the source strengths for each of the four vehicle operating conditions through a 20 dB(A) range in Part 6 of Table 2. Results of these runs appear in Fig. 18.

For deceleration (Fig. 18a), reducing the source strengths by 10 dB(A) appears to have a negligible effect on the overall noise history. An increase of 10 dB(A) has the effect of introducing a few more peaks into the history. These would be associated particularly with the already high levels of the H and M category source strengths. Such deceleration levels would be rare in practice but might be around the level associated with the rapid deceleration of a heavy vehicle with air brake assistance (Broner and Mizzi 1980). Generally, therefore, the effects of varying deceleration source strength are minor.

The situation for the stationary source strength (Fig. 18b) is, however, quite different. Here the variations in source strength either reduce or increase the noise history level in that period between the major peaks. The magnitude of these changes is approximately equal to the magnitude of the source strength changes. Further, when the stationary strengths are increased by 10 dB(A), this compounds the effect by adding to some of the peak levels as shown in Fig. 18b. The fluctuations in the noise history from periods of high noise level to those of low level are much reduced. This results in a much more uniform or continuous noise history. It would appear that there is some scope for interrupted flow traffic noise control by controlling the stationary, idle, noise output of all vehicles. The present model is obviously quite sensitive to variations in this parameter for all vehicles. This pattern is known to be further emphasised at greater distances from the intersection where the rise and fall of the peaks in the history are more gradual (see Fig. 13).

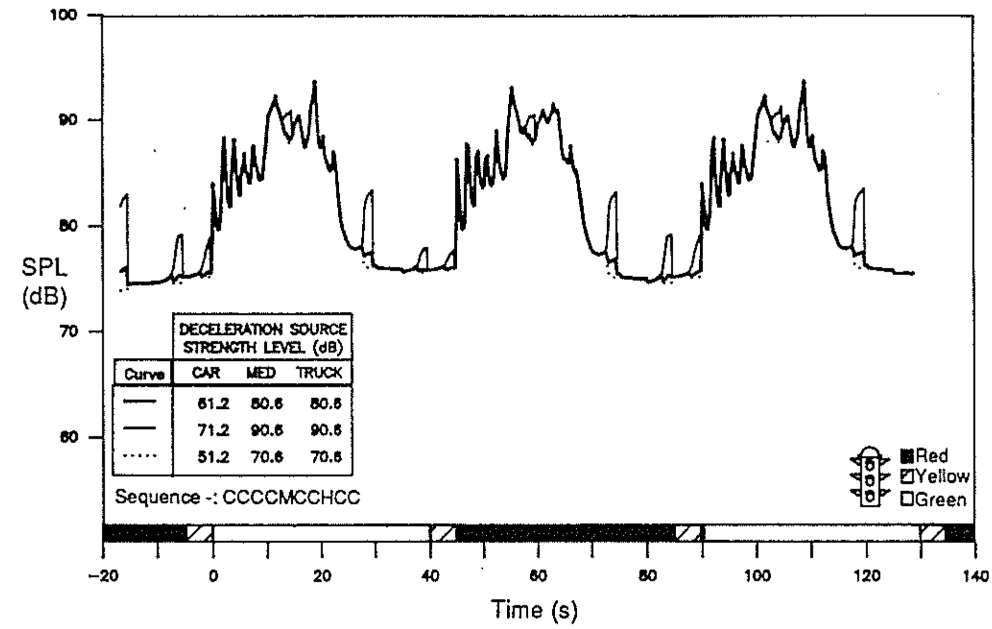


Fig. 18a - Noise level variations with vehicle deceleration source strength.

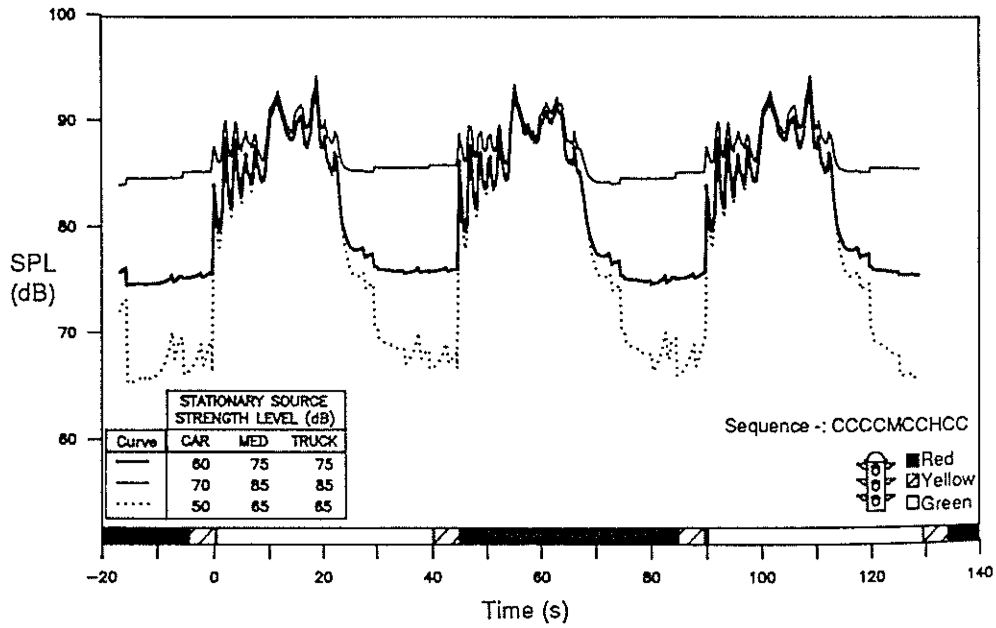


Fig. 18b - Noise level variations with vehicle stationary source strength.

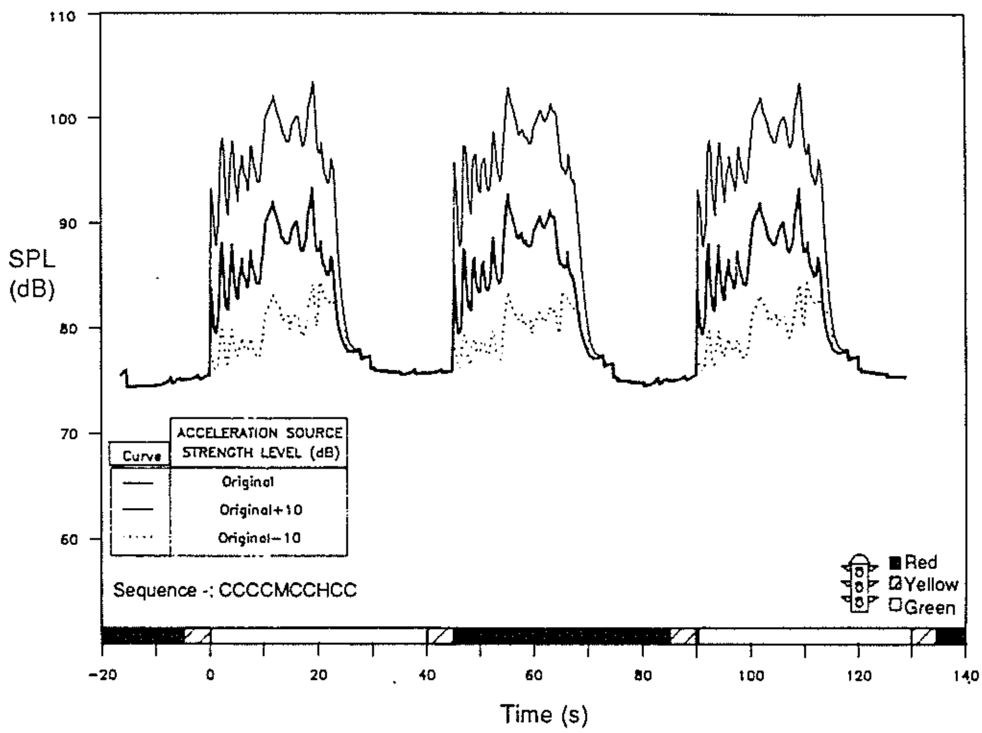


Fig. 18c - Noise level variations with vehicle acceleration source strength.

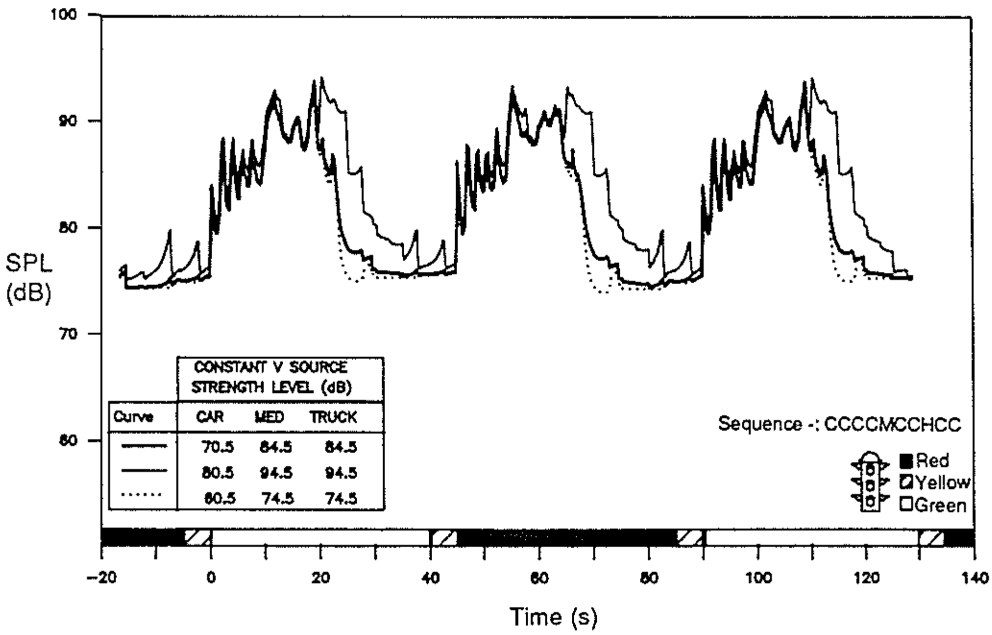


Fig. 18d - Noise level variations with vehicle constant speed source strength.

Varying the acceleration noise source strengths (Fig. 18c) has perhaps the most dramatic effect of any source strength change considered in this study. Here the major components of the noise history increase and decrease in direct relation to the acceleration source strength variations. While these variations were uniform for all vehicles, the observed sensitivity of the model does emphasise the importance of the acceleration manoeuvre in the noise generation process. Note that, with a 10 dB(A) reduction in all acceleration source strengths, the peaks in the noise history fall to within around 10 dB(A) of the lower levels of the given noise history. Reduction of acceleration source levels would appear to offer good potential for the control of interrupted traffic flow noise.

Increasing the duration of the noise history peaks seems to be the primary effect of increasing the constant speed source levels (Fig. 18d). These higher source levels during the intersection departure phase add considerably to the overall noise history. Minor, but compounding, increases also raise the approach levels. Reducing the constant speed source strengths apparently has a negligible effect on the noise histories. From these results, a prudent noise control strategy might ensure that constant speed source levels do not increase above existing levels. However a strategy that reduces noise from free flowing traffic might have little or no effect as far as interrupted traffic flow noise is concerned.

4.4 Summary of Sensitivity Analysis

Generally consistent results from the sensitivity analysis have demonstrated both the performance of the model and how relevant parameters interact to generate interrupted flow traffic noise. The ARRB model appears to produce output which is consistent with acoustic theory and which varies reasonably with variations in a range of input parameters. The major effects of the relevant parameters may be summarised as follows:

> OBSERVER LOCATION
> Noise levels decrease with increasing distance from the roadways, but this decrease is dependent upon the direction in which distance is increased. When moving parallel to one road the peaks generated from either road vary somewhat differently, as expected. The greater reduction at these locations occurs in the noise history peaks associated with the arm of the intersection perpendicular to the direction in which the Observer moves away from the intersection.

PLATOON COMPOSITION AND SEQUENCE
Heavy and Medium category vehicles appear to dominate the noise generation process. Peaks in the roadside noise history decrease as platoon sizes reduce. Platoons in each arm of the intersection appear to operate as independent source arrays. It also seems that modelling using equivalent, repeated platoons in each direction represents a reasonable first approximation. Roadside noise histories respond directly to variations in platoon size, composition and sequence.

VEHICLE HEADWAY
The duration of the noise history of any given platoon is increased or decreased as headway varies similarly. Peak levels are not so directly affected, thus the primary result of headway variations is to control the duration of the higher level components of the given noise history.

VEHICLE NOISE-SOURCE STRENGTHS
With the possible exception of deceleration, variations in vehicle noise-source strengths have a marked effect on the roadside noise histories. Both the acceleration and the stationary components appear to be most important and reducing these two strengths in combination could result in substantial noise reductions. These conclusions are based on an overview of the range of noise levels produced by varying source strengths amounting to a substantial 20 dB(A) in total. While such increases or decreases of 10 dB(A) are rather unlikely in practice, the analysis has allowed examination of likely trends. Further, the analysis involved uniform source strength changes for all vehicle types. For a multi-source, complex, noise generation process, it is generally accepted good noise control practice to treat all sources. Clear trends were discernable as a result of this treatment. As far as reducing interrupted traffic flow noise is concerned, it would seem appropriate to apply higher initial priority to reducing truck (H and M) source strength, because of the dominance of truck-related noise in the intersection noise histories.

In summary therefore, the sensitivity analysis has revealed that the model displays a variety of factors that interact to generate interrupted traffic flow noise. It is adequately sensitive to each of the relevant noise generation and propagation parameters used in this ARRB model (as listed on page 30) to allow determination of the noise effects that result from changes in these parameters. It has, therefore, application in the selection and evaluation of noise control strategies.

5. INVESTIGATION OF ITFNS MODEL UNDER NEW ZEALAND CONDITIONS

5.1 Background

The ITFNS model is both theoretically and empirically based. As explained previously in this report, the theory revolves around the noise generation from vehicles moving through the intersection. The magnitudes of these source levels are the basis for the calculation of noise levels (taking into account propagational factors) at observer locations.

The model was studied under New Zealand conditions but first it was necessary to establish any differences between the Australian and New Zealand vehicle noise source levels. This approach reflected reasonable concerns that differences in the vehicle populations of the two countries may alter the traffic noise conditions at intersections.

Observations of the noise produced by vehicles operating under constant speed, acceleration, deceleration and stationary idle conditions are described below. Comparing the results from the original Australian data we find that there are significant differences in New Zealand vehicle noise levels.

A comparison of measured and predicted traffic noise levels at New Zealand intersections was made using a new version of the ITFNS prediction program corrected for typical New Zealand source noise levels. The modified version is referred to as ITFNS'.

5.2 Vehicle Noise

5.2.1 Data Collection

Vehicle noise data were collected using the techniques adopted by Samuels (1988) during development of the ITFNS model. These involved monitoring the passby noise levels of test vehicles as they drove past an observation point. Vehicles drove past several times under conditions of constant speed, acceleration and deceleration, and were also positioned opposite the observation station for measurement of stationary (idle) levels. Peak, A-weighted, noise levels were measured in all cases. A microphone height of 1.2 m and a microphone distance of 15 m were adopted. The site was flat, open, paved with a chip seal surface and, in all other respects, conformed with the specifications of Australian Standard AS2240 - Methods of Measurement of the Sound Emitted by Motor Vehicles (SAA 1979). All data were collected in fine, mild, generally still conditions. The test vehicles are described in Table 3.

Table 3 - Test Vehicles

Vehicle Category	Vehicle Number	Vehicle Specifications	Truck Gross Mass (tonnes)
Car (C)	1	Mitsubishi V3000, 3 litre 5 Speed manual, sedan	-
	2	Commodore VN, 3.6 litre 4 speed automatic, sedan	-
	3	Ford Sierra, 2.4 litre 5 speed manual.	-
Medium Truck (M)	4	Isuzu, flat bed, two axle, (R11), COE. 135 hp, 6 cyl. diesel	5.0
Heavy Truck (H)	5	International, flat bed 3 axle (R12), COE. 210 hp, 6 cyl. diesel	12.0

This range of vehicles was selected to typify the range of vehicles currently operating in New Zealand. In addition, the test runs for Vehicle 1 were repeated on a separate occasion to check the reproducibility of the measurements. All vehicles were tested during March and April 1990.

5.2.2 Vehicle Noise Data

All data are documented in Table 4 and graphed in Fig. 19, along with the Australian data of Samuels (1988) included in the model. Initially it is apparent that for each vehicle, good repeatability was achieved. Generally the runs are within 1 to 2 dB(A), which is of the same order as Samuels (1988). For all runs, except the Stationary Idle condition, the background levels were 10 dB(A) or more below the vehicle noise data.

