

2. LITERATURE REVIEW

2.1 GENERAL

In India, the growing population and economic development are resulting into a sizable number of mid-sized cities. Due to the shortage of available land in such mid-sized cities, the urban habitats are growing rapidly with narrow roadways. Buildings are being constructed close to the roadway for residential and business purposes which seriously affects town planning in terms of location of land-use with safety from noise pollution. Literature has reported several adverse effects of noise pollution due to road traffic operation on individuals which include annoyance, loss of concentration, reduction of work efficiency, apart from other physiological and psychological damages [7, 8]. At certain pitch level, individual reactions translate into community reactions and we are already witnessing demands for enforcing a ban on traffic in certain urban areas for the tranquility of livelihood in civilized society [9]. Literature also suggested that traffic noise intensity undergoes geometric progression in pace with our economic and technological growth. Also, mixed traffic flow was reported to generate higher noise level than segregated traffic flow due to complex vehicular interaction, reduction in traffic speed, high vehicular population, and presence of over-aged vehicles etc. [10]. The urban noise enviroscape of such mid-sized city roads is quickly worsening and is engulfing newer areas into its domain. When roads are widened for capacity augmentation of traffic in such mid-sized cities, the source is shifted further closer to the receiver, thereby aggravating the noise scenario [11, 12].

It is an acknowledged fact that road traffic induced noise pollution is accorded lowest priority among vehicular pollutants in the Indian context because they do not leave any visible reminder of unpleasantness. Of late, it is observed that this pollutant is

assuming dangerous proportions engulfing more areas in its domain and the affected community is gradually becoming vigilant and demanding better living conditions. Unlike western countries, integrated efforts are still wanting for enquiring into road traffic noise pollution due to vehicular operation under mixed traffic flow conditions, and in particular for jammed traffic [13]. Within their limited resources, some Institutions have conducted few low scale studies in the past [14-39]. With the passage of time, a distinct gap has appeared between the field situation and technological solutions for mitigation, and therefore these models warrant revalidation and relook with a holistic scientific approach to for sustainable town planning and abatement strategies.

In the western countries, several assessment and mitigation models are in vogue [40], but owing to different traffic, geophysical and social conditions, geographically transferable solutions are not available. Therefore, this issue as of now cannot be left unattended for long in a highly populous country like India for the reason that economic development of the urban population of mid-sized cities has its roots in their collective demand as a community for a better living. Therefore, the time has arrived now that we consolidate our mandate as a society to seek sustainable solutions to this pollutant in terms of models for predicting its propagation and attenuation. Knowledge is available from the experiences of the western world [41-55] other developing economies [56-66] and few studies conducted in India and South-East Asia [67-80].

Traffic jam due to overcrowded vehicles on roads is becoming a regular phenomenon on roads of Indian mid-sized cities and Varanasi is one of them. There is a dearth of literature on assessment and modeling of traffic jam noise pollution under mixed traffic flow. However, literature relevant to the context has been collected and presented in the subsequent paragraphs along with the statutory regulations adopted for India.

2.2 STATUTORY REGULATIONS

Statutory body like the Ministry of Environment and Forests has framed noise standards which are documented in the Noise Pollution (Regulation and Control) Rules 2000 under the Environment Protection Act 1986 mandating certain safe value of noise levels for various urban landuse like residential, commercial, industrial and silence zone as shown in Table 2.1 [81].

Table 2.1 Ambient air quality standards in respect of noise [81]

| Area Code | Category of Area/Zone | Limits in dBA, L_{eq} * | |
|-----------|-----------------------|---------------------------|------------|
| | | Day Time | Night Time |
| (A) | Industrial area | 75 | 70 |
| (B) | Commercial area | 65 | 55 |
| (C) | Residential area | 55 | 45 |
| (D) | Silence Zone | 50 | 40 |

Note:

1. Day time shall mean from 6.00 a.m. to 10.00 p.m.
2. Night time shall mean from 10.00 p.m. to 6.00 a.m.
3. Silence zone is defined as an area comprising not less than 100 metres around hospitals, educational institutions and courts. The silence zones are zones which are declared as such by the competent authority.
4. Mixed categories of areas may be declared as one of the four above mentioned categories by the competent authority.

*dBA L_{eq} denotes the time weighted average of the level of sound in decibels on scale A which is relatable to human hearing.

A "decibel" is a unit in which noise is measured.

"A", in dBA L_{eq} , denotes the frequency weighting in the measurement of noise and corresponds to frequency response characteristics of the human ear.

L_{eq} : It is an energy mean of the noise level, over a specified period.

For TNI and NPL as discussed in Section 1.4.3, the permissible limits are 74 and 88 dBA, respectively [5, 6].

Depending on the efficacy of the existing noise standards, an attempt was made by Garg et al. (2015) to suggest ambient noise standards for India based on international practice [82].

2.3 MIXED TRAFFIC ON INDIAN ROADS

Punith et al. (2016) [83] mention in their study that majority of the vehicles (70.9%) on Indian roads preferred to travel in the middle of the road. Lane discipline was not strictly enforced, it was found that two-wheelers and auto-rickshaws were distributed almost over the entire width of the road because of their smaller sizes and higher maneuverability. Cars were mostly distributed near the middle of the road so as to maintain higher speeds. Heavy vehicles are also concentrated near the middle of the road so as to avoid side interferences and also due to their larger sizes and lower maneuverability. Two-wheelers, cars, and auto-rickshaws adjust their lateral position when opposed. Heavy vehicles due to their larger sizes are not much influenced by opposing vehicles and thus, lateral positions do not vary significantly when opposed than when unopposed. The lateral separation of vehicles decreases with increase in subject vehicle size and increases with increase in the speed of opposing vehicle. The probability of a subject vehicle to choose either left or right lateral shift increases with the decrease in subject vehicle size and increases with leader vehicle size. The increase in the lateral gap between the leader in the current path and target path increases the probability of a subject vehicle to shift either to left or right path. The increase in lateral gap between the leader in the current path and opposite vehicle increases the

probability of a subject vehicle to shift to the right and decreases the probability to shift to left.

Das et al. (2016) [84] reported that traffic congestion was the most common phenomenon observed on traffic corridors of the metropolitan cities in India. Traffic volume, traffic composition, and roadside friction were the main influencing factors of traffic congestion. Roadside parking, pedestrian encroachment, traffic interruptions due to intersection traffic and land use activities were the critical factors of roadside friction. The vehicle composition, particularly of larger dimensions and slow moving vehicles, had significant inter-mode interactions to pull down the vehicle speeds. It was, however, difficult to evaluate the inter-mode interactions.

2.4 CONGESTION CHARACTERISTICS OF INTERRUPTED FLOW FOR URBAN ROADS

Sharma and Swamy (2016) [85] presented a detailed study on congestion characteristics of interrupted flow for urban roads with heterogeneous traffic structure. Traffic congestion is one of the main liabilities of present time [86]. It occurs when the cost of travel is increased by the presence of other vehicles, either because speed falls or because greater attention is required to drive safely [87]. It is a price that people pay for the different benefits derived from the agglomeration of population and economic activity. Since the land is scarce and road capacity is costly to construct, it would be uneconomical to spend heavily to increase capacity to the extent that travels become congestion-free. Since the demand for travel depends on the cost, improvements in travel conditions induce people to take more trips, and it would probably be impossible to eliminate congestion [88]. Traffic engineers often compare traffic with fluid, assuming that certain volume must

flow through the road system. But urban traffic may be more comparable to a gas that expands to fill available space [89]. Congestion can be defined as traffic condition caused by a downstream bottleneck, or increase in travel time compared to low traffic conditions [85].

The selection of congestion performance indicators and data collection techniques must be carefully coordinated with the definition adopted to capture the true nature of congestion [90]. Transportation researchers have long struggled to find satisfactory ways to describe and analyse congestion, as evident from a large number of often competing approaches and models that have been developed. Early researchers developed models based on fluid dynamics, but congestion, unlike fluid flow, is not a purely physical phenomenon but rather the result of people's trip-making decisions and minute-by-minute driving behavior. One should, therefore, expect the quantitative and qualitative, characteristics of congestion to vary with automobile and road design, rules of the road, the pace of life, and other factors. Efforts have been made by many researchers to understand and quantify congestion, however, it is found that most of the works have been concentrated on the area wise quantification of congestion i.e., Congestion Severity Index [91]; Roadway Congestion Index, Percentage of Congested Freeway, K-Factor [86]; Lane Mile Duration Index and Freeway Congestion Index [92]. Models calibrated and validated in a developed country may not fit well a developing country for the difference in traffic conditions [85, 87].

2.4.1 Interrupted traffic flow

Flows may be further classified as uninterrupted flows and interrupted flows. In uninterrupted flow, traffic flow condition results from interactions among vehicles in traffic stream between vehicles and the geometric and environmental characteristics of the

roadway. These flows do not have external elements such as traffic signals which might interrupt the traffic flow. However, interrupted-flows have controlled and uncontrolled access points that can interrupt the traffic flow. These access points include traffic signals, stop signs, yield signs and other types of control that stop traffic periodically or slow it significantly, irrespective of the amount of traffic [85, 93].

2.4.2 Level of Service (LOS) based on congestion

LOS has also been defined by several researchers based on quantified congestion. Since quantified congestion is a measure of loss in freedom of movement that accounts for the variation of speed level with increase in traffic volume (along with its character) under prevailing roadway, traffic, and control conditions, the congestion level is a logical and better measure of effectiveness (MOE) to define LOS in a quantitative manner. The degradation of the quality of operation and increase in congestion level due to traffic volume is not uniform at all flow levels. To represent the variation of level of service through congestion in a complete manner, 10 different levels of service have been proposed by researchers with congestion levels of 5, 10, 20, 30, 40, 50, 60, 80, and 100%; distinguishing nine LOS (A – I) within the stable flow zone, and one LOS (J) with congestion more than 100%, indicating the unstable (forced) flow. The limiting values of congestion for different LOS are stated to be consistent with the usual shape of the speed-flow curve with a relatively lesser speed drop near free-flow operation and sharp drop near the capacity flow. The service volumes are governed by congestion levels, and therefore, any change in the prevailing roadway, traffic, and control conditions would normally be reflected by the changes in service volumes corresponding to various levels of service [85, 94].

Darshana and Krishna Rao (2016) [95] mention that the traffic characteristics and the user behaviour in developing countries like India are significantly different from other developed countries. The perception of users at signalized intersections differs among various vehicle classes. Analysis of the heterogeneous vehicle classes revealed that waiting time was the most important factor while perceiving Level of Service for all the vehicle type users while aesthetics was the least important factor. Waiting was always considered as a negative experience, which makes the users frustrated. Other factors ranked differently for different vehicle type users. For motorized two-wheeler users, road surface quality and presence of pedestrians were the second and third most important factors. The presence of heavy vehicles has a higher impact on the maneuverability of vehicles like motorized two-wheelers and motorized three-wheelers. The increase in the number of crossing pedestrians, lead to an increase in the number of accidents, reduction in the speed of the vehicles etc. Similar is the case with the presence of heavy vehicles and the presence of obstructions.

2.4.3 Quantification of congestion

The level of congestion varies with the roadway, traffic control conditions, and operating traffic volume. While the majority of studies regarding congestion were based on highways, quantification of congestion on urban roads has been attempted by several researchers [96-99]. Since the loss in freedom of movement can be measured as the area under the speed-flow envelope (between the free-flow operation and the actual operating condition), the congestion can be quantified as the percentage loss in freedom of movement under prevailing roadway, traffic, and control conditions [85, 94].