Table 4 - Vehicle Noise Data

Run Type	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5
Constant Speed					
50 km/hr	62.6 63.2	62.2 63.3	61.8 62.0	72.8 73.0	77.2 77.0
	63.3 62.7	62.3 60.9	61.3 62.3	72.1 72.7	77.8 76.8
	62.1	63.2	61.8	73.0	76.8
65 km/hr	67.4 66.1	65.1 66.4	66.0 65.7	77.0 76.8	81.8 82.3
	67.1 66.2	65.2 64.9	65.4 65.1	77.1 76.7	81.1 80.6
	66.3	64.0	64.8	76.5	81.4
80 km/hr	70.3 70.6	66.9 68.9	68.2 66.9	79.6 79.8	84.3 84.5
	69.8 69.6	67.3 68.6	67.5 68.1	79.9 79.2	84.4 84.2
	69.2	67.5	67.2	79.4	84.4
Acceleration to 50 km/hr					
	63.9 64.9	64.6 63.6	63.5 64.8	78.0 75.8	78.8 80.3
	63.6 63.1	63.3 65.0	64.1 64.7	77.6 78.3	80.4 80.6
	64.0	66.1	64.6	79.3	81.6
Deceleration from 50 km/hr					
	58.5 57.1	56.1 56.9	55.3 56.4	68.0 70.2	73.2 73.2
	61.0 62.0	57.5 57.9	56.8 57.1	69.8 68.1	72.8 73.3
	59.6	57.9	57.0	68.0	74.0
Stationary idle	49.3 50.0	51.7 52.0	49.3 50.3	62.0 61.5	60.5 60.1
	50.5 48.1	51.5 51.4	49.8 50.6	61.8 61.7	60.1 59.6
	47.0	52.0	51.2	61.9	60.2

5.2.3 Comparison With Australian Data

For the constant speed data (Fig. 19a), the same trend of increasing noise level with speed is apparent in the New Zealand data, compared to the Samuels (1988) Australian data. Furthermore, the truck levels exceed the car levels by the same order as that of Samuels (1988). In the cases of acceleration and deceleration (Fig. 19b) the New Zealand data are generally lower in level than those measured in Australia. As mentioned before, the idle levels were within 10 dB(A) of the background levels. Consequently it is not possible to ascribe any differences in idle levels between the Australian and New Zealand data on the basis of the present data set. It would be reasonable to expect that no such differences exist.

There is, however, one important difference between the Australian and the New Zealand measurement conditions, and it is the test road surface used. Samuels (1988) used a smooth asphaltic concrete, while the present data were collected on a chip seal surface. Studies on the effects of road surface on vehicle noise, e.g. Samuels (1982), reveals that the chip seal would contribute some 4 dB(A) to the measured vehicle noise levels. In order to make a direct comparison with the Samuels (1988) data, therefore, all the present levels, except those of the stationary idle condition, must be reduced by 4 dB(A). When this is done, it becomes apparent that the New Zealand vehicle noise levels range from 3 to 10 dB(A) below the Australian levels. Averaging replicate runs for each speed condition reveals the differences listed in Table 5.

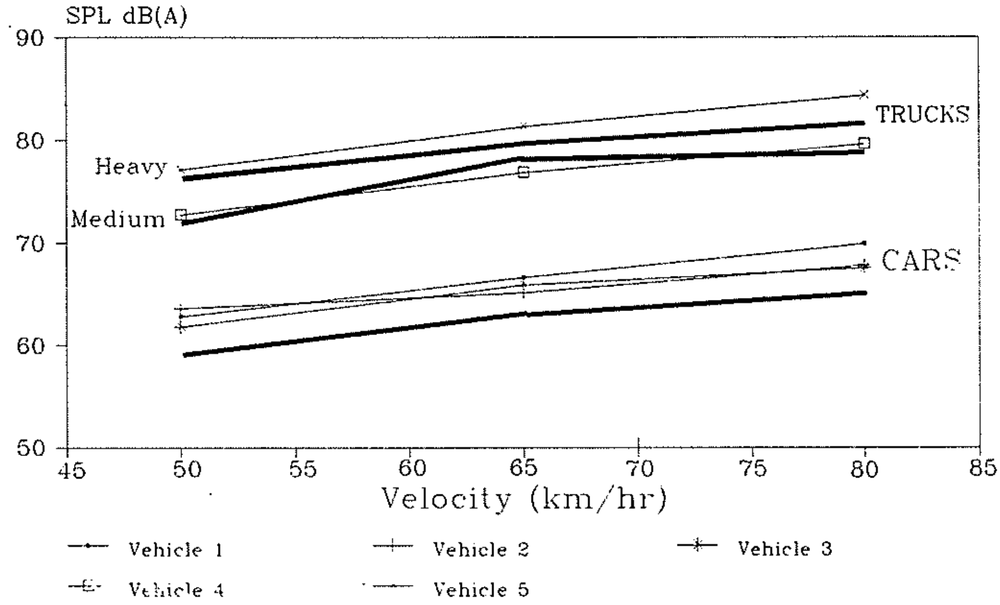
Table 5

Average Vehicle Noise Level Differences (in dB(A))
Australian minus New Zealand vehicle noise levels.

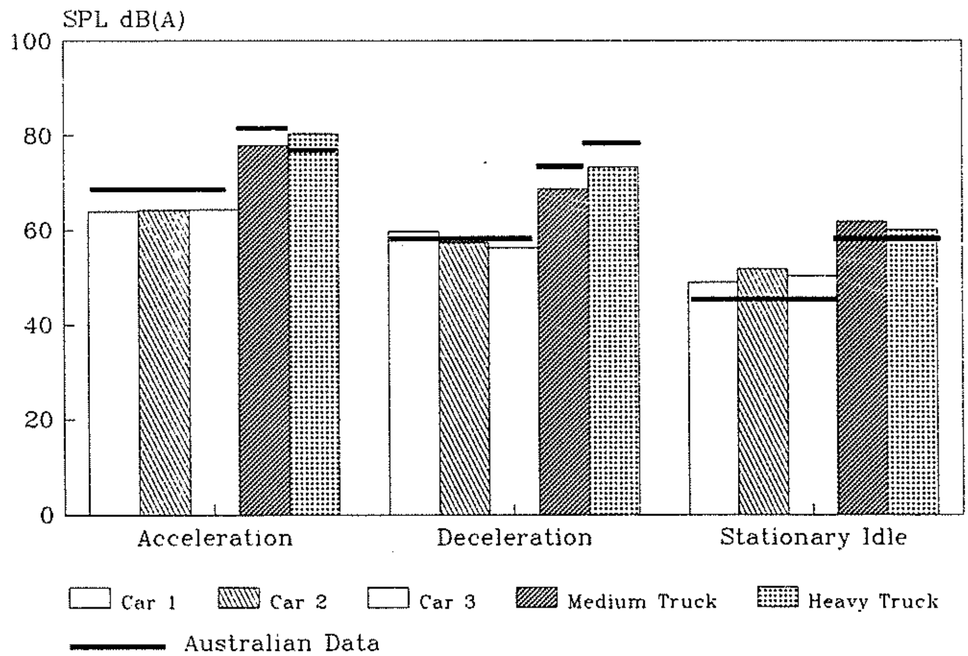
Speed Condition	Car	Medium Truck	Heavy Truck
Constant	2.8	7.7	3.2
Acceleration	7.5	6.5	2.0
Deceleration	3.5	10.5	9.5

Fig. 19 - Comparison with Australian Data

(a) Constant Speed Data



(b) Acceleration, Deceleration, and Stationary Idle



5.2.4 Application to the Model

On the basis of the vehicle noise results, it appears necessary to reduce the model source strengths by the values given in Table 5. Vehicle noise-source strength have considerable effects on the model outputs as determined by Samuels (1988). Consequently, the Table 5 values were applied to the ITFNS model for use in New Zealand (as ITFNS'). This is the only factor which differentiates ITFNS from ITFNS'.

5.3 Traffic Characteristics

The ITFNS (and therefore ITFNS') prediction model calculates the noise level at the observer location by assessing the distance between the observer and each vehicle that passes through the intersection. The location of the vehicle, at any given instant, is related to both the signal phasing and the acceleration/deceleration profile of each category of vehicle. Owing to a lack of information on vehicle trajectories at signalised intersections in New Zealand it was seen as appropriate to use Australian data and to test them under New Zealand conditions.

A detailed explanation of the basis of the Australian data (Samuels 1988) on vehicle trajectory profiles through signalised intersections is provided in Appendix A.

5.4 Traffic Noise

5.4.1 Traffic Noise Data Collection

Traffic noise measurements were made, in a pilot study of the model performance in New Zealand, at two intersections in Wellington. Both were relatively simple intersections at flat, open sites. Weather conditions were fine and mild, with little or no breeze. At both sites, four sets of traffic noise measurements were made. During each measurement, traffic counts were made (manually) on both roads, noting volumes and heavy vehicle content in all lanes. Site details such as road dimensions, cycle sequences and observer locations were also recorded. The sites were as follows:

Site WWL: Waiwhetu Road and Whites Line East, Lower Hutt

Site SPC: Wellington Road and Evans Bay Parade, Wellington

Further details of the sites are presented in Table 4. Note that the noise measurement sample times are, as close as practicable, integral multiples of the total cycle times. The observer locations refer to a grid around the intersection as specified by the model in Samuels and Shepherd (1989), e.g. Fig. 12.

Table 6 - Traffic Noise Data Collection.

Site Details

Site	Observer Location	Lane Widths N-S S-N E-W W-E	Total Cycle Time (s)	Sample Time (min, sec)
WWl	8,8	6.5, 6.5, 8.4, 8.4	65	10 min 50s
SPC	3,3	7.8, 7.8, 9.6, 9.6	85	14 min

Legend: N = North, S = South, W = West, E = East

Sites: WWL, SPC (see p.52)

5.4.2 Traffic Noise Data

Measured traffic noise data are presented in Appendix B. Shown are the various traffic noise indices and a histogram of the distribution of each traffic noise sample. These data are typical of those at intersections studied in Australia (Samuels 1988) with similar traffic flows. The traffic flows measured on site (and converted to hourly figures) are shown in Table 7.

Table 7 - Traffic Flow Data

Site	Sample No.	Lane Volumes N-S	S-N	E-W	W-E	% Heavy Vehicles
	1	240	300	336	396	7
	2	372	336	492	492	4
WWL	3	372	212	552	348	9
	4	516	336	456	480	3
	1	283	283	557	540	7
	2	274	360	617	488	11
SPC	3	437	274	745	488	7
	4	360	291	600	523	7

5.4.3 Traffic Noise Predictions

Predictions were made for all eight samples, both with the original ITFNS model and with the modified version (ITFNS') suggested in 5.2.4. All predictions are presented in Appendix C. Brown (1980) showed that all traffic noise indices are highly inter-related. Thus assessment of the model performance at these two sites may be undertaken by considering the L_{10} index, which is the index most commonly used for traffic noise studies in Australia. These predictions are presented in Table 8, along with the measured values and the prediction differences (the differences between the measured and predicted values).

Inspecting first the two columns of predicted values, it is apparent that the New Zealand modified version (ITFNS') produces somewhat lower levels than the original version (ITFNS). This is expected and reflects the lower vehicle source levels used in ITFNS'. For both sites, the ITFNS' predictions are closer to the measured values, as evidenced by the lower mean prediction differences. At both sites the range of the two sets of prediction differences are very similar. This is also to be expected because the source levels will uniformly alter the prediction difference and not change its distribution.

Both models over-predict and exhibit similar scatter. The ITFNS' version has a smaller prediction difference. On this evidence, albeit from a limited pilot study, ITFNS' would therefore appear to be more suited to New Zealand conditions than its Australian predecessor (ITFNS). For ITFNS, the 4.7 dB(A) standard deviation of the prediction differences is of a similar magnitude to those of other traffic noise prediction models for free flow conditions (Saunders *et al.* 1983). That is, the present study suggests that ITFNS' has exhibits an accuracy which is typical of traffic noise prediction models generally. (Note that prediction accuracy is defined by the range of the 95% confidence limits extracted from the prediction difference distribution (Saunders *et al.* 1983).)

Measured and predicted traffic noise histograms are also presented in Appendices B and C. The measured histograms are of generally similar form and this would suggest similarities between the traffic conditions and between the sites. On the other hand, the predicted histograms exhibit a little more variability, primarily a function of the way in which the model randomises the traffic and heavy vehicle parameters.

Generally ITFNS and ITFNS' produce histograms of similar form, amplitude and range. The predicted histograms exhibit a similar consistency to those measured, and are also of generally similar form to the measured histograms.

Table 8 - Comparison of Predicted and Measured L_{10}(1 hr), dB(A).

Comparison of Predicted and Measured L_{10}(1 hr)

Site	Sample No.	Measured L_{10}(1hr)	ITFNS L_{10}(1hr)	ITFNS' L_{10}(1hr)	Measured - ITFNS	Measured - ITFNS'
WWL	1	66.9	70.0	63.0	-3.1	+3.9
	2	69.4	70.0	63.0	-0.6	+6.4
	3	67.4	78.0	72.0	-10.6	-4.6
	4	65.9	70.0	63.0	-4.1	+2.9
				Site Mean	-4.6	+2.2
				Site Std. Deviation	4.3	4.7
SPC	1	66.4	71.5	67.0	-5.1	-0.6
	2	65.4	75.0	71.0	-9.6	-5.6
	3	65.4	75.0	71.0	-9.6	-5.6
	4	65.9	75.0	71.0	-9.1	-3.1
				Site Mean	-8.4	-3.7
				Site Std. Deviation	2.2	2.4
			OVERALL MEAN		-6.5	-0.8
			OVERALL STD. DEVIATION		3.7	4.7

6. CONCLUSIONS AND RECOMMENDATIONS

This report has shown the important differences between the noise generated from freely flowing traffic and noise generated from interrupted traffic flows. A consideration of the source characteristics of interrupted traffic flow indicates the reasons for the differences in noise spectra and temporal distribution. That is, interrupted flow involves much acceleration, deceleration, and idling resulting in large fluctuations in level and character of the resulting noise emission.

The implications for a predictive procedure to effectively model the noise emission across all interrupted flow situations (signalised intersections, unsignalised intersections, roundabouts, etc.) are that the model must have input parameters that accurately define the flow condition and the timing of acceleration/deceleration/idle manoeuvres within the acoustical range of the receivers' position. These data requirements are in addition to the data on bulk flow, composition, distance, etc. required by models for the prediction of noise levels for free flowing traffic.

No single model examined in this report was able to calculate the prediction of interrupted traffic flow noise at all situations where interrupted traffic flows occur. By selecting a model which appears to perform well at signalised intersections, a large number of interrupted flow situations in urban areas can now be acoustically modelled. The ITFNS' model serves a useful base from which models can be developed to cover other interrupted flow situations. For example, ARRB are currently modifying their model to cover the multiple lane situation.

The pilot study was limited to two sites in Wellington, and thus it is recommended that the study be extended to incorporate a wider range of sites in more than one city. Such a study should provide a robust estimate of the accuracy of the model in New Zealand.

The model provides an insight into the interaction of the characteristics of interrupted traffic flow noise. Apart from the more obvious use to determine the noise "climate" around signalised intersections, the ITFNS model (and its New Zealand counterpart, ITFNS') can be used to study traffic management strategies and vehicle noise control strategies that may be used to control noise from signalised intersections.

6.1 Conclusions

This report represents the findings of a Transit NZ research project. The conclusions of the investigations to date (1991) are as follows.

(1) The prediction of traffic noise originating from interrupted traffic flow conditions requires different techniques from those currently available for free flow traffic conditions.

(2) A critical review of techniques available for predicting interrupted traffic flow noise has been made. The findings indicate that an appropriate model, given the current level of understanding on this subject, is preferred.

(3) The preferred model, referred to as the ITFNS model, developed by ARRB, is described in some detail.

(4) Information on both the sensitivity of the model and an assessment of its performance under Australian conditions has shown the satisfactory performance of the model. The ways in which relevant parameters interact in the model are consistent with what is known about traffic noise generation and propagation from signalised intersections.

(5) Measurements of the noise emitted by a set of typical vehicles operating on New Zealand roads revealed some differences compared to Australian vehicles. On this basis, the vehicle noise source levels incorporated in the ITFNS model were replaced by those determined by the New Zealand measurements. The resultant modified model is referred to as ITFNS'.

(6) A pilot study at two intersections (8 prediction runs) indicated that the model, modified for New Zealand vehicles, predicted traffic noise levels to a degree of accuracy consistent with that of free flow prediction models. Consequently it may be concluded that the present study has revealed the potential suitability of the model for New Zealand.

(7) The model allows noise control strategies for signalised intersections to be modelled. Traffic management factors (such as vehicle headway and signal phasing) and vehicle noise levels can be manipulated in the model and the resultant noise effects studied.

6.2 Recommendations

(1) Further investigations should be carried out to establish conclusively that the model is an accurate prediction method for signalised intersections in New Zealand.

Such an investigation should include:

- Integrated research on vehicle trajectories in New Zealand. Other research projects may provide this information as part of traffic management investigations.

- A comprehensive validation programme to assess the model performance at a large number of signalised intersections. This should include variations in bulk flow, platoon composition, receiver position, signal phasing, and vehicle headway. A sample of at approximately 25 intersections in a range of urban situations would be required to fully validate the model under New Zealand conditions.

- An assessment of a multiple lane version of ITFNS currently under development at ARRB.

(2) Once the model is shown to adequately predict noise from signalised intersections, the incorporation of the prediction procedures into traffic management strategies which limit traffic noise (and other vehicle emissions) should be investigated. Significant reductions in traffic emissions and fuel consumption are possible, especially when large networks of signalised intersections are involved.

(3) Established contacts should be maintained with the developers (ARRB) of the model to ensure that refinements and upgraded versions of the software can be assessed for use in New Zealand.

7. REFERENCES AND FURTHER READING

ADVISORY COMMITTEE OF SAFETY IN VEHICLE DESIGN (1976). Mangalore motor vehicle noise test program. Working Group on Motor Vehicle Noise Report to ATAC, 1976.

AGENT, K.R., ZEGEER, C.V. (1980). Effect of interrupted flow on traffic noise. Kentucky Department of Transportation, Bureau of Highways Report 1980-03: 542.

AKCELIK, R. (1986). SIDRA Version 2.2 Input and Output. Australian Road Research Board, Technical Manual ATM 19.

AL-SAMARRAI, H.S., WATERS, D.M.(1979a). Noise from interrupted traffic flows. Proceedings Inter Noise 79: 539-542.

---------- (1979b). The simulation of noise from traffic flows with particular reference to signalised intersections. Acoustics Letters 3(1): 9-15.

BOWLBY, W., WAYSON, R.L., STAMMER, R.E.Jr (1989). Predicting stop-and-go traffic noise levels. National Cooperative Highway Research Program (NCHRP) Report 311, Transportation Research Board, Washington.

BRONER, N., MIZZI, S. (1980). Noise emission and braking efficiency of engine and exhaust brakes on heavy vehicles. VIPAC Report 30/799.

BROWN, A.L. (1980). The noise-response relationship near a freeway. Proceedings of 10th ARRB Conference 10(5): 144-53.

BUNA, B. (1984). Predicting the noise of accelerating road traffic. Proceedings FASE 84: 265-268.

COUNTRY ROADS BOARD VICTORIA (CRBV) (1980). Environmental effects statement for route E6. (Now Road Construction Authority, Victoria.)

DELANEY, M.E., HARLAND, D.C., HOOD, R.A., SCHOLES, W.E. (1976). The prediction of noise levels L10 due to road traffic. Journal of Sound and Vibration 48(3): 305-325.

DEPARTMENT OF TRANSPORT AUSTRALIA (DoTA) (1987). Australian design rules for motor vehicles and trailers. Third Edition. DoTA Federal Office of Road Safety, Canberra, ACT.

DIGGORY, I.S., OAKES, B. (1980). Computer simulation model for the prediction of traffic noise levels. Applied Acoustics, 13: 19-31.

FAVRE, B. (1978). Noise at the approach to traffic lights: result of a simulation program. Journal of Sound and Vibration 58(4): 563-578.

FRASER, P.J. (1984). The Australian Road Research Board Vehicle detector data acquisition system (VDDAS). Proceedings of Institute of Electrical Engineers Conference. Road Traffic Data Collection (IEE Conference Publication 242): 35-39.

FLYNN, D.R., VOORHEES, C.R., YANIV, S.L. (1980). Highway noise criteria study: traffic noise data base. USA Department of Commerce, National Bureau of Standards, Technical Note 1113-1.

GILBERT, D. (1977). Noise from road traffic (interrupted flow). Journal of Sound and Vibration 51(2): 171-181.

GILBERT, D., MOORE, L., SIMPSON, S. (1980). Noise from urban traffic under interrupted flow conditions. Transport and Road Research Laboratory Report SR620.

HEMDAL, J.F., BAKER, R.N., SAHA, P. (1984). Effects of environmental variables on truck noise emission noise propagation to test microphones. Journal of the Acoustical Society of America 76(4): 1150-1160.

HOTHERSALL, D.C., JONES, R.R.K. (1976). Observed and predicted noise levels around road junctions in the UK. ARRB Proceedings 8: 31-35.

HUNT, M.J. (1987). Traffic noise prediction in New Zealand. Paper to New Zealand Acoustical Society conference, Wellington, 1987.

HUNT, M.J. (1988). A survey to determine the subjective reaction to measured traffic noise levels in Christchurch, New Zealand. Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand. Master of Mechanical Engineering thesis.

JACOBS, L.J.M., NIJS, L., VANWILLENBURG, J.J. (1980). A computer model to predict traffic noise in urban situations under free flow and traffic light conditions. Journal of Sound and Vibration 72(4): 523-537.

JARVIS, J.R. (1982). In-service vehicle performance. Proceedings of SAE/ARRB 2nd Conference on Traffic, Energy and Emissions, Melbourne: 21.1-21.15.

JAMESON, G.W. (1979). Eastern Freeway noise generation of surface treatments. Country Roads Board, Victoria (now Road Construction Authority). Internal Report 981515.

JONES, R.R.K., HOTHERSALL, D.C. (1979). Effect of operating parameters on noise emission from individual vehicles. Applied Acoustics 13: 121-136.

JONES, R.R.K., HOTHERSALL, D.C., SALTER, R.J. (1979). The prediction ofnoise levels from unrestricted traffic in urban situations by means ofdigital computer simulation. Traffic Engineering and Control 20(10): 479-481.

---------- (1981). Techniques for the investigation of road traffic noise in regions of restricted flow by the use of digital computer simulation methods. Journal of Sound and Vibration 75(3): 307-322.

JRAIW, K.S. (1987). A computer model to assess and predict road transport noise in built up areas. Applied Acoustics 2: 146-162.

KUGLER, A., COMMINS, D.E., GALOWAY, W.J. (1976). Highway noise. A design guide for prediction and control. US NCHRP Report 174.

KURZE, U.J. (1974). Frequency curves of road traffic noise. Journal of Sound and Vibration 33(2): 171-185.

LAWRENCE, A. (1974). Stop-start traffic noise. Proceedings 8th ICA, London.

LAY, M.G. (1985). Source book for Australian roads. Third edition. Australian Road Research Board, Victoria, Australia.

LEWIS, P.T., JAMES, A. (1978). On the noise emitted by single vehicles at roundabouts. Journal of Sound and Vibration 58(2): 293-299.

---------- (1980). Noise levels in the vicinity of roundabouts. Journal of Sound and Vibration 72(1): 51-69.

NATIONAL ASSOCIATION OF AUSTRALIAN STATE ROAD AUTHORITIES (1970). Guide to traffic engineering practice. NAASRA, Sydney, NSW, Australia.

---------- (1976). A study ofthe economics of road vehicle limits. NAASRA, Sydney, NSW, Australia.

---------- (1985). Review of road vehicle limits for vehicles using Australian roads. NAASRA, Sydney, NSW, Australia.

RADWAN, M.M., OLDHAM, D.J. (1987). The prediction of noise from urban traffic under interrupted flow conditions. Applied Acoustics 21(2): 163-185.

SAMUELS, S.E. (1978). Evaluation of noise prediction techniques. Preliminary appraisal of existing data base. Australian Road Research Board Internal Report AIR 818-1.

----------(1982). The generation of tyre/road noise. Australian Road Research Board. Research Report ARR 121.

---------- (1985). The effects of gross vehicle mass variations on heavy vehicle noise emission. Proceedings of Australian Acoustical Society 1985 Conference: 100-107.

---------- (1986). Traffic noise measurement and prediction practices in Australia. Proceedings of 13th ARRB/5th REAAA Conference 13(2): 30-37.

---------- (1988). The generation of road traffic noise under interrupted flow conditions. PhD thesis, Department of Mechanical Engineering, University of Newcastle, NSW, Australia.

---------- (1990). The generation and prediction of noise at simple, signalised intersections. Australian Road Research Board Special Report SR47.

SAMUELS, S.E., FAWCETT, G. (1984). A study of the US NCHRP traffic noise prediction method. Proceedings of 12th ARRB Conference 12(6): 90-98.

---------- (1985). An interactive traffic noise prediction program. Australian Road Research Board, Technical Manual ATM 16.

SAMUELS, S.E., JARVIS, J.R. (1978). Acceleration and deceleration of modern vehicles. Australian Road Research Board. Research Report ARR 86.

SAMUELS, S.E., SAUNDERS, R.E. (1982). The Australian performance of the UK DoE traffic noise prediction procedure. Proceedings of 11th ARRB Conference 11(6): 30-44.

SAMUELS, S.E., SHEPHERD, R. (1989). Prediction of traffic noise at simple, signalised intersections. Australian Road Research Board ATM 27.

SAMUELS, S.E., THOMAS, C.D.L. (1978). The measurement and analysis of road noise. Australian Road Research Board, Internal Report AIR 258-1.

SANDBERG, U. (1979). Tyre noise as a part of total vehicle noise emission. Proceedings of the International Conference on Tyre Noise, Stockholm, Sweden: 169-184.

SHARP, K., POTTER, D.W., SWEATMAN, P.F. (1986). A comparative study of the effects of wide, single and dual tyres on rebound pavement deflection. Australian Road Research Board, Internal Report AIR 1137-1.

SLUTSKY, S., McSHANE, W.R., ULERIO, J.M., LEE, S.H., GREALY, P.J. (1983). Stop-go intersection noise. Transportation Research Record 937: 15-23.

SPARKES, C., LARGE, J.B. (1980). Noise prediction of heavy vehicles in non-uniform traffic flow. US Society of Automotive Engineers, SAE 780388. SAE, Warrendale, Pa, USA.

SPIEGEL, M.R. (1968). Mathematical handbook. Schaum's Outline Series. McGraw-Hill, New York, USA.

STANDARDS ASSOCIATION OF AUSTRALIA (SAA) (1979). Australian Standard AS2240-1979. Methods of measurement of the sound emitted by motor vehicles. Standards Association of Australia, Sydney, NSW, Australia.

---------- (1984). Australian Standard AS2702-1984. Methods for the measurement of road traffic noise. Standards Association of Australia, Sydney, NSW, Australia.

STATE POLLUTION CONTROL COMMISSION (SPCC) (1984). A comparison of methods for measuring the noise of individual motor vehicles. NSW SPCC Report MV N1, Lidcombe, NSW, Australia.

STONE, G.E., SAUNDERS, R.E. (1982). The use of traffic noise barriers by the Country Roads Board, Victoria. Proceedings of 11th ARRB Conference 11(6): 115-125.

TROUTBECK, R.J., DODS, J.S. (1986). Collecting traffic data using the ARRB Video Analysis Data Acquisition System. Proceedings of 13th ARRB/5th REAAA Conference, Adelaide, 13(7): 183-195.

UNITED KINGDOM DEPARTMENT OF ENVIRONMENT (UK DoE) (1975). The calculation of road traffic noise. HMSO, London, UK.

US SOCIETY OF AUTOMOTIVE ENGINEERS (1980). Exterior sound levels for heavy trucks and buses. SAE J366B. SAE, Warrendale, Pa, USA.

WANG, N. (1975). Some aspects of vehicular traffic noise pollution. University of Newcastle, NSW, Australia, Department of Mechanical Engineering, Master of Engineering Science Thesis.

---------- (1981). Progress report on noise simulation of an interrupted traffic flow. Australian Road Research Board. Internal Report AIR 307-1.

WEISS, G.H. (1970). On the noise generated by a stream of vehicles. Transportation Research 4: 229-233.

APPENDIX A

DESCRIPTION OF ARRB MODEL:

Chapter 3.2 Vehicle Behaviour
and
Chapter 3.3 Source Receiver Geometry

from
"The Generation and Prediction of Noise at Simple, Signalised Intersections"
ARRB Special Report SR47, 1990.

3.2 Vehicle behaviour

3.2.1 Stationary at Intersection

The stationary position of each vehicle in a particular platoon may be determined via reference to the example in *Fig. 11*. Here the first four vehicles of a platoon are depicted and it is assumed that in all cases adjacent vehicles are separated by 0.5 m. Vehicles are classified as a Car (C), a Medium Truck (M) or a Heavy Truck (H) and this system will be considered in more detail subsequently. Thus the stationary position of the n^{th} vehicle in a platoon proceeding in the x-direction along the line y = A in *Fig. 11* is given by eqn (4).

$$
\begin{aligned}
A1_n &= 4W - \frac{L_n}{2} \text{ for } n = 1 \\
&= 4W - \left[\frac{L_n}{2} + \sum_{n=1}^{n-1} L_n + (n-1) \times 0.5\right] \text{ for } n>1
\end{aligned}
\tag{4}
$$

where $A1_n$ = stationary position of n^{th} vehicle in *Fig. 11* platoon (m),

W = lane width as shown in *Fig. 9* (m), and

L_n = Length of n^{th} vehicle (m).

Note that the vehicle counter, n, commences from the first vehicle in the platoon and increments, therefore, in the negative x-direction in this case. Values of $A1_n$ approximate the location geometric centres of vehicles in the platoon. Similar equations are used to determine $B1_m$, $C1_p$ and $D1_q$, the stationary positions of vehicles in the other platoons proceeding.

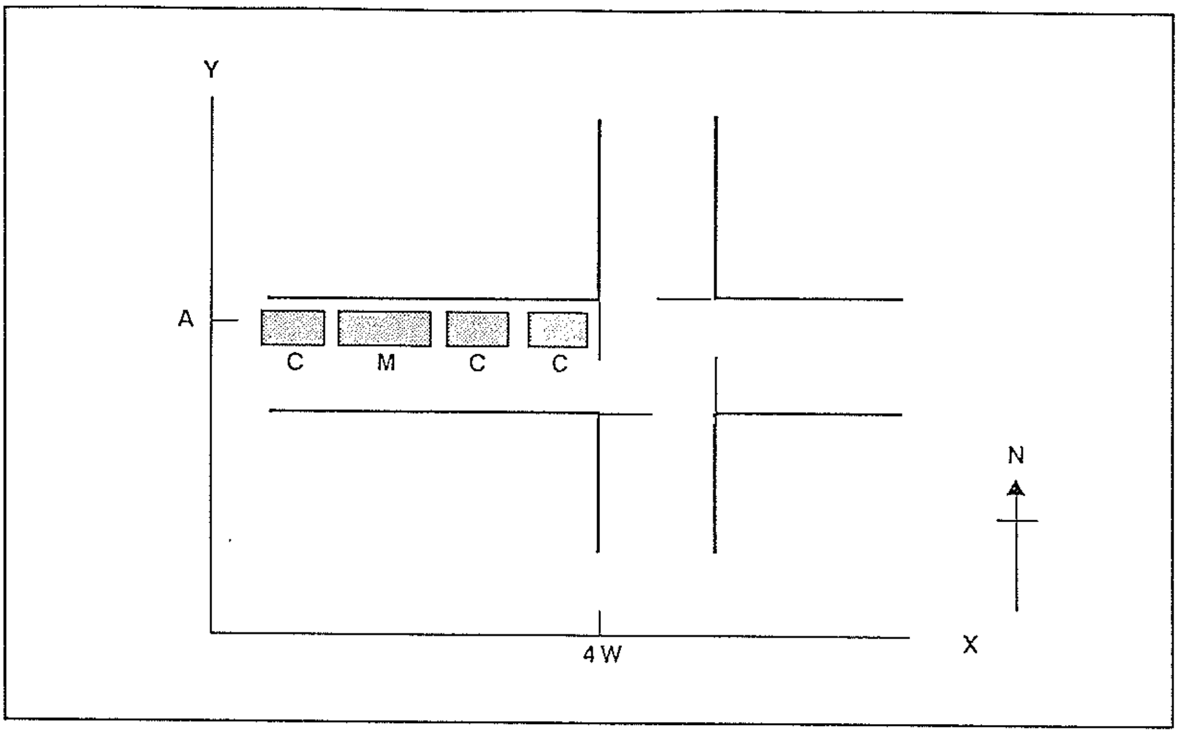


Fig. 11 — *Stationary queue positions of four vehicles in a platoon*

Two other parameters concerning the stationary queue are required and these are the Queue Length and what has been defined as the Stationary Period for each vehicle. These are given as follows in eqns (5) and (6).

$$Q_L = \sum_{n=1}^{n} L_n + (n-1) \times 0.5 \quad (5)$$

$$t_s = t_q + (n-1)\, t_h \quad (6)$$

with $$t_q = t_q = \frac{(Q_c + 1 - n)}{Q_c}\, t_{ng} \quad (7)$$

where Q_L = queue length (i.e. length of the given platoon) (m),

L_n = length of n^{th} vehicle (m),

t_s = stationary period (s),

t_q = queue period (s)

= time between vehicle stopping and commencement of green phase,

t_h = average headway (s),

Q_c = the number of vehicles in the given lane that proceed through the intersection in one direction during the green phase, and

t_{ng} = non-green time (s).