Figure 2.1 (a) and 2.1 (b) represents quantification of congestion proposed by Maitra et al.[94]. Although, the worst operating condition represented by point D (*Figure*

2.1a) normally be defined as 100% congestion; the behavior of midblock traffic is seldom observed in the range BD (the lower portion of the speed-flow envelope). Therefore, point B (i.e., the capacity) should be taken as traffic condition representing 100% congestion.

With the capacity as 100% congested operation, the generality of the philosophy of quantification of congestion remains valid, and when the lower envelope or a part of it is observed, it will be representing forced flow with the quantified congestion more than 100%. Therefore, in that case, a point near the capacity in the stable flow zone may be taken to represent 100% congestion. In Figure 2.1(b) point A_1 represents the operation with free-flow speed v_f , whereas point B_1 represents a 100% congested operation in the stable flow zone with a realized speed v_n and volume level Q_1 . Therefore, 100% congested operation represented by point B_1 indicates an amount of loss in freedom of movement equivalent to an area $A_1B_1G_1$ under the envelope. Similarly, the amount of loss in freedom of movement for an operating point P_1 , represented by a flow level q_a , and realized speed v_u under the same operating conditions, can be expressed as the area $A_1P_1D_1$. Consequently, congestion at operating point P_1 can be expressed as $(\text{Area } A_1P_1D_1 / \text{Area } A_1B_1G_1) * 100$ [94] [85].

2.5 EFFECT OF TRAFFIC COMPOSITION ON ROAD NOISE

Filho et al. (2004) [57] studied the effect of traffic composition on road traffic noise for the city of Florianopolis located in Southern Brazil. Traffic composition was defined as the percentage of heavy vehicles with respect to the total number of vehicles. Measurements were made from Monday to Friday, 6:00 to 10:10 a.m. A total of 149

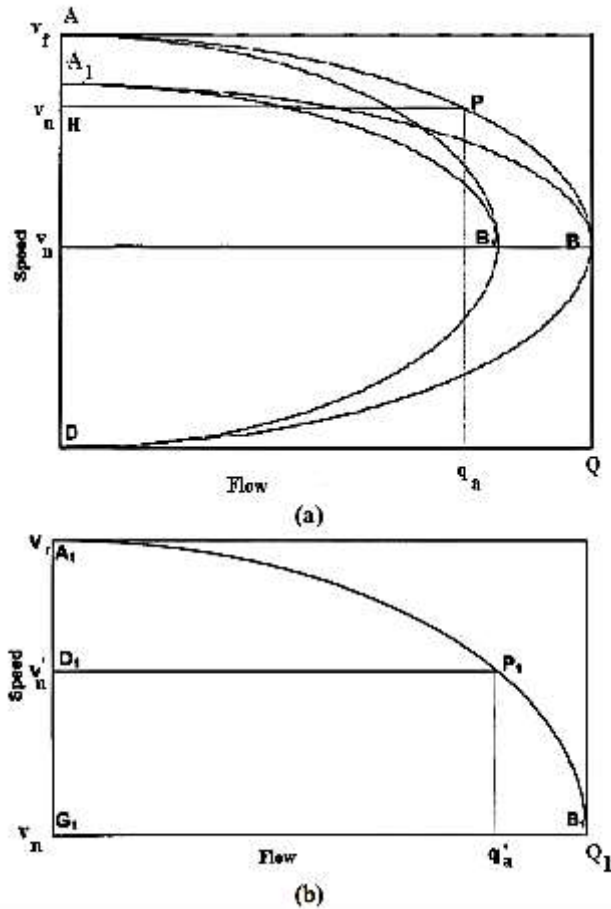


Figure 2.1. Quantification of congestion (a) unsaturated and saturated flow (b) unsaturated flow (c) unsaturated, saturated and oversaturated flows [94].

measurements were made on three roads. For each, the percentile level L_{10} and the equivalent level L_{eq} were measured. These levels were plotted against the composition of the traffic and empirical expressions were obtained with reasonably good correlation indexes as shown in Eq. (2.1) and (2.2).

$$L_{10} = 64.29 + 4.67 \log_{10}(QP + 0.03QL), \quad R = 0.61 \quad (2.1)$$

$$L_{eq} = 62.10 + 3.88 \log_{10}(QP + 0.07QL), \quad R = 0.49 \quad (2.2)$$

where L_{10} is the percentile level which is surpassed in 10% of the measurement period, expressed in dBA; L_{eq} the equivalent noise level, expressed in dBA; QP the heavy vehicle flow and QL the light vehicle flow, both expressed in (vehicles/hour).

Earlier, Crompton and Gilbert (1985) [100] had obtained the expression for L_{10} as shown in Eq. (2.3).

$$L_{10} = 61.8 + 5.13 \log_{10}(QP + 0.2QL), \quad R = 0.49 \quad (2.3)$$

The difference between the findings of Filho et al. with the findings of Crompton and Gilbert was attributed to the higher noise levels generated by the vehicles in Brazilian roads as compared to those in Britain. This may be due to poor maintenance of a good portion of the vehicle fleet, to the non-standardization of the exhaust system position and also to the habits of Brazilian drivers. The latter use their horns for any purpose, with or without apparent reason, accelerate in traffic jams or while waiting for a green traffic light; and drive fast in urban regions.

2.6 TRAFFIC NOISE PREDICTION MODELS

In the traffic noise investigation framework, the need for a suitable predictive model is quite important, since it allows to evaluate the environmental impact, in case of existing infrastructures, or to design the road network such that noise is minimized if the infrastructures are going to be built. The traffic noise produced by motor vehicles, as main sources in urban areas, is part of general environment problem which inflicts a serious damage to the health of human beings and lowers the labour productivity. In order to control acoustical sound level in urban areas, methods for prediction of the traffic noise are necessary. In the literature, many works are devoted to the development of a predictive Traffic Noise Model (TNM) [101].