The Queue Length is used in subsequent calculations concerning vehicle departure from the stationary position. It depends on both the type and number of vehicles in the particular platoon. Vehicle type may be set to prescribed values or determined via a random number operator which selects the type of each vehicle in all platoons passing through the intersection. The operator used was the random number generator available on the ARRB CYBER computer. A practical constraint was that the proportion of heavy vehicles (M + C) in the traffic did not exceed 10 per cent. This figure was based on the extensive observations of traffic and traffic noise documented by Samuels and Saunders (1982).

It was further necessary to constrain the maximum size of a platoon that may pass through the intersection during the green phase. That is, the maximum value of the parameter Q_c in eqn (7) had to be specified so that the model would not generate unrealistic flows that exceeded the capacity of the roads and the cycle phasing the intersection. This was achieved by manipulating the lane saturation flow (NAASRA 1970) as follows.

$$\hat{Q}_c = Q_s \times \frac{t_g}{T_g} \qquad (8)$$

where $\hat{Q}_c$ = maximum number of vehicles passing through the intersection in one lane in one direction during the green phase,

t_g = green cycle time (s),

T_g = total green cycle time during one hour (s/h), and

Q_s = lane saturation flow (veh/h).

Note that under this constraint a platoon of $\hat{Q}_c$ in one lane would clear during t_g.

Vehicle lengths L_n were also required and these were extracted from the studies of Samuels and Jarvis (1978) and Jarvis (1982) of the Australian vehicle population. Scrutiny of the data provided in these studies revealed that typical values of L_n representative of each of the three vehicle categories of the model were as presented in *Table III*. These values were adopted for the model.

In determining the total Stationary Period of each vehicle, the stationary times before and after commencement of the green phase are summed in eqn (6). The before component, t_q, is given by the simple ratio in eqn (7), while the after component depends on what has been termed the Average Headway, t_h. This parameter is, for the present model, the average time between the departure of successive vehicles in the platoon. It is quantified in a relationship which is developed in Section 3.2.2.

TABLE III VEHICLE LENGTHS

Vehicle Category	Vehicle Length (m)
C - Car	5.0
M - Medium Truck	8.0
H - Heavy Truck	16.0

3.2.2 Departure from the Intersection

The departure of each vehicle in a platoon involves an acceleration followed by a constant speed component. It is considered that vehicles depart sequentially and that successive departures are separated in time by the Average Headway t_h. For a given lane in an intersection t_h is determined from $\hat{Q}_c$, the maximum platoon which may clear the intersection at the saturation flow condition. This headway is subsequently assigned to all platoons in that lane. Such an approach was considered appropriate as it ensured reasonable continuity of vehicle behaviour that was, in effect, independent of platoon size. Thus, t_h was set via eqn (9) for each lane.

$$t_h = \frac{t_g - t_*}{\hat{Q}_c} \tag{9}$$

where t_* = the time for the last vehicle in the maximum sized queue to travel from its stationary position to the intersection stop line (s).

To determine t_* the following relationships concerning the acceleration and (in some cases) subsequent constant speed manoeuvres are required.

At the appointed time, each vehicle is deemed to accelerate up to and then proceed at a constant speed. For the n^{th} vehicle in the platoon proceeding along the $y = A$ line, the instantaneous x value of the vehicle's position is given by eqn (10) during the acceleration phase.

$$x_n(t) = \psi_n(t) + Al_n \tag{10}$$

with $x_n(t)$ = instantaneous x position of n^{th} vehicle in the platoon proceeding along $y = A$ of *Fig. 9* (m), and

$\psi_n(t)$ = distance travelled by n^{th} vehicle during speed change (m)

Similar relationships apply to the other platoons proceeding through the intersection. In this instance the time t commences with the onset of acceleration. For the n^{th} vehicle in the platoon this time is adjusted to an overall time base for the intersection (that is, a 'real' time) by correcting it by $(n-1)\ t_h$ having first reset $t = 0$ for the first vehicle in the platoon to the common time base. These time adjustments have been achieved via programming logic rather than by mathematical manipulation.

In effect eqn (10) states that the instantaneous location of a vehicle in a platoon during acceleration is the sum of the initial queue position and the distance travelled during the acceleration. The initial queue position has already been determined (eqn (4)) so what remains is to quantify the acceleration distance $\psi_n(t)$. Rather than introduce a set of necessarily complicated mathematical equations for this purpose, a somewhat empirical approach has been adopted. This has the advantanges firstly of making the model as realistic as possible and secondly of avoiding many assumptions concerning matters such as vehicle performance characteristics and driver behaviour.

Extensive observations of acceleration and deceleration manoeuvres over a range of vehicles and conditions had been made previously in Australia (Samuels and Jarvis 1978; Jarvis 1982). In quantifying their controlled test maximum acceleration data, Samuels and Jarvis (1978) utilised standard regression analysis techniques and their regression equation is presented as eqn (11).

$$V^2 = \alpha + \beta t + \gamma t^2 \qquad (11)$$

where V = vehicle speed (km/h),

t = time (s), and

α, β, γ = regression coefficents

This equation proved both robust and reliable so that Jarvis (1982) subsequently adopted it to quantify in-service acceleration data collected at an outer surburban intersection. The relevant results of Jarvis (1982) for the vehicle categories of the present model are reproduced in *Table IV*.

TABLE IV REGRESSION ANALYSES OF IN-SERVICE VEHICLE ACCELERATION DATA

(Reproduced from Jarvis 1982)

$$V^2 = \alpha + \beta t + \gamma t^2$$

Vehicle Category	α (km^2/h^2)	β ($km^2/h^2/s$	γ ($km^2/h^2/s^2$)	R^2 (-)	Sample Size (-)
C	1432	518.6	-23.9	0.69	481
M	973	328.1	-14.4	0.51	46
H	1052	340.8	-15.6	0.45	48

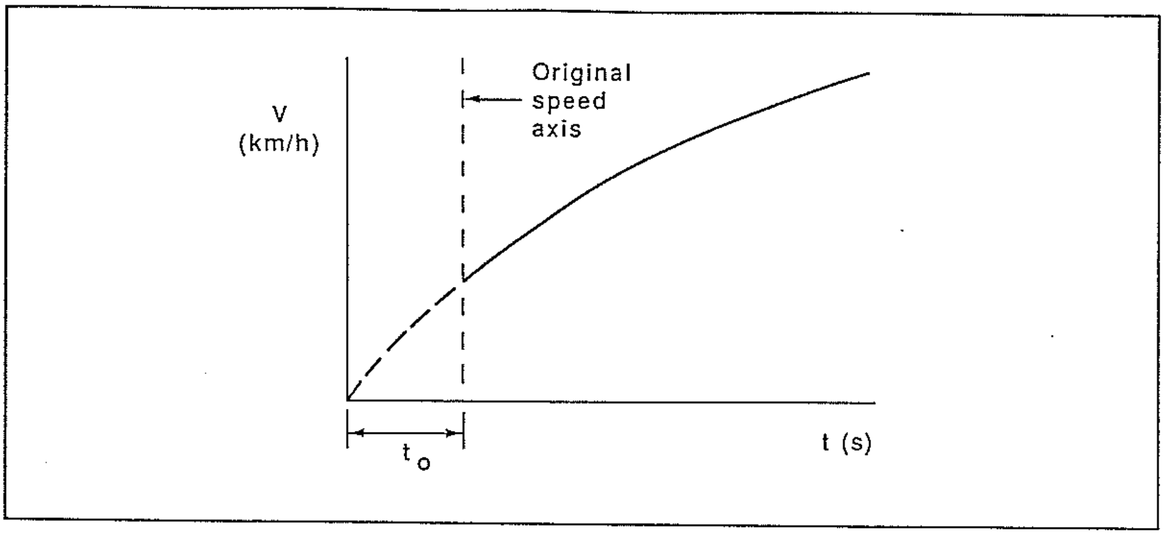


Fig. 12 — *Speed axis transformation for acceleration relationship*

As reflected in the Coefficent of Determination (R^2) values in *Table IV*, the equation performed reasonably well for cars. (As R^2 approaches unity, the fit of a regression equation is deemed to improve.) The performance was not quite as good for the two truck categories and this may have been due in part to the smaller sample sizes of these vehicles. Nevertheless, the overall performance of the equation was satisfactory and it was regarded as suitable for application to the present model. It should also be noted that finite values of the Regression Coefficent a were obtained. These are appropriate since Jarvis was generally not able (for instrumentation reasons) to monitor accelerations from rest. Typically his data commenced from speeds around 30 km/h and this is consistent with the initial speeds determined by $\sqrt{\alpha}$. However in originating eqn (11), Samuels and Jarvis (1978) had measured all accelerations from rest and on this basis the Jarvis (1982) coefficients were adopted with eqn (11) transformed to pass through a speed/time origin.

The transformation involved shifting the speed axis by a time t_o as shown in *Fig. 12*. To do this, the value of t_o is assigned the negative solution of eqn (11) as given in eqn (12).

$$t_o = \frac{-\beta - (\beta^2 - 4\alpha\gamma)^{\frac{1}{2}}}{2\gamma} \qquad (12)$$

Thus, eqn (11) was transformed to eqn (13).

$$V^2 = \alpha + \beta\,(t + t_o) + \gamma\,(t + t_o)^2 \qquad (13)$$

On expansion, eqn (13) may be rewritten.

$$V^2 = \alpha + \beta t + \beta t_o + \gamma t^2 + 2\gamma t t_o + \gamma t_o^2$$

i.e. $$V^2 = (\alpha + \beta t_o + \gamma t_o^2) + (\beta + 2\gamma t_o)\,t + \gamma t^2$$

But, by definition of t_o, the first expression of this equation dissolves to zero.

$$\therefore \quad V^2 = (\beta + 2\gamma t_o)\,t + \gamma t^2 \qquad (14)$$

Eqn (14) is the required relationship which passes through the new speed-time origin and maps exactly the original equation from which it was derived.

Also of interest in the present model are the maximum vehicle speeds $(\hat{V})$ suggested by eqn (14). These were determined by differentiating eqn (14) as follows.

$$\frac{dv}{dt} = \frac{\beta + 2\gamma t_o + 2\gamma t}{2\left[(\beta + 2\gamma t_o)\, t + \gamma t^2\right]^{\frac{1}{2}}}$$

$$\text{Thus} \quad \frac{dv}{dt} = 0 \text{ when } t = \frac{-(\beta + 2\gamma t_o)}{2\gamma} \qquad (15)$$

On substitution into eqn (14) the required maximum speeds are determined.

$$\hat{V} = \left(\frac{-\beta + 2\gamma t_o)^2}{4\gamma}\right)^{\frac{1}{2}} \qquad (16)$$

Values determined from eqn (16) are listed in *Table V* along with t_o for each vehicle category. Times to achieve these maximum speeds, calculated from eqn (15), are also presented in *Table V*. These values appear reasonable. In particular, the maximum speeds and times are consistent with those monitored by Jarvis, thereby confirming that the transformed eqn (14) has indeed mapped the original data.

TABLE V VEHICLE ACCELERATION CHARACTERISTICS

Vehicle Category	$\hat{V}$ (km/h)	Time to $\hat{V}$ (s)	t_o (s)
C	65.2	13.3	-2.48
M	53.3	14.1	-2.66
H	54.0	13.7	-2.74

It is now possible, therefore, to investigate eqn (14) to determine the required relationships for $\psi_n(t)$, the distance travelled by each vehicle during acceleration. Spiegel (1968) provides the integration, but eqn (14) must first be adjusted so that speed appears in units of m/s.

$$V^2 = (\beta + 2\gamma t_o)\, t + \gamma t^2 \tag{14}$$

Thus $$V = \left[(\beta + 2\gamma t_o)\, t + \gamma t^2\right]^{\frac{1}{2}}$$

i.e. $$v = \frac{\left[(\beta + 2\gamma t_o)\, t + \gamma t^2\right]^{\frac{1}{2}}}{3.6} \tag{17}$$

where v = speed (m/s)

On integration, eqn (17) becomes, in general form:

$$\psi(t) = \frac{(2\gamma t + \beta + 2\gamma t_o)\left[(\beta + 2\gamma t_o)\, t + \gamma t^2\right]^{\frac{1}{2}}}{3.6 \times 4\gamma}$$

$$\frac{-(\beta + 2\gamma_o)^2}{3.6 \ \times 4\gamma} \times \phi + \xi \tag{18}$$

with $$\phi = \frac{-\text{Sin}^{-1}\left(\frac{\beta + 2\gamma t_o}{|\beta + 2\gamma t_o|}\right)}{(-\gamma)^{\frac{1}{2}}}$$

i.e. $$\phi = \frac{-\text{Sin}^{-1}\left(\frac{2\gamma t + \beta + 2\gamma t_o}{|\beta + 2\gamma t_o|}\right)}{(-\gamma)^{\frac{1}{2}}} \tag{19}$$

Also, ξ = Integration constant

It is further necessary that eqn (18) satisfies the initial condition that $\psi(t) = 0$ for $t = 0$. At this condition, eqn (18) allows determination of ξ.

$$\psi\,(t = 0) = \frac{-(\beta + 2\gamma t_o)^2 \times \phi}{3.6 \times 8\gamma} + \xi$$

and $$\phi\,(t = 0) = \frac{-\text{Sin}^{-1}\left(\frac{\beta + 2\gamma t_o}{|\beta + 2\gamma t_o|}\right)}{(-\gamma)^{\frac{1}{2}}}$$

$$= \frac{-\text{Sin}^{-1}\,(1)}{(-\gamma)^{\frac{1}{2}}}$$

i.e. $\phi(t=0) = \frac{-1.571}{(-\gamma)^{\frac{1}{2}}}$

$$\therefore \quad \psi(t=0) = \frac{-1.571\ (\beta + 2\gamma t_o)^2}{8\gamma\ (-\gamma)^{\frac{1}{2}}} = \xi \tag{20}$$

Thus the initial condition is satisfied on substitution of eqn (20) into eqn (18). For each vehicle in a given platoon, eqn (18) may be substituted into eqn (10) to determine the vehicle trajectory during acceleration. Again it is noted that similar calculations are required for vehicles in each lane.

Following the acceleration phase vehicles proceed at constant speeds which are assigned by the model according to the values previously given in *Table V*. During this constant speed component, the distance travelled is calculated by the simple expression in eqn (21).

$$\psi(t) = \frac{Vt}{3.6} \tag{21}$$

In this case the time t increments from the onset of constant speed and the requisite time matching was achieved via programming logic.

While overtaking manoeuvres during the departure phase have not been included (because of their relative infrequency and consequent negligible influence on the intersection noise climate), allowance has been made for the phenomenon known as bunching. This involves a vehicle catching up to a slower vehicle in front. Under this condition the faster following vehicle assumes and maintains a position at a fixed distance behind the leading vehicle. For the model purposes, this distance was set to 1m. Again programming logic was used to allow for bunching and the procedure involved continuously monitoring the positions of all vehicles.

3.2.3 Approach to Intersection

Vehicles are deemed to approach the intersection at constant speed and then to decelerate such that they come to rest at their stationary queue position ($A1_n$ in the case of eqns (4) and (10)). As with departure from the intersection, an empirically based method was adopted to describe the approach phase. A regression equation developed by Samuels and Jarvis (1978) to quantify modern vehicle deceleration performance was applied to the deceleration component. This equation is presented in eqn (22) and, on integration, became eqn (23) for vehicles in *Fig. 9* proceeding along y = A.

$$V = c - dt \tag{22}$$

where V = speed (km/h),

t = time (s), and

c,d = regression coefficents.

Thus, $x_n(t) = \frac{ct}{3.6} - \frac{dt^2}{7.2} + \delta$ (23)

with δ = Integration constant

By rearranging eqn (22) and substituting into eqn (23), the value of can be determined via the requirement that for V = 0, xn(t) = Aln.

From eqn (22),

$$t = \frac{c - V}{d}$$

Thus on substitution and rearranging, eqn (23) becomes eqn (24).

$$x_n(t) = \frac{c^2 - V^2}{7.2d} + \delta \quad (24)$$

Now, for V = o, $x_n(t) = Al_n$

i.e. $Al_n = \frac{c^2}{7.2d} + \delta$

$\therefore \quad \delta = Al_n - \frac{c^2}{7.2d}$ (25)

Eqns (25) and (22) may now be substituted into eqn (24) to obtain the final form of the deceleration relationship as eqn (26).

$$x_n(t) = \frac{c^2 - V^2}{7.2d} + Al_n - \frac{c^2}{7.2d}$$

$$= Al_n - \frac{V^2}{7.2d}$$

i.e. $x_n(t) = Al_n - \frac{(c - dt)^2}{7.2d}$ (26)

As with acceleration, equations of this type are applied to vehicles proceeding in all directions through the intersection. The regression coefficent c merely quantifies the initial speed from which vehicles decelerate. Samuels and Jarvis (1978) provided values of c, but these may be replaced in the present model by the speeds of vehicles approaching the intersection. Any appropriate values may be input here. As discussed subsequently, the acceleration maxima of *Table V* were selected as first estimates. A range of values of d were provided by Samuels and Jarvis (1978). For a sample of 16 cars chosen to be representative of the Australian vehicle population, the mean value of d was 42.8 km/h/s with an accompanying standard deviation of 4.0 km/h/s. This mean value was adopted for the model. No comparable values for trucks were available so estimates were made of 0.9 d for Medium trucks and 0.8 d for Heavy trucks. Selection of these estimates was made on the basis that, despite improving brake technology it might reasonably be expected that heavier vehicles decelerate in-service at a slower rate than cars. (NAASRA (1976) deals in part with modern truck braking performance.)

Time elapsed during the deceleration manoeuvre may be calculated as follows by application of eqn (22).

$$t_d = \frac{c}{d}$$

where t_d = deceleration time of each vehicle (s),

c = vehicle approach speed (regression coefficent) (km/h), and

d = deceleration regression coefficent from eqn (22)

Once this t_d value has been determined it may be added to the queue period t_q (obtained in eqn (7)) to calculate the time at which each vehicle commenced decelerating. This time is required to assemble the vehicle trajectory during the intersection approach phase. The distance/time relationship for each vehicle during the constant speed approach is given by an equation of the same form as eqn (21). Finally it is noted that programming logic was also applied to the intersection approach relationships to ensure that the time base involved is coordinated with that already established for the stationary and departure manoeuvres.

3.2.4 Vehicle Trajectories

Having constructed the necessary relationships describing the manoeuvres of each vehicle proceeding through the intersection, what is next required is to assemble complete vehicle trajectories such as that illustrated in *Fig. 10*. However this necessitates specification of both the signal phasing and the traffic flow. These factors tend to be related, with signal phasings being set to handle extreme flows at any given intersection. Cycle phasings are generally configured as shown in *Fig. 13*, although there is not always a yellow phase following the red. The scheme of *Fig. 13* is consistent with the assumptions and philosophy of the simple intersection approach of the model. Phase times are also identified in *Fig. 13* and these are input variables to the model.

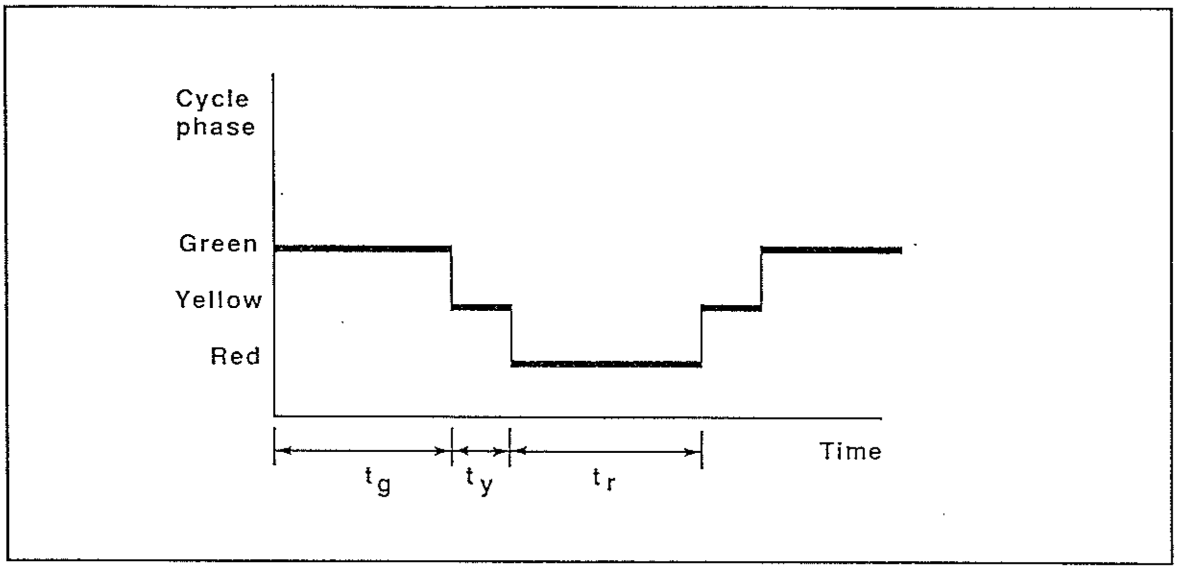


Fig. 13 — *Simple signal phasing*

Well established analytical techniques are available to quantify and design the operating characteristics of signalised intersections (e.g. NAASRA (1970); Lay (1985); Akcelik (1986)). Generally these procedures provide various means of selecting cycle phasing to handle traffic flows while also allowing for many other factors, such as signal network coordination, which are largely outside the scope of the present report. Traffic flow and composition are indeed input variables to the noise model and these, along with some practical constraints have been considered previously (Section 3.2.1). The point here is that these parameters can be selected by the user of the noise model within the framework of conventional or novel traffic engineering practice.

A typical example of the trajectories of a platoon of vehicles produced by the model is given in *Fig. 14*. This shows a platoon of 19 vehicles (17 cars, 1 heavy truck and 1 medium truck) proceeding through an intersection with phasing as per *Fig. 13* and cycle times of $t_g = 40$ s, $t_y = 5$ s and $t_r = 40$ s. (Note that the flow and phase parameters here are consistent with those which may be determined according to the procedures of NAASRA (1970).) Inspection of any curve in *Fig. 14* over increasing time shows the constant speed approach followed by the deceleration and subsequent stationary period. Next there is an acceleration followed by a constant speed departure. Note the staggered departures of successive vehicles and the two instances of bunching during departure. These are reflected in the asymptotic behaviour of the faster following vehicles trajectories with the slower preceeding (heavy) vehicle curves. For computing convenience in this case, each trajectory spans the same total time and this explains the envelope of the commencement and finish of the trajectories.

Similar families are produced for platoons proceeding in the other three directions through the intersection. Series of these families are built up over time as successive platoons pass through the intersection. Note again that the vehicle composition of each platoon is required to generate the trajectories. As mentioned previously the composition may be determined by a random number operator or set by direct input to the program.

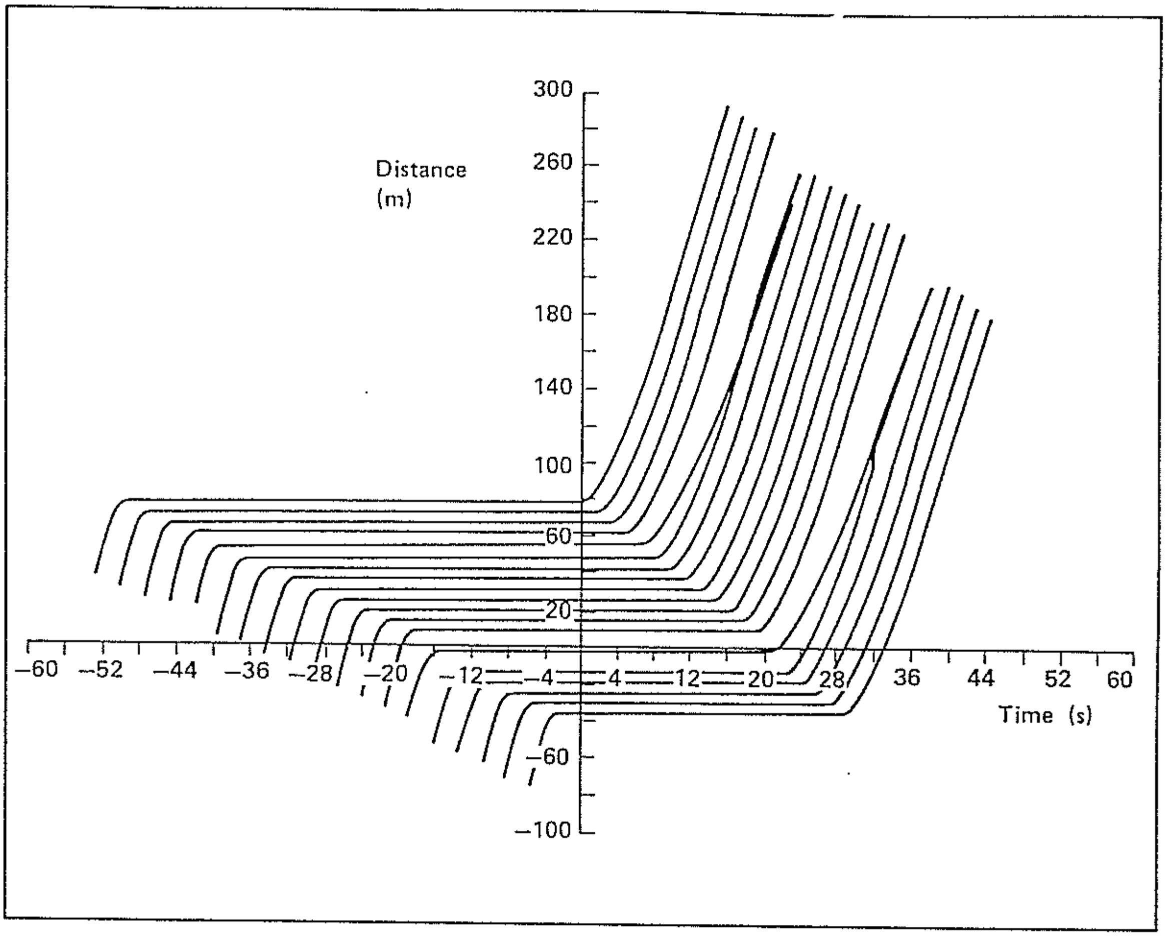


Fig. 14 — *Family of trajectories for a platoon proceeding from left to right through intersection along line y = A in Fig. 9. The platoon consists of 19 vehicles (17C, 1M, 1H) and the cycle phase times are $t_g = 40s$, $t_y = 5s$ and $t_r = 40s$ for the arrangement of Fig.13.*

3.3 Source-receiver geometry

Observers monitor the progress of vehicles passing through the intersection. Over time, the instantaneous distance from each vehicle to any observer of interest is required in order to determine the vehicle noise attenuation. For a vehicle proceeding along the y = A line of *Fig. 9*, the straight forward source-receiver geometrical situation is shown in *Fig. 15*. If the n^{th} vehicle in a particular platoon is considered, then the required Source-Receiver distance is given by eqn (27).

$$R_{kln} = \left([x_k - x_n(t)]^2 + (y_l - A)^2\right)^{\frac{1}{2}} \qquad (27)$$

where R_{kln} = instantaneous distance from n^{th} vehicle to observer at (x_k, y_l) (m), and

$x_n(t)$ = Instantaneous x location of n^{th} vehicle in platoon. Refer to eqns (4), (10), (23) and (26).

Equations of this type have been established for vehicles in all platoons proceeding in every direction through the intersection.

From here, the attenuation of vehicle noise at each observer is determined by combining the time-varying radii of eqn (27) with a 6dB per doubling of distance factor. This factor was selected on the basis of the technology review presented in Chapter 2 and, in particular, of the findings of Wang (1975 and 1981). Further justification of this approach lies in the relatively short attenuation distances required by the present model. For example, in *Fig. 9* the most extreme observer is 4L from the roadside, which for a typical L of 5 m, represents a propagation distance of 22.5 m for a vehicle directly opposite this observer in the centre of the nearside lane. While the model can handle any number of observers at further distances from the intersection, the general approach involves relatively short propagation distances where the 6dB per doubling of distance factor is valid (Wang 1975). By way of comparison UK DoE (1975) uses alternative propagation algorithms, based on a line source model, and extends out to distances of 300 m and greater.

The noise attenuation was incorporated simply as follows.

$$SPL_{D1} = SPL_{D2} - 6D \qquad (28)$$

where SPL_{D1} = noise level at distance D1 (dB),

SPL_{D2} = noise level at distance D2 (dB), and

D = number of distance doublings from D2 to D1.

Thus, $D2 \times 2^N = D1$

i.e. $2^N = \frac{D1}{D2}$

$\therefore \quad N = \frac{\log \frac{D1}{D2}}{\log 2}$

From which,

$$6N = 19.93 \log \frac{D1}{D2}$$

On substitution, eqn (28) becomes eqn (29):

$$SPL_{D1} = SPL_{D2} - 19.93 \log \frac{D1}{D2} \qquad (29)$$

On incorporation into the model, SPL_{D1} becomes the vehicle noise level received at any instant by a given observer, while SPL_{D2} represents the relevant vehicle noise source level. Both of these parameters vary with time during the vehicle trajectory through the intersection.

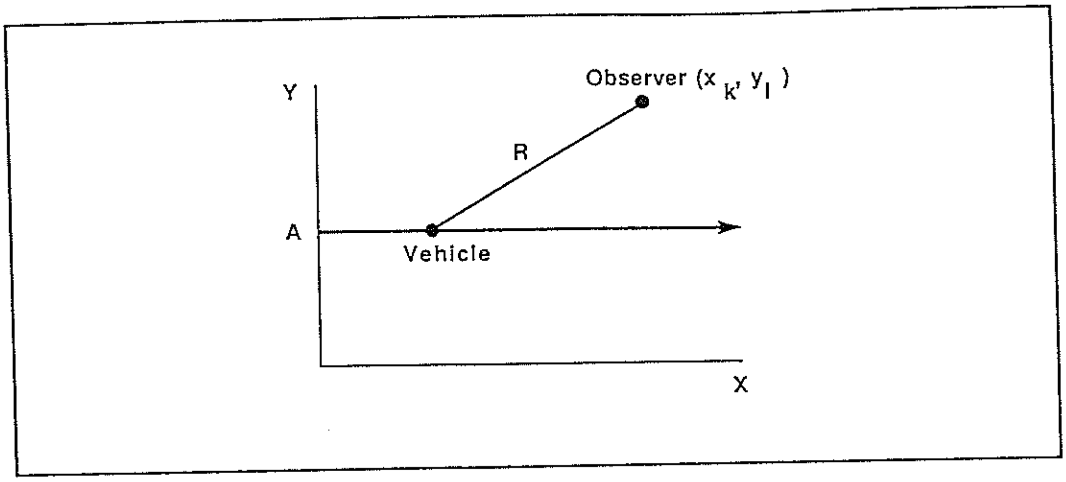


Fig. 15 — *Source-Receiver geometry for one vehicle proceeding from left to right along $y = A$ in Fig. 9.*

APPENDIX B

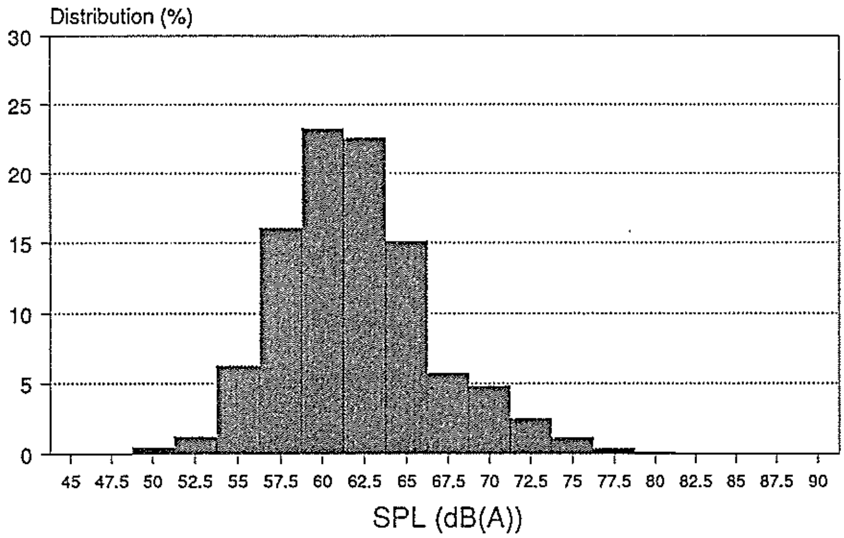
Measured Noise Levels
in New Zealand Evaluation of
ARRB Model

For two sites in Wellington:

(1) WWL (1 to 4) = Whites Line East/Waiwhetu Road, Lower Hutt.
(2) SPC (1 to 4) = Wellington Road/ Evans Bay Parade, Wellington.