In urban settlements, the evaluation of traffic noise impact is very important. The quality of human life, in fact, is heavily influenced by a continuous exposure to acoustical noise exceeding a threshold [102-106], usually defined in the dedicated country regulation or in the International Standards. Therefore, the evaluation of Environmental Noise Impact due to acoustical noise has to be performed. This can be achieved either by a measurement campaign or by a software simulation. The latter needs a very precise mathematical modelling of the environment, of the sources and of the propagation law of sound [101].

In their work Guarnaccia et al. [107] mentions that road traffic noise pollution in urban environments is a quite relevant problem in the framework of human health care. The impact of long-term noise exposure, in fact, has been adequately investigated in the literature [108]. On the other hand, road infrastructures and vehicles number have undergone a period of improvement and development, especially in recent advancing countries, where transport facilities are improving in order to support the economic and industrial growth. In this framework, the development and the utilization of a suitable mathematical predictive model, i.e. a Traffic Noise Model, is quite relevant in order to perform an estimation of noise emitted in the environment, even without the aid of experimental measurements. This issue can be of fundamental importance when a new infrastructure has to be settled down, that is in a preliminary planning program, or when a road is already "in operam", in order to monitor the noise impact on the surrounding environment just by knowledge of few traffic and road parameters.

Garg and Maji [109] mention that noise prediction is one of the vital tools for town planners for noise abatement and control. This technique got a special impetus after the European Directive on Environmental Noise 2002/49/EC, wherein noise maps have been recommended for transportation sources and urban agglomerations [110]. Consequently, many scientific models have been developed in recent years focusing on this aspect and introducing exclusively source emission and sound propagation empirical formulations.

These models have been developed and validated in respective countries and brought in regular usage and are integrated with GIS interface for generating noise maps.

The development of models to predict traffic noise started more than 50 years ago and, the results have often been very accurate. Usually, this kind of models were developed taking into account mainly traffic flow, both of light and heavy vehicles, features of the road surface, the distance between carriage and receivers. Moreover, since several models have been developed all around the world, the peculiarities of different countries, in terms of roads, kind of vehicles and weather features have to be taken into account. The aim of using a TNM is twofold: on one side it can be used in the designing of new road infrastructures in order to evaluate the acoustical impact and to avoid post-construction mitigation actions that often present a greater cost; on the other side it can be used on an existing road network, so that the measurement campaign can be minimized and can be used just for the tuning of the model. Many countries decided to regulate the use of these models, establishing which one can be adopted in a traffic noise simulation [101].

While understanding the underlying necessity of TNMs, a comprehensive review of some prominent models are placed in the subsequent paragraphs with the objective of evaluating the ranges of good functioning of each model.

- Basic statistical models from 1952 to 1995.
- FHWA of USA.
- England standard: CoRTN procedure.
- German standard: RLS 90 model.
- Italian C.N.R. model.
- French model: NMPB – Routes.
- Japan model: ASJ RTN 2008.
- HARMONOISE of Europe.

- Son Road model of Switzerland.
- Nord 2000 of Scandinavian.
- CNOSSOS-EU model

Steele [111] made a comprehensive review of traffic noise pollution models. According to him, the traffic noise prediction models in the 1950s and 1960s were designed to predict a single vehicle sound pressure level (L_p) at the roadside. These models were based on constant speed experiments, the predicted levels then being expressed as functions of speed, and with zero acceleration. Later models were not intended to predict single vehicle levels but to predict the equivalent continuous level (L_{eq}) for traffic over a chosen period. Still later models predicted (L_{eq}) under interrupted and varying flow conditions. Early models predicted linear levels whereas the later models predicted A-weighted levels. Several more recent models predict one-third octave band spectra. Early models assumed single point sources, some assumed short line sources, later ones' double point, and even one with thirty-two point sources; some with different spectra. Six commonly used models and others under development were reviewed in the paper.

Traffic noise prediction models are required as aids in the design of highways and other roads and sometimes in the assessment of existing or envisaged changes in traffic noise conditions. They are commonly needed to predict sound pressure levels, specified in terms of L_{eq} , L_{10} etc., set by government authorities. Environmental laws require the Environmental Impact Statement (EIS) to take into account the effect of the proposed noise on all existing and potential elements of the environment, not only statutory criteria. This calls for a variety of descriptors and criteria. Special descriptors are sometimes required for the assessment of complaints about road traffic noise [111].

2.6.1 Early models

Probably the earliest road traffic noise model was that given in the 1952 Handbook of Acoustic Noise Control [112]. It was offered for speeds of 35±45 mph and distances greater than 20 feet. The 50 percentile level is shown in Eq. (2.4).

$$L_{50} = 68 + 8.5 \log(Q) - 20 \log(d) \quad (2.4)$$

where

Q = traffic volume in vehicles per hour,

d = distance from the traffic lane, in feet.

In 1965, Nickson [113] and Lamure [114] separately advanced models shown in Eq. (2.5).

$$L_{50} = C + 10 \log\left(\frac{Q}{d}\right) \quad (2.5)$$

where C is a constant for individual noise levels and L_{50} is in dBA.

Vehicle speed was introduced as a relevant factor by Johnson et al. [115], who proposed Eq. (2.6).

$$L_{50} = 3.5 + 10 \log\left(\frac{Qv^3}{d}\right) \quad (2.6)$$

where v = mean vehicle speed in mph, and L_{50} is in dBA.

This was stated to apply to 20% heavy vehicles, but their data were said to agree within 1 dB for heavy vehicles from 0 to 40%. Corrections were included for excess ground attenuation and for gradients [111].

In the next year, Galloway et al. [116] introduced a further variable, P , the percentage of heavy trucks. Their predictive equation is shown in Eq. (2.7).

$$L_{50} = 20 + 10 \log\left(\frac{Qv^2}{d}\right) + 0.4P \quad (2.7)$$

where L_{50} is in dBA.

Later developments introduced further variables and changes from L_{50} to L_{10} and L_{eq} . One of the most used is the Burgess Model [117] applied for the first time in Sydney

in Australia. Using the same notation of the previous expression, the sound level is given by Eq. (2.8).

$$L_{eq} = 55.5 + 10.2 \log(Q) + 0.3P - 19.3 \log(d) \quad (2.8)$$

Another most used calculation formula is called “Griffiths and Langdon Method” [118]. In particular, they proposed the evaluation of equivalent level starting from the percentile level as shown in Eq. (2.9).

$$L_{eq} = L_{50} + 0.018(L_{10} - L_{90})^2 \quad (2.9)$$

where the statistical percentile indicator has the expression as shown in Eq. (2.10) to Eq. (2.12).

$$L_{10} = 61 + 8.4 \log(Q) + 0.15P - 11.5 \log(d) \quad (2.10)$$

$$L_{50} = 44.8 + 10.8 \log(Q) + 0.12P - 9.6 \log(d) \quad (2.11)$$

$$L_{90} = 39.1 + 10.5 \log(Q) + 0.06P - 9.3 \log(d) \quad (2.12)$$

Years later Fagotti et al. [119] improved the previous models by introducing the motorcycles and buses in the model, Q_M and Q_{BUS} . The proposed model is shown in Eq. (2.13).

$$L_{eq} = 10 \log(Q_L + Q_M + 8Q_P + 88Q_{BUS}) + 33.5 \quad (2.13)$$

Another model was formulated by the French “Centre Scientifique et Technique du Batiment” (C.S.T.B.) [120], which proposed a predictive formula of equivalent emission level, based on the average acoustic level (L_{50}) with the expression shown in Eq. (2.14).

$$L_{eq} = 0.65L_{50} + 28.8 \text{ dBA} \quad (2.14)$$

The value of L_{50} is calculated taking into account only the equivalent vehicular flows (Q_{eq}), and is given by Eq. (2.15).

$$L_{50} = 11.9 \log Q + 31.4 \text{ dBA} \quad (2.15)$$

for urban road and highway with vehicular flows lower than 1000 vehicles/hour, L_{50} is given by Eq. (2.16).

$$L_{50} = 15.5 \log Q - 10 \log L + 36 \text{ dBA} \quad (2.16)$$

for urban road with elevated buildings near the carriageway edge, with L the width (in meters) of the road near the measurement point.

It is noticeable that all the previous models can be expressed in a general form as mentioned in Eq. (2.17) [101].

$$L_{eq} = A \cdot \log Q \left[1 + \frac{P}{100} (n - 1) \right] + b \cdot \log(d) + C \quad (2.17)$$

Since a heavy vehicle generates a noise of higher intensity than a light one, a factor n , called the acoustical equivalent of heavy vehicles, has been considered in Eq. (2.17). Therefore, an equivalent traffic flow, Q_{eq} , can be formulated as shown in Eq. (2.18).

$$Q_{eq} = Q \left[1 + \frac{P}{100} (n - 1) \right] \quad (2.18)$$

The coefficients A , b and C may be derived, for a fixed investigated area, by linear regression methods on many L_{eq} data taken at different traffic flows (Q , P) and distances (d). The acoustical equivalent, n , (defined as the number of the light vehicles that generate the same acoustic energy as that of a heavy one) can be estimated by applying regression method on single vehicle emission measurements. Similarly, it is possible to define an acoustical equivalent for other categories such as motorcycles, buses, etc. [101].

However, the prediction Equation which includes speed and heavy vehicle corrections have inconsistent units [111]. Hooker et al. [121] pointed out that the practice of taking logarithms of physical quantities is, at best, inelegant. Acousticians have conventionally used arbitrary reference quantities to overcome this criticism [111].

2.6.2 Models in recent use

The prediction models take into consideration the national responses to the noise pollution concerns, which arose from the great increase in automobile ownership after World War II, and also from the current interest in environmental matters generally. The FHWA Traffic Noise Model Version 1.0 is a development of the earlier FHWA Traffic Noise Prediction Model. Most models in recent use had parallel independent development, albeit with some theoretical interaction [111].

Most current models assume point sources, although some assume line sources. Rathe [122] found an analytic solution to the problem for incoherent point sources in a line with given spacings and given angles of view. The Japanese model (ASJ Model-1993) had adopted this form. Steele [123] had given some more general solution which admits of roads of any shape with either line or multiple point sources, but with time-, not distance-determined spacings. It allows for acceleration and braking as well as steady flow. Directivity can be accommodated in several models.

Recent models incorporate a propagation section, even though there is a current international standard [124] for the calculation of outdoor sound attenuations. Although individual in their detail, these propagation equations are generally similar to that of Maekawa [125]. The intervening terrain between traffic and receivers is usually assumed to be uniformly hard or soft, or fibrous in one model. Although some actual surfaces have these properties, a more general solution would admit of random roughness and random surface admittance at the reflecting and scattering surfaces. A number of European models incorporate sub-models for the prediction of traffic flow itself, whereas American and British models assume such input is to be had from other sources [111].

Six commonly used models are further discussed.

(a) FHWA Traffic Noise Prediction Model (TNM)

Prior to the release of the FHWA TNM, the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108), or "108 model," was in use for over 20 years [126]. It was developed by Barry and Reagan [127], although they used some material from previous National Cooperative Highway Research Program (NCHRP) [128] reports and was published as Report No. FHWA-RD-77-108 [129], which included a programmable calculator program. This program was further developed, separately, under the title STAMINA, in several successive versions. The model assumes point sources travelling at a constant speed [111].

The authors compared predicted A-weighted sound pressure levels with data collected in a program known as the Four State Noise Inventory [130]. The accuracy of the method was found to depend on the distance of the receiver from the source, and also on vehicular composition. This procedure is strictly applicable to straight roads and vehicles of constant speed, but methods are incorporated for the use of segments to simulate curved roads and multiple lanes. Three major assumptions were made in this model, viz. [111]

- (i) the vehicles are adequately represented by acoustic point sources,
- (ii) emission levels within groups (automobile, medium and heavy trucks) are normally distributed (although they are really skewed to the high side),
- (iii) propagation losses are adequately represented by distance effects.