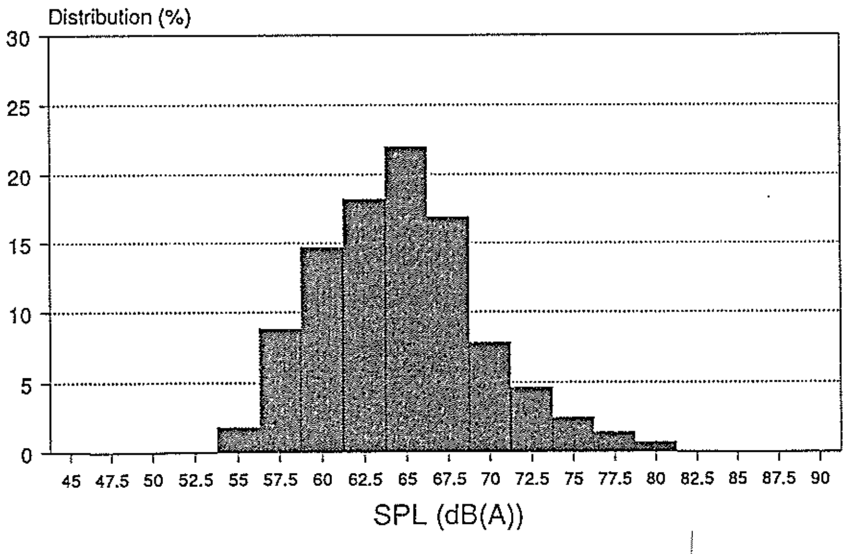
Four runs per site, conducted on 21 March, 1990.

Measured Traffic Noise
WWL 1



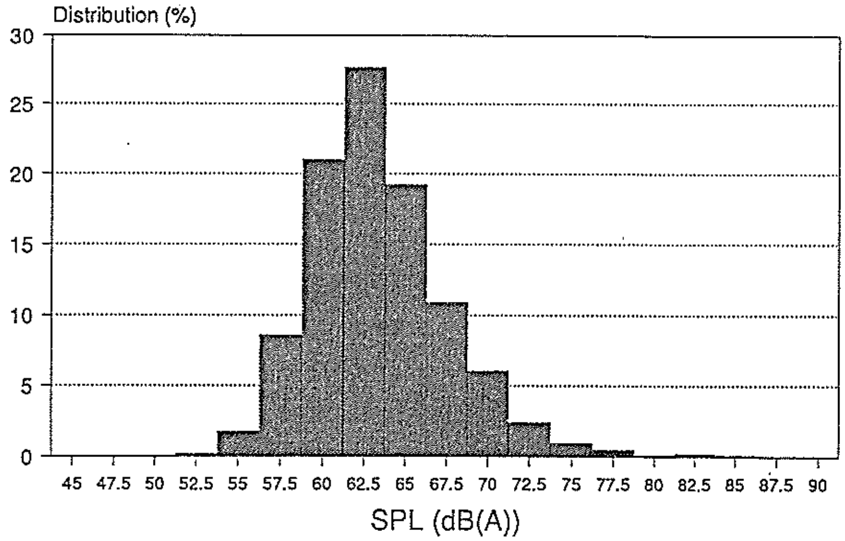

```
MODULAR SLM TYPE 2231
========================
REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*14:38:31..
WWL1..................
......................
......................
......................

SET-UP:
------------------------
Module #: 2 (BZ 7101)
Mic.Corr: + 1.4 dB
S.I.Corr: "FRONTAL"
Pr. Time: 10:50:00
Time W. : "FAST"
Freq.W. : "A"
Rg. (dB): 31.4 - 104.4

MEASUREMENTS:
------------------------
MAXP         101.3 dB
MAXL          88.4 dB
L(01.0)       73.4 dB
L(10.0)       66.9 dB
L(50.0)       59.9 dB
L(90.0)       54.9 dB
L(99.0)       50.4 dB
MINL          47.9 dB
LEQ           63.8 dB
SEL           92.0 dB

No overload.

ELAPSED TIME:
------------------------
Hours   Min.   Sec.
 00      11     12
```

Measured Traffic Noise
WWL 2




```
MODULAR SLM TYPE 2231
========================
REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*14:53:34..
WWL2..................
......................
......................
......................

SET-UP:
------------------------
Module #: 2 (BZ 7101)
Mic.Corr: + 1.4 dB
S.I.Corr: "FRONTAL"
Pr. Time: 10:50:00
Time W. : "FAST"
Freq.W. : "A"
Rg. (dB): 31.4 - 104.4

MEASUREMENTS:
------------------------
MAXP          97.7 dB
MAXL          80.1 dB
L(01.0)       76.9 dB
L(10.0)       69.4 dB
L(50.0)       62.9 dB
L(90.0)       56.9 dB
L(99.0)       53.9 dB
MINL          52.6 dB
LEQ           66.3 dB
SEL           94.5 dB

No overload.

ELAPSED TIME:
------------------------
Hours   Min.   Sec.
 00      11     02
```

Measured Traffic Noise
WWL 3



MODULAR SLM TYPE 2231

REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*15:07:15..
WWL3..................

SET-UP:

Module #:	2 (BZ 7101)
Mic.Corr:	+ 1.4 dB
S.I.Corr:	"FRONTAL"
Pr. Time:	10:50:00
Time W. :	"FAST"
Freq.W. :	"A"
Rg. (dB):	31.4 - 104.4

MEASUREMENTS:

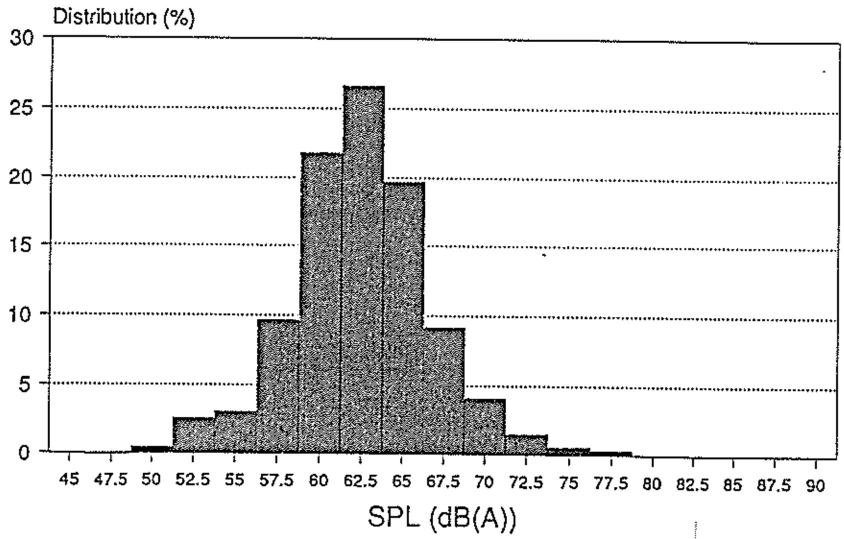
MAXP	98.3 dB
MAXL	83.6 dB
L(01.0)	74.4 dB
L(10.0)	67.4 dB
L(50.0)	61.4 dB
L(90.0)	56.9 dB
L(99.0)	53.9 dB
MINL	51.6 dB
LEQ	64.8 dB
SEL	92.9 dB

No overload.

ELAPSED TIME:

Hours	Min.	Sec.
00	10	54

Measured Traffic Noise
WWL 4



MODULAR SLM TYPE 2231

REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*15:20:20..
WWL4..................

SET-UP:

Module #:	2 (BZ 7101)
Mic.Corr:	+ 1.4 dB
S.I.Corr:	"FRONTAL"
Pr. Time:	00:10:50
Time W. :	"FAST"
Freq.W. :	"A"
Rg. (dB):	31.4 - 104.4

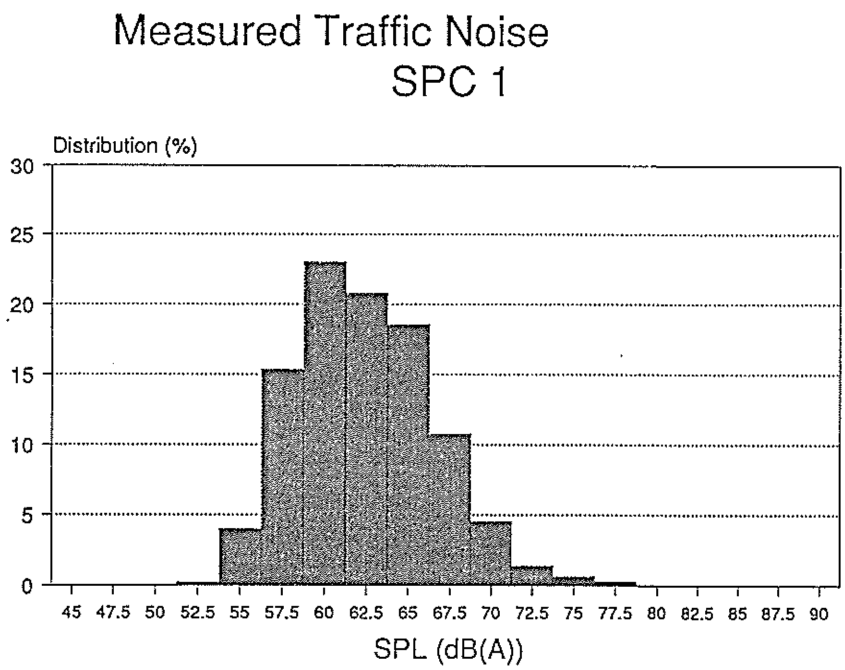
MEASUREMENTS:

MAXP	89.0 dB
MAXL	77.0 dB
L(01.0)	71.9 dB
L(10.0)	65.9 dB
L(50.0)	60.9 dB
L(90.0)	55.9 dB
L(99.0)	50.4 dB
MINL	46.6 dB
LEQ	63.1 dB
SEL	91.1 dB

No overload.

ELAPSED TIME:

Hours	Min.	Sec.
00	10	50



MODULAR SLM TYPE 2231

REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*10:22:01..
SPC1..................

SET-UP:

Module #:	2 (BZ 7101)
Mic.Corr:	+ 1.4 dB
S.I.Corr:	"FRONTAL"
Pr. Time:	00:14:00
Time W. :	"FAST"
Freq.W. :	"A"
Rg. (dB):	31.4 - 104.4

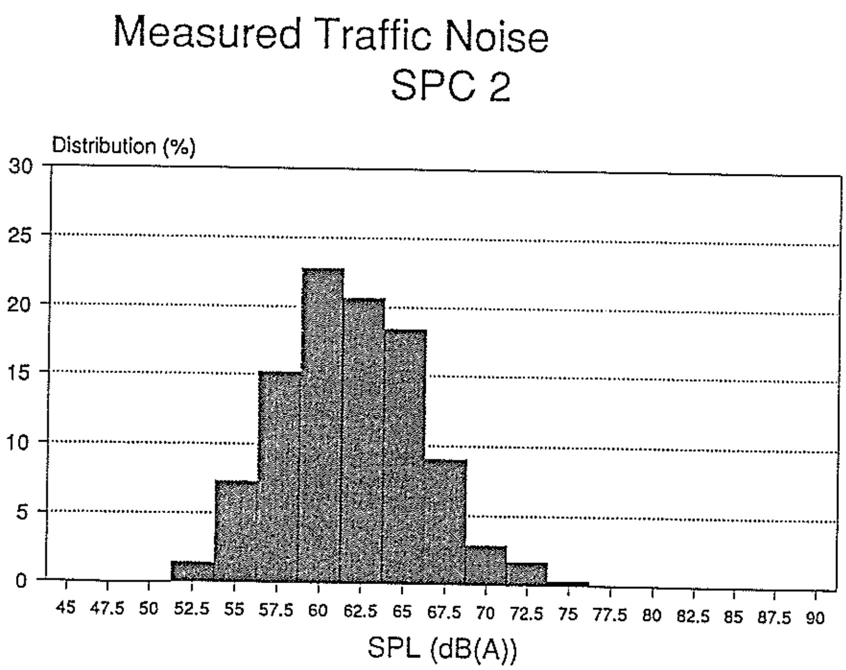
MEASUREMENTS:

MAXP	101.0 dB
MAXL	86.2 dB
L(01.0)	72.4 dB
L(10.0)	66.4 dB
L(50.0)	60.4 dB
L(90.0)	55.9 dB
L(99.0)	52.9 dB
MINL	51.4 dB
LEQ	63.6 dB
SEL	92.7 dB

No overload.

ELAPSED TIME:

Hours	Min.	Sec.
00	14	00



MODULAR SLM TYPE 2231

REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*10:39:56..
SPC2..................

SET-UP:

Module #:	2 (BZ 7101)
Mic.Corr:	+ 1.4 dB
S.I.Corr:	"FRONTAL"
Pr. Time:	00:14:00
Time W. :	"FAST"
Freq.W. :	"A"
Rg. (dB):	31.4 - 104.4

MEASUREMENTS:

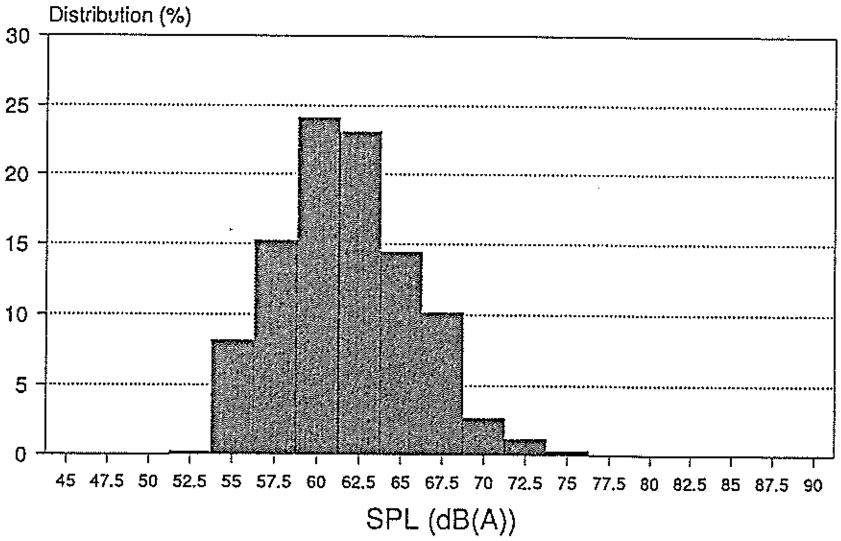
MAXP	93.4 dB
MAXL	75.0 dB
L(01.0)	70.9 dB
L(10.0)	65.4 dB
L(50.0)	59.9 dB
L(90.0)	54.9 dB
L(99.0)	51.9 dB
MINL	50.0 dB
LEQ	62.3 dB
SEL	91.5 dB

No overload.

ELAPSED TIME:

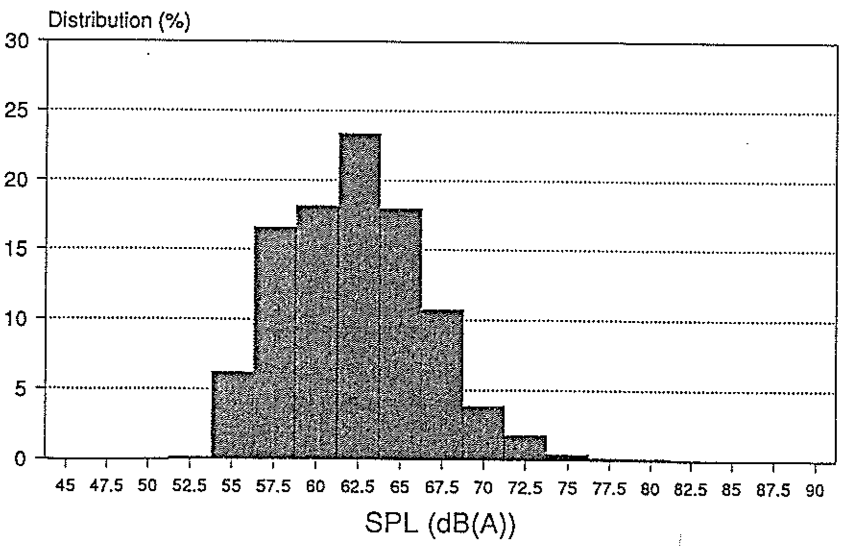
Hours	Min.	Sec.
00	14	00

Measured Traffic Noise
SPC 3




```
MODULAR SLM TYPE 2231

=========================
REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*10:56:41..
SPC3..................
......................
......................
......................

SET-UP:
-------------------------
 Module #: 2 (BZ 7101)
 Mic.Corr: + 1.4 dB
 S.I.Corr: "FRONTAL"
 Pr. Time: 00:14:00
 Time W. : "FAST"
 Freq.W. : "A"
 Rg. (dB): 31.4 - 104.4

MEASUREMENTS:
-------------------------
 MAXP          92.7 dB
 MAXL          78.4 dB
 L(01.0)       70.9 dB
 L(10.0)       65.4 dB
 L(50.0)       59.9 dB
 L(90.0)       54.9 dB
 L(99.0)       52.4 dB
 MINL          51.5 dB
 LEQ           62.2 dB
 SEL           91.3 dB

No overload.

ELAPSED TIME:
-------------------------
 Hours   Min.   Sec.
  00      14     00
```