In the original FHWA-RD-77-108 format, standardised reference energy mean emission levels (REMEL) for the three classes, automobiles, medium trucks and heavy trucks, were employed. They are, expressed as sound pressure levels at 15 meters from the sources, as functions of the speed of the vehicle. In addition to the mean levels, an account was taken of the statistical distribution at each speed for each class. In STAMINA, the

REMELs were allowed as input. L_{eq} is calculated for each class of vehicle and for each hour (on the hour) according to Eq. (2.19) [111]

$$L_{eq} = \bar{L}_0 + 0.115 \cdot \sigma^2 + 10 \cdot \log \frac{N \cdot \pi \cdot D_0}{T \cdot S} + 10 \cdot \log \left[\frac{D_0}{D} \right]^{1+\alpha} + 10 \cdot \log \left(\frac{\psi_{\alpha(\varphi_1, \varphi_2)}}{\pi} \right) + \Delta_S \quad (2.19)$$

L_{eq} is the equivalent continuous sound pressure level. For the i th class it is expressed as $L_{eq}(h)_i$.

\bar{L}_0 is the class SPL at the reference distance. The bar indicates the mean.

σ is the standard deviation for the class.

N_i is the number of vehicles of the i th class passing during the relevant hour.

D_0 is the reference distance (usually 15 m).

D is the perpendicular distance from the centre line of the traffic lane to the receiver.

α is a site parameter, $0 < \alpha < 1$.

S_i is the mean speed of the i th class.

T is the duration, usually 1 h.

φ_1 and φ_2 are the angles from the perpendicular of the limits of the observer's view of a section of the roadway.

Δ_S is the excess attenuation due to barriers, buildings, wood, etc.

A simplistic conversion from L_{eq} to a pseudo- L_{10} is also incorporated in the model [111].

The FHWA TNM was developed for predicting the $L_{eq}(1 \text{ h})$ of free-flow highway conditions in the USA based on the reference energy mean emission level (\bar{L}_0) for each of three vehicle types. These vehicle types consisted of the automobile (<4500 kg), medium truck (4500–12,000 kg), and heavy truck (412,000 kg). The basis of the model, in terms of vehicular emission levels, was the L_{max} (maximum noise level) of a passing vehicle of each of these three vehicle types. Their assumption was that each vehicle is an acoustical

monopole, or single point source, moving along the traffic lane. The overall highway noise model was then analyzed based on this monopole propagation of vehicle noise along the traffic lane of that highway by using the noise reduction of 6 dBA for every double of distance farther from the noise source, and the volume of each vehicle type on that particular highway section together with the propagation coefficient based on two types of ground surface as hard site and soft site [131].

Although an effective model for its time, the "108 model" was comprised of acoustic algorithms, computer architecture, and source code that dated to the 1970s. Since that time, significant advancements have been made in the methodology and technology for noise prediction, barrier analysis and design, and computer software design and coding. Given the fact that over \$500 million were spent on barrier design and construction between 1970 and 1990, the FHWA identified the need to design, develop, test, and document a state-of-the-art highway traffic noise prediction model that utilized these advancements. This need for a new traffic noise prediction model resulted in the FHWA TNM [126].

The core vehicle noise emissions database for the "108 model" was collected in the mid-1970s. Because of the age and associated limitations with this database (e.g., no data for vehicles on grade or vehicles subject to interrupted-flow conditions), it was essential that a state-of-the-art, nationally representative database be developed for the FHWA TNM. A state-sponsored, pooled-fund effort supported the development of the national Reference Energy Mean Emission Levels (REMEL) database for the FHWA TNM. Between 1993 and 1995, data were collected for over 6000 vehicle pass-bys at over 40 sites in 9 states across the country [126].

The FHWA TNM (Version 1.0) was released in March of 1998. The model was the culmination of six years of extensive research. It included a new/expanded vehicle noise emissions database and state-of-the-art acoustical algorithms [126]. It was

introduced by Anderson et al. [132], although derived from the STAMINA 2.0 program. It admits of imports from CAD programs and STAMINA 2.0. Improvements on earlier models include provision for acceleration, stop signs, toll booths, traffic signals, etc. Another improvement is the provision for the input of user-defined vehicles using their REMEL data. This is represented in the form of one-third octave band spectra. Attenuation is calculated in the usual way, but it includes atmospheric absorption and topography. Attenuation under roadways and barriers may also be calculated. The general REMEL equation is a function of speed and frequency [111], as shown in Eq. (2.20).

$$L_{E(s,f)} = 10 \cdot \log_{10} \left[10^{(C+\Delta E_c)/10} + (S^{A/10}) (10^{(B+\Delta E_b)/10}) \right] - (K1 + K2 \cdot s) + D1 + D2 \cdot s + (E1 + E2 \cdot s) \log_{10} f + (F1 + F2 \cdot s) (\log_{10} f)^2 + (G1 + G2 \cdot s) (\log_{10} f)^3 + (H1 + H2 \cdot s) (\log_{10} f)^4 + (I1 + I2 \cdot s) (\log_{10} f)^5 + (J1 + J2 \cdot s) (\log_{10} f)^6 \quad (2.20)$$

where:

A is the slope of the tyre/pavement portion of the regression curve;

$B + \Delta E_b$ is the height of the tyre/pavement portion;

$C + \Delta E_c$ is the height of the engine/exhaust portion;

$D1$ to $J2$ are constants of the 6th order polynomial fit curve for the 1/3rd spectra;

$K1$ and $K2$ give the A-weighted level $L_{(s)}$, instead of $L_{(s,f)}$.

These sound pressure levels are then apportioned between the sub-sources tyre/road and engine/exhaust according to frequency as per Eq. (2.21).

$$SSR(f) = L + [1 - L - M] \left[1 + e^{(N \log f + P)} \right]^Q \quad (2.21)$$

where:

L is the sub-source ratio at low frequencies,

$1 - M$ is the ratio at high frequencies,

N , P , and Q are constants.