Measured Traffic Noise
SPC 4




```
MODULAR SLM TYPE 2231

=========================
REMARKS:
Measurement No= 1.....
Date:.......Time:......
21/3/90.....*11:14:12..
SPC4..................
......................
......................
......................

SET-UP:
-------------------------
 Module #: 2 (BZ 7101)
 Mic.Corr: + 1.4 dB
 S.I.Corr: "FRONTAL"
 Pr. Time: 00:14:00
 Time W. : "FAST"
 Freq.W. : "A"
 Rg. (dB): 31.4 - 104.4

MEASUREMENTS:
-------------------------
 MAXP          91.9 dB
 MAXL          79.3 dB
 L(01.0)       71.9 dB
 L(10.0)       65.9 dB
 L(50.0)       60.4 dB
 L(90.0)       55.4 dB
 L(99.0)       52.9 dB
 MINL          51.3 dB
 LEQ           63.2 dB
 SEL           92.3 dB

No overload.

ELAPSED TIME:
-------------------------
 Hours   Min.   Sec.
  00      14     00
```

APPENDIX C

Predicted Noise Levels
in New Zealand Evaluation
of ARRB Model

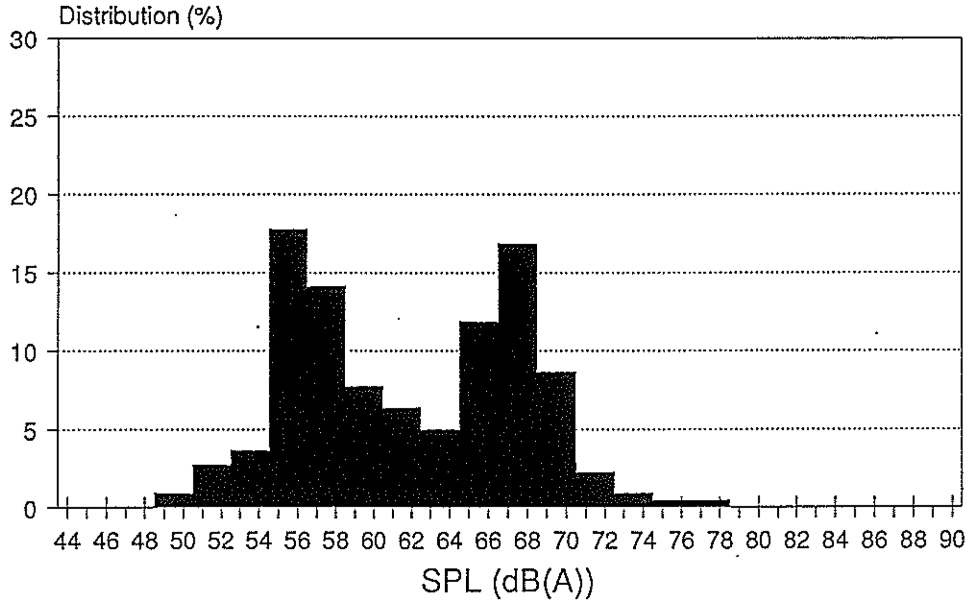
Predictions carried out for the two sites in Wellington where measurement data was collected:

(1) WWL (1 to 4) = Whites Line East/Waiwhetu Road, Lower Hutt.
(2) SPC (1 to 4) = Wellington Road/ Evans Bay Parade, Wellington.

Predictions made using two versions of model:

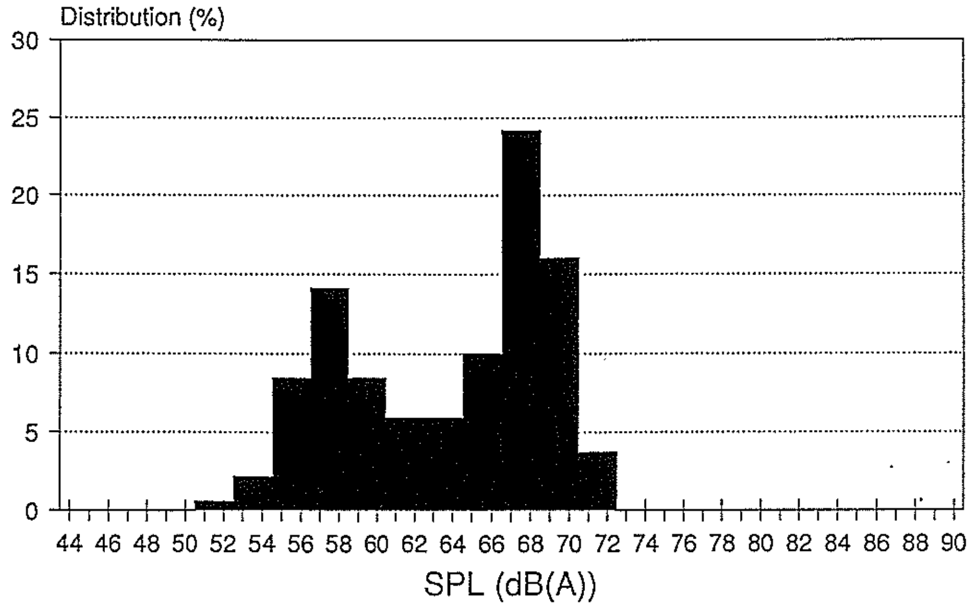
ITFNS = Original version of ARRB model.
ITFNS' = New Zealand modified version of ARRB model.

WWL1
ITFNS Original Version



L10 = 70.0 L50 = 62.0 L90 = 55.5 LEQ = 67.0

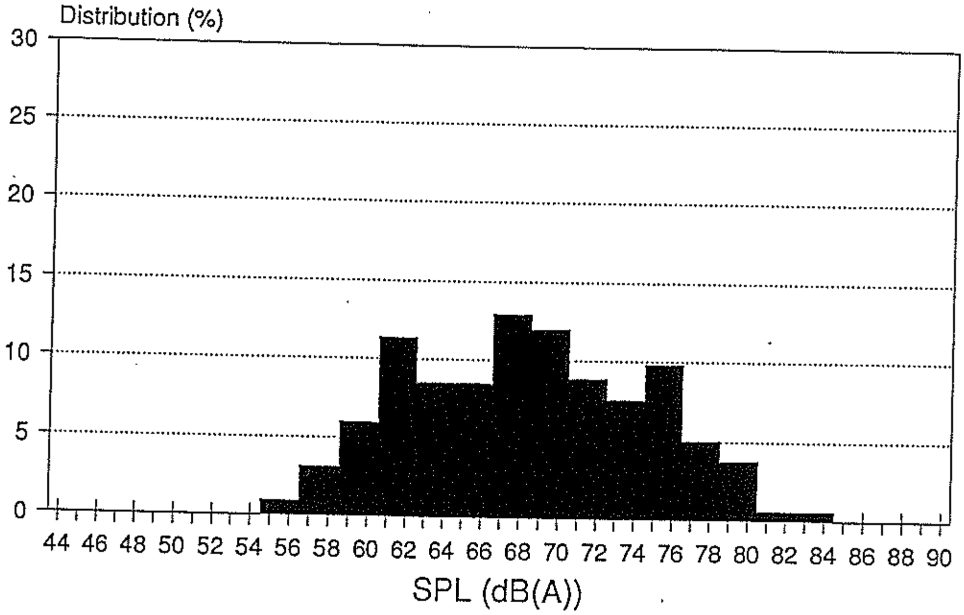
WWL2
ITFNS Original Version



L10 = 70.0 L50 = 67.0 L90 = 57.0 LEQ = 67.0

WWL3

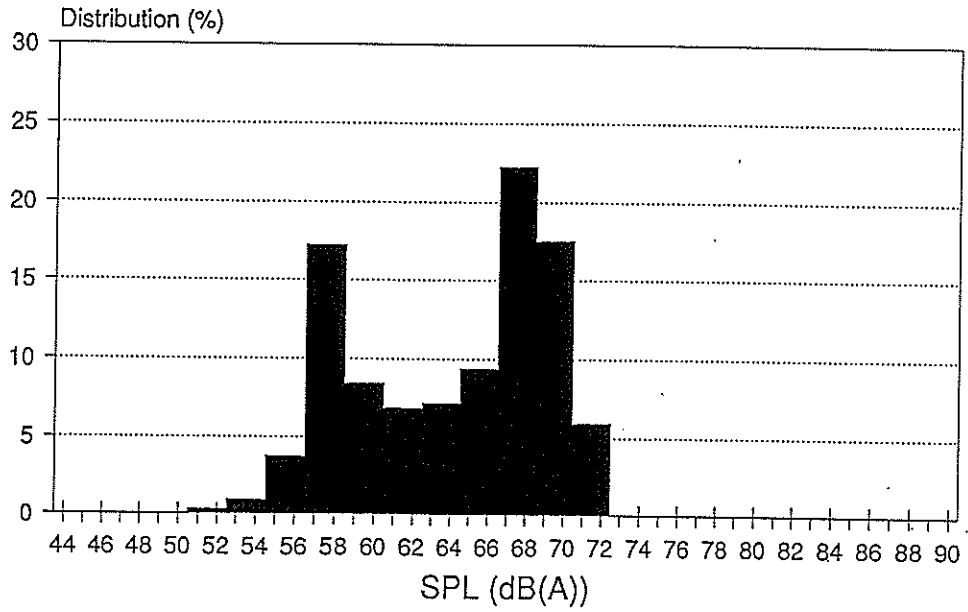
ITFNS Original Version



L10 = 78.0 L50 = 69.0 L90 = 61.0 LEQ = 75.0

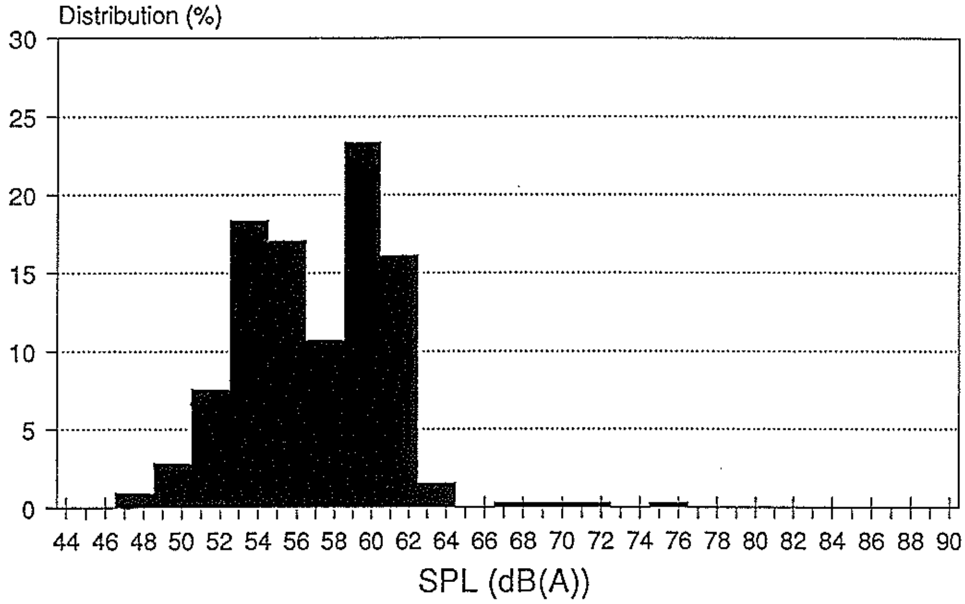
WWL4

ITFNS Original Version



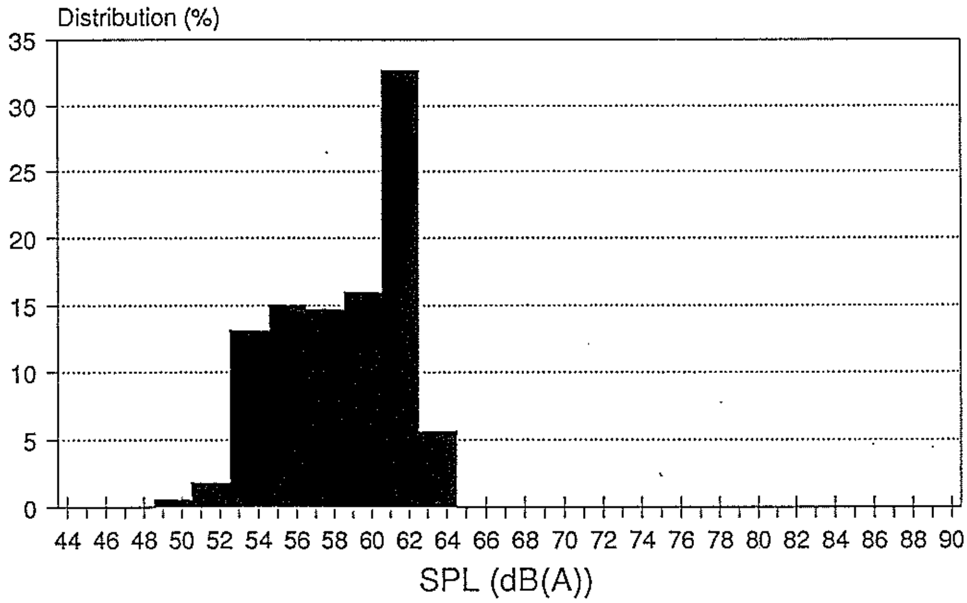
L10 = 70.0 L50 = 66.5 L90 = 58.0 LEQ = 67.0