Later, Menge et al. [133] mentioned in their work that the Federal Highway Administration Traffic Noise model computes a predicted noise level through a series of adjustments to a reference sound level. The reference level is the vehicle noise emission level, which refers to the maximum sound level emitted by a vehicle pass-by at a reference distance of 15 m as per Eq. (2.22) [109].

$$L_{Aeq,1h} = EL_i + A_{traffic(i)} + A_d + A_s \quad (2.22)$$

where $A_{traffic(i)}$ is an adjustment for traffic flow, A_d represents the adjustment for the distance between the roadway and receiver and for the length of the roadway and A_s represents the adjustment for all shielding and ground effects between the roadway and the receiver. TNM needs 17 constants (A , B , C , D_1 to J_1 & D_2 to J_2) for noise emissions of vehicles categorized as automobiles, medium trucks, heavy trucks, buses, and motorcycles, depending upon vehicle type and pavement type. Automobiles were reckoned as vehicles with two axles and four tires carry nine or fewer people or cargo i.e. passenger car, van, light truck with gross weight <4500 kg; medium truck being cargo vehicles with two axles and six tires with gross vehicle weight between 4500 and 12,000 kg; heavy truck being cargo vehicles with three or more axles with gross weight 412,000 kg); bus being vehicles designed to carry more than nine passengers; and motorcycle (vehicles with two or three tires and an open-air driver/passenger compartment [131]. The empirical formulation used in computing A-weighted emissions in 1/3rd-octave band spectra in terms of speed s_i in km/h is as per Eq. (2.23) to (2.25) [109]:

$$E_A(s_i) = (0.6214s_i)^{A/10} 10^{B/10} + 10^{C/10} \quad (2.23)$$

$$L_{emis,i}(s_i, f) = 10 \log(E_A) + (D_1 + 0.6214D_2s_i) + (E_1 + 0.6214E_2s_i)[\log f] + (F_1 + 0.6214F_2s_i)[\log f]^2 + (G_1 + 0.6214G_2s_i)[\log f]^3 + (H_1 + 0.6214H_2s_i)[\log f]^4 + (I_1 + 0.6214I_2s_i)[\log f]^5 + (J_1 + 0.6214J_2s_i)[\log f]^6 \quad (2.24)$$

$$E_{emis,i}(s_i, f) = 10^{(L_{emis,i}(s_i, f)/10)} \quad (2.25)$$

After the release of FHWA TNM (Version 1.0), a survey was distributed to FHWA TNM users to allow user input for program Graphical User Interface (GUI) enhancements and bug fixes. This list was prioritized, and many of the enhancements/bug fixes were incorporated into FHWA TNM Versions 1.0a, 1.0b, and 1.1. Version 1.1 also included a major improvement to the computational speed of the program, upgrading the architecture from 16 to 32-bit. Unfortunately, this version also introduced some new bugs. Version 2.0, released in June 2002, focused on removing Version 1.1 bugs while maintaining the faster computational speed. Version 2.1, released in March 2003, fixed additional bugs and included over 20 enhancements to the TNM GUI. Version 2.5, released in April 2004, is the first version of the software, since the original release, with major improvements to the acoustics, and was endowed with FHWA TNM® is a registered copyright and trademark. The FHWA TNM contains the following components [126]:

- (i) Modeling of five standard vehicle types, including automobiles, medium trucks, heavy trucks, buses, and motorcycles, as well as user-defined vehicles.
- (ii) Modeling of both constant-flow and interrupted-flow traffic using a 1994/1995 field-measured database.
- (iii) Modeling of the effects of different pavement types, as well as the effects of graded roadways.
- (iv) Sound level computations based on a one-third octave-band database and algorithms.
- (v) Graphically-interactive noise barrier design and optimization.
- (vi) Attenuation over/through rows of buildings and dense vegetation.
- (vii) Multiple diffraction analysis.

- (viii) Parallel barrier analysis.
- (ix) Contour analysis, including sound level contours, barrier insertion loss contours, and sound-level difference contours.

These components are supported by a scientifically founded and experimentally calibrated acoustic computation methodology, as well as an entirely new, and more flexible database, as compared with that of its predecessor, STAMINA 2.0/OPTIMA. The database is made up of over 6000 individual pass-by events measured at forty sites across the country. It is the primary building block around which the acoustic algorithms are structured. The most visible difference between the FHWA TNM and STAMINA 2.0/OPTIMA is the FHWA TNM's Microsoft Windows interface. Data input is menu-driven using a digitizer, mouse, and/or keyboard. Users also have the ability to import STAMINA 2.0/OPTIMA files, as well as roadway design files saved in CAD, DXF format. Color graphics eventually play a central role in both case construction and visual analysis of results.

Development on TNM 3.0 acoustical algorithms began in 2008 in cooperation with the Volpe Center. In 2013, the FHWA issued a BAA for completion of the TNM 3.0, particularly the Graphical User Interface (GUI) and Interoperability portions. Gannet Fleming won the award and has been working with the FHWA and Volpe Center to complete the TNM 3.0. In late 2015 the TNM 3.0 software underwent Beta Testing by selected State DOTs. Currently, the development is addressing those comments in addition to optimizing the model to reduce run times [134].

TNM 3.0 features a new map-based GUI for data entry and analysis, new acoustical algorithms (including the ability to process reflections off of single barriers, as well as L_{10} / L_{50} capabilities), and interoperability via a TNM plug-in to Esri's ArcGIS®, AutoDesk's AutoCAD®, and Bentley's MicroStation®. These enhancements are expected to provide users with more flexibility and accuracy during the data entry process, and better

visual representations during the data analysis phase of highway traffic noise. A draft version of TNM 3.0 was released on March 14, 2017, and the full version is expected shortly [134].