WWL1
ITFNS Modified NZ Version



L10 = 63.0 L50 = 58.0 L90 = 53.0 LEQ = 60.0

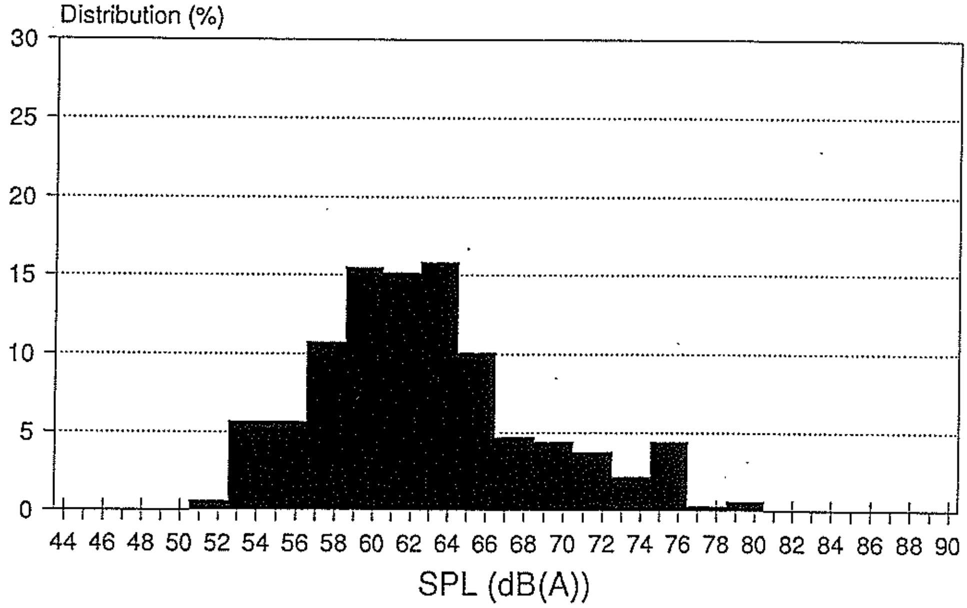
WWL2
ITFNS Modified NZ Version



L10 = 63.0 L50 = 60.0 L90 = 54.5 LEQ = 60.0

WWL3

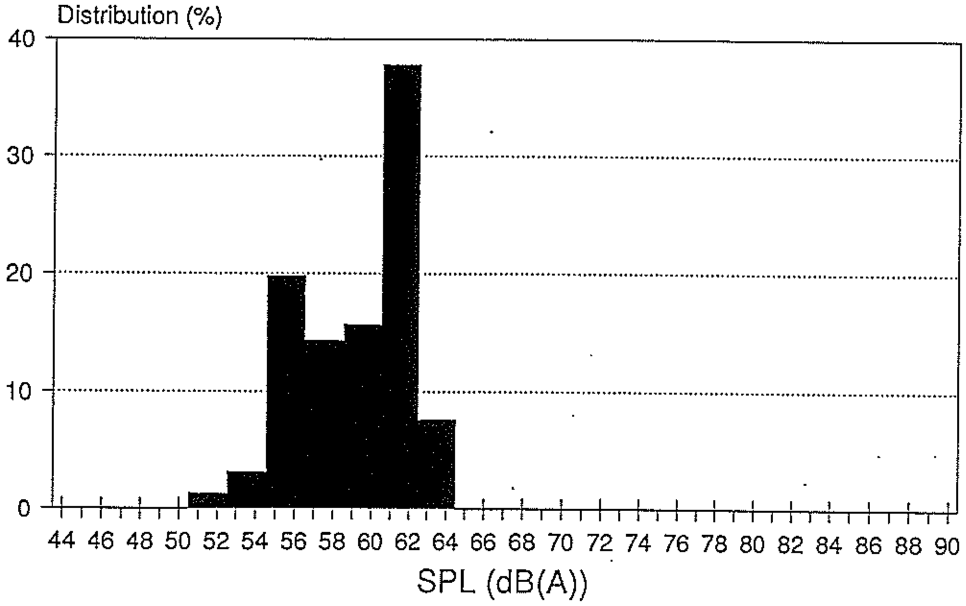
ITFNS Modified NZ Version



L10 = 72.0 L50 = 63.0 L90 = 56.0 LEQ = 69.0

WWL4

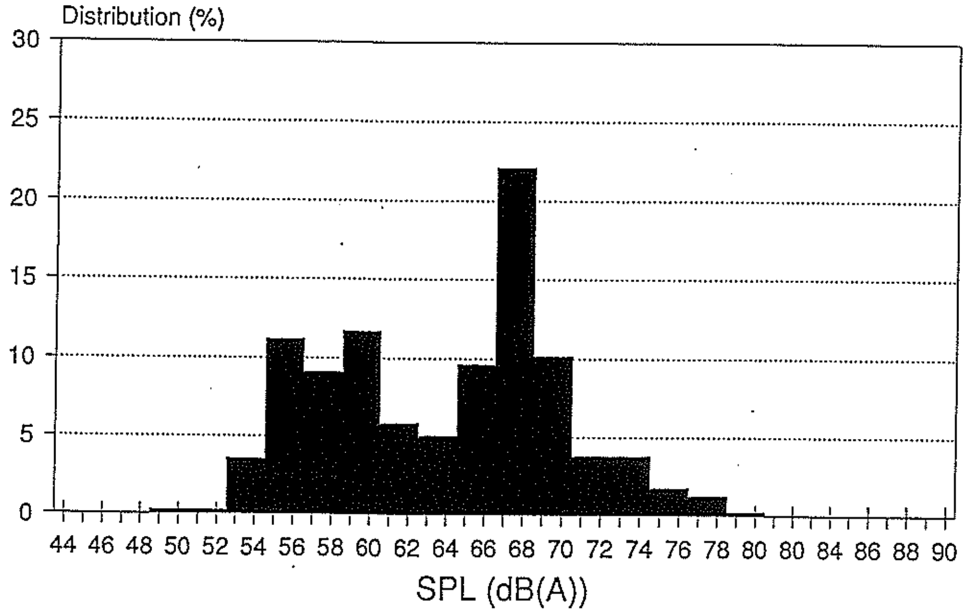
ITFNS Modified NZ Version



L10 = 63.0 L50 = 61.0 L90 = 56.0 LEQ = 60.0

SPC1

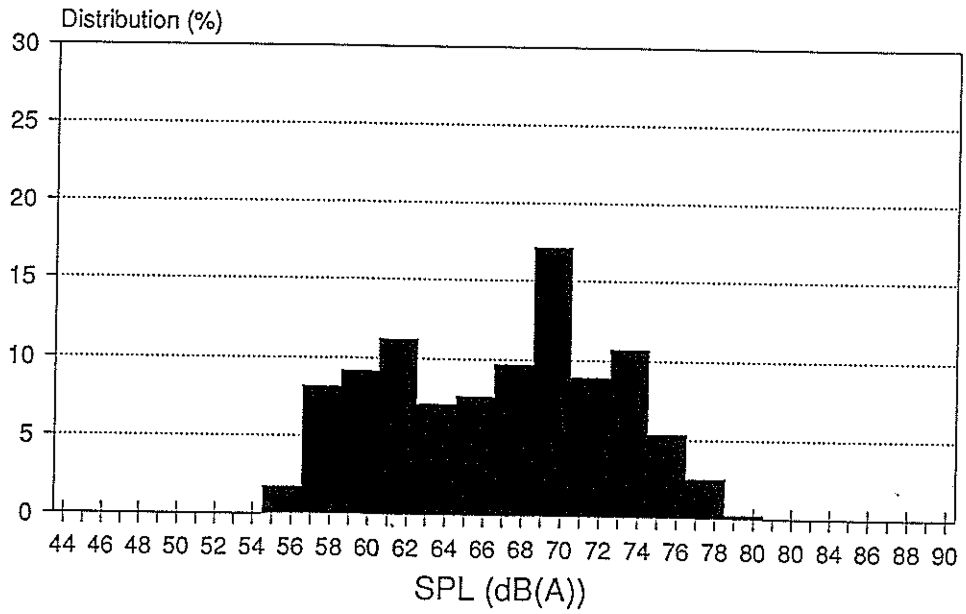
ITFNS Original Version



L10 = 71.5 L50 = 66.0 L90 = 57.0 LEQ = 68.5

SPC2

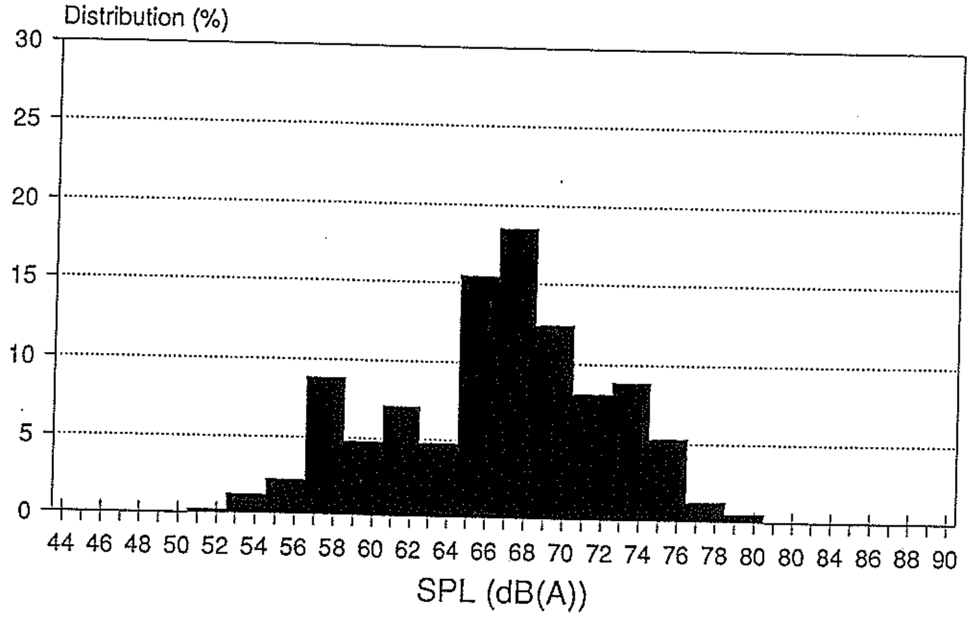
ITFNS Original Version



L10 = 75.0 L50 = 68.0 L90 = 60.0 LEQ = 72.0

SPC3

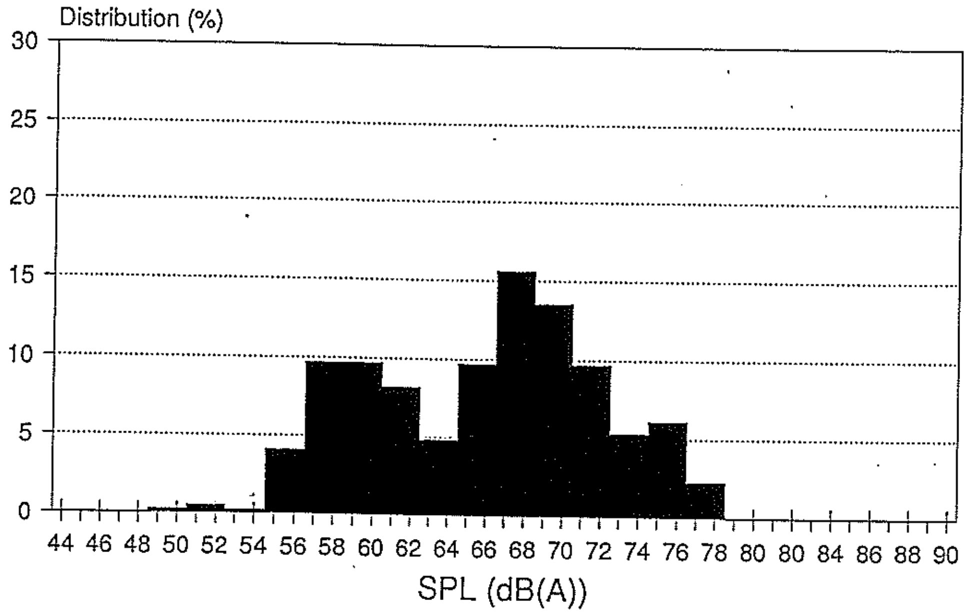
ITFNS Original Version



L10 ≒ 75.0 L50 ≒ 67.5 L90 ≒ 59.0 LEQ = 72.0

SPC4

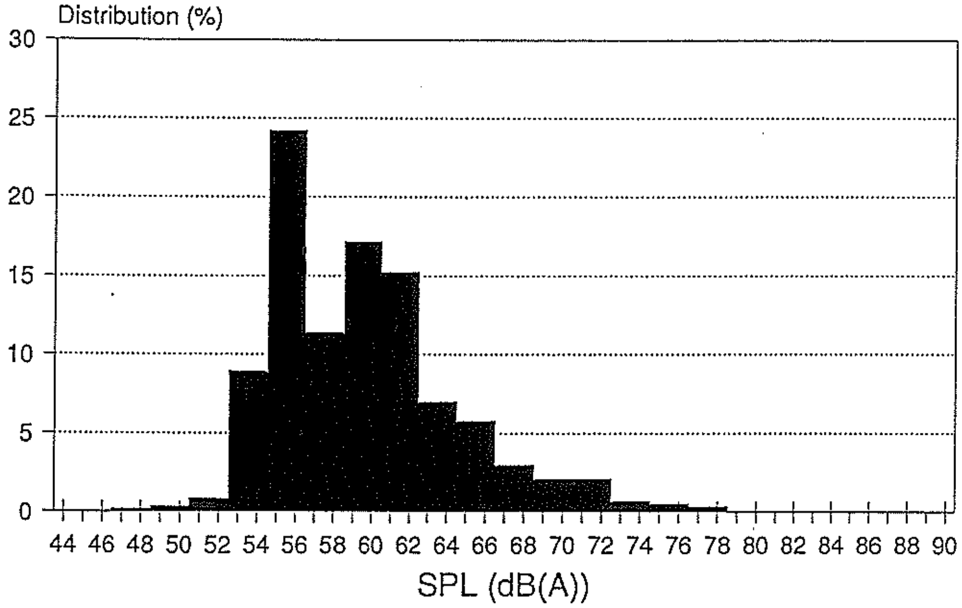
ITFNS Original Version



L10 ≒ 75.0 L50 = 68.0 L90 = 59.0 LEQ = 72.0

SPC1

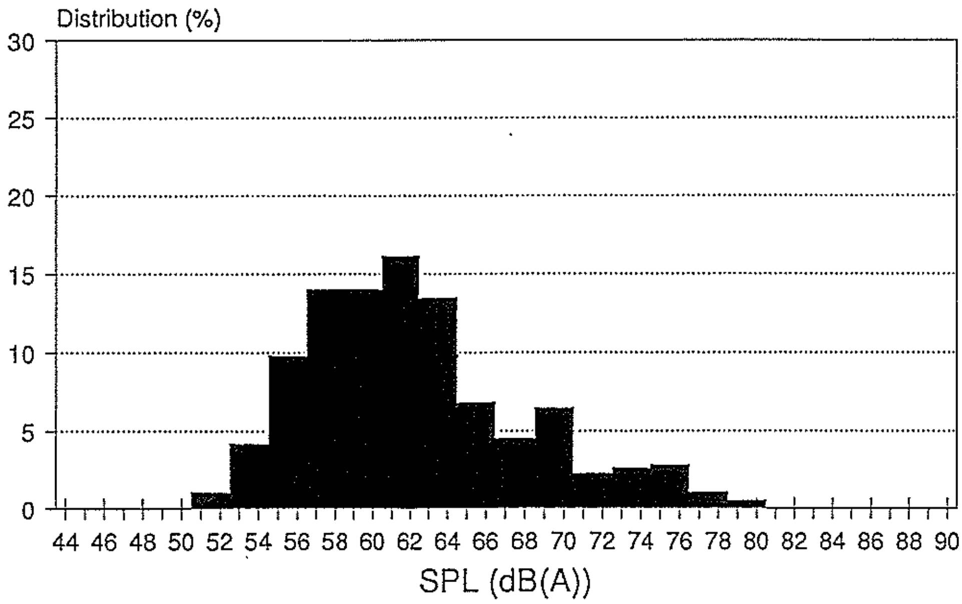
ITFNS Modified NZ Version



L10 = 67.0 L50 = 59.5 L90 = 55.0 LEQ = 64.0

SPC2

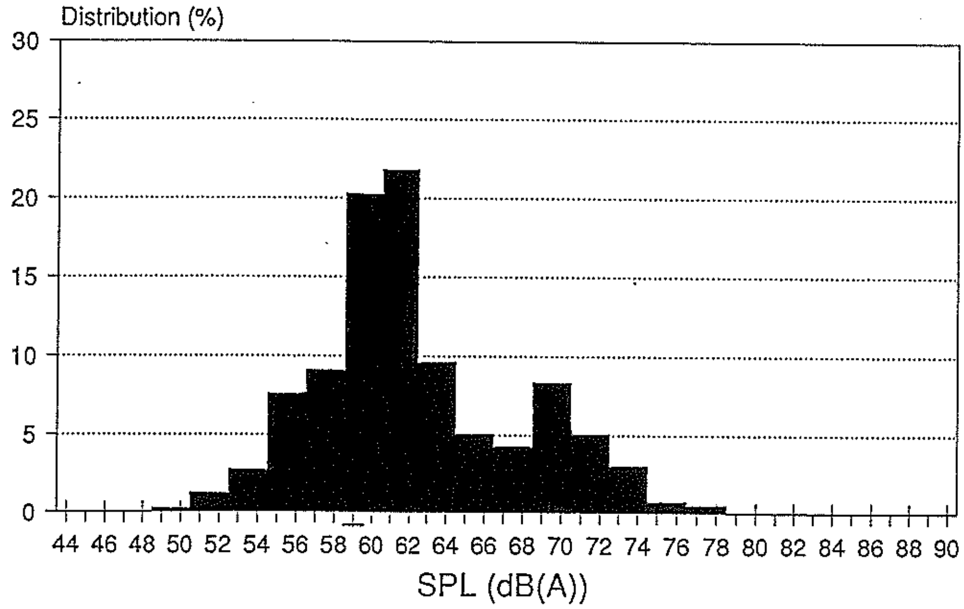
ITFNS Modified NZ Version



L10 = 71.0 L50 = 62.0 L90 = 56.5 LEQ = 68.0

SPC3

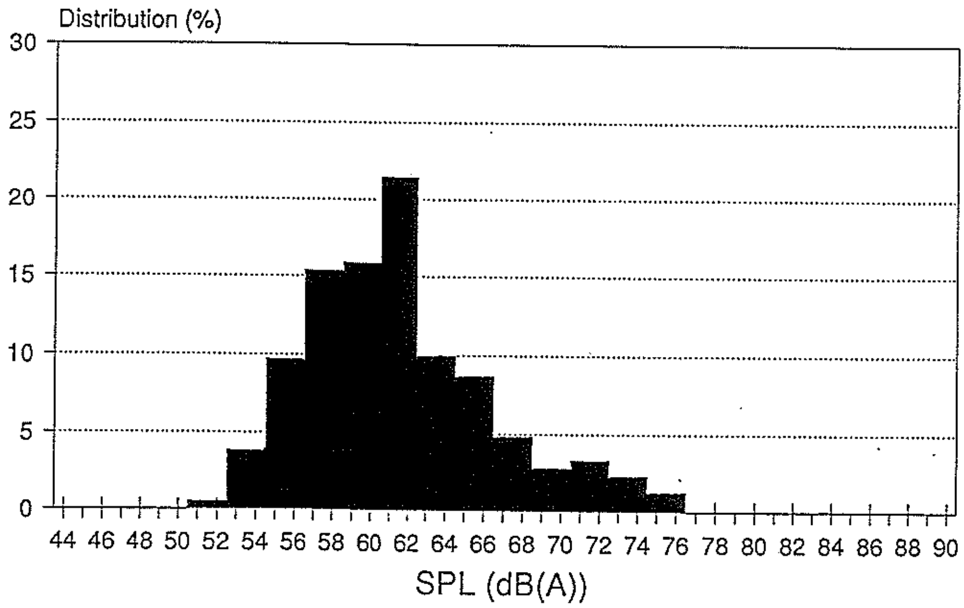
ITFNS Modified NZ Version



L10 = 71.0 L50 = 62.0 L90 = 57.0 LEQ = 68.0

SPC4

ITFNS Modified NZ Version



L10 = 69.0 L50 = 61.5 L90 = 57.0 LEQ = 66.0