(b) England standard: The CoRTN procedure

The CoRTN procedure for the estimation of road traffic noise was developed for the United Kingdom Department of the Environment by Delany, Harland, Hood, and Scholes. It is used as an aid to design roads, and also for the determination of entitlements for sound insulation of private dwellings at public expense under the British Land Compensation Act. This later influenced the choice of L_{10} as the index of noise [111]. It estimates the basic noise level L_{10} both on 1 h and 18 h reference times at a reference distance of 10 m from the nearest carriageway edge of a highway [109]. The CoRTN model is represented by Eq. (2.26) [62].

$$L_{A10} = 42.2 + 10 \log q + \Delta_f + \Delta_g + \Delta_p + \Delta_d + \Delta_s + \Delta_a + \Delta_r \quad (2.26)$$

where q is the total hourly flow calculated at a reference distance of 10 m from the nearside carriageway edge at a reference hourly mean traffic speed of 75 km/h, Δ_f is traffic flow adjustment, Δ_g is gradient adjustment, Δ_p is pavement type adjustment, Δ_d is distance adjustment, Δ_s is the shielding adjustment, Δ_a is angle of view adjustment and Δ_r is the reflection adjustment. The corrections for heavy vehicles and speed are determined using the Eq. (2.27) [109].

$$\Delta_f = 33 \log \left(v + 40 + \frac{500}{v} \right) + 10 \log \left(1 + \frac{5P}{v} \right) - 68.8 \quad (2.27)$$

where v is hourly mean traffic speed in km/h and P is the percentage of heavy vehicles calculated as $P = \frac{100f}{q}$ where f is the hourly flow of heavy vehicles and q is total hourly flow.

CoRTN is distinguished by its extensive use of curve fitting between empirical data, even when this was known not to conform to theory and it treats L_{10} as if it were Lebesgue measurable. The descriptor is, therefore, a pseudo- L_{10} . This greatly simplifies the calculations, albeit with the concomitant loss of validity [111].

This model assumes a line source and constant speed traffic, and in Britain is the sole instrument for the assessment of road traffic environmental impacts by road authorities. Calculation of Road Traffic Noise [135] (CoRTN) was replaced by a more convenient, Predicting Road Traffic Noise [136], which followed Delany, et al.'s. [137] rationale for the procedure. These authors reported that for the range 50 to 54.9 dBA the mean difference between their predicted and measured levels was +1.4 dBA. On the other hand, between 80 and 84.9 dBA, the mean error was -1.2 dBA. That is CoRTN underestimated high levels and overestimated low levels. Samuels et al. [138] (up-dated by Saunders et al. in [139] observed significant differences from the model with Australian vehicles, depending upon the prevailing conditions. The mean overestimation was 0.7 for free field conditions and 1.7 dBA, in front of facades with corresponding standard deviations 1.8 and 2.5 dBA. Some users came to depend on CoRTN for applications for which it was not strictly valid, for which Steele [140] found even greater under or overestimates by as much as +12.5 dB in one case. Computer programs based on CoRTN were written for various authorities [111], for example, in Weatherall [141].

This model has applicability to a long line of free-flowing rush hour traffic or trains at a distance from the observer. It is less suitable where the distance is not great in relation to the inter-vehicular spacing, or when the spacing is very even or uneven. The procedure starts with a L_{10} value determined by the traffic flow rate, and the attenuation calculations for distance, reflections, and barriers follow established, and simplified procedures. The principal assumption is of a long homogeneous line source with cylindrical radiation, but

with given angles of view. To the datum value of L_{10} are added corrections for mean speed, the percentage of heavy vehicles (>1525 kg), the gradient, the road surface and a constant term. No account is taken of acceleration. The value of G the gradient, whose coefficient becomes 0.2 if the vehicles are assumed to slow down up the hill. CoRTN equation was derived from curve fitting of measured values of L_{10} under the various conditions indicated. Although this stratagem must have compromised the generality of the procedure, it certainly simplified the calculation of L_{10} . CoRTN contains a calculation of the attenuation of thin barriers. Instead of calculating the attenuations, frequency by frequency, an A-weighted attenuation is attempted. No allowance is made for differences between spectra, and like most of the CoRTN procedure, the simplification is made statistically [111].

(c) German standard: RLS 90 model

Richtlinien für den Lärmschutz an Straßen (RLS-90) (Guidelines for Noise Protection on Streets) is the anonymous legal standard for noise prediction in Germany [142]. The current 1990 issue replaced the original 1981 issue [143]. RLS 90 calculates noise emission level $L_{m,E}$ at a distance of 25 m from the centre of a road lane [101]. It incorporates traffic flow design data where the actual flow is not known. It is different from others considered here for including a program for parking lots. The assessed sound pressure level for a street is shown in Eq. (2.28) [111],

$$L_r = L_m + K \tag{2.28}$$

where

L_m is the mean A-weighted level,

K is the addition for the increased effect of traffic light controlled intersections and other intersections.

The mean A-weighted level is given by Eq. (2.29):

$$L_m = 10. \log\{10^{0.1L_{m,n}} + 10^{0.1L_{m,f}}\} \quad (2.29)$$

where n and f represent the nearer and further lanes, respectively.

For each lane, the mean level is calculated from Eq. (2.30) [111];

$$L_m = L_{m,E} + D_{S\perp} + D_{BM} + D_B \quad (2.30)$$

where

$L_{m,E}$ is the emission level,

$D_{S\perp}$ is the attenuation due to distance and air absorption,

D_{BM} is the attenuation due to ground and atmospheric effects,

D_B is the attenuation due to the topography and building dimensions.

The emission level is shown in Eq. (2.31) [111],

$$L_{m,E} = L_m^{(25)} + D_V + D_{StrO} + D_{Stg} + D_B \quad (2.31)$$

where

$L_m^{(25)}$ is the A-weighted mean level,

D_V is the correction for speed limits,

D_{StrO} is a correction for road surfaces,

D_{Stg} is a correction for rises and falls,

D_B is a correction for the absorption characteristics of building surfaces.

$$L_m^{(25)} = 37.3 + 10. \log\{M. (1 + 0.082p)\} \quad (2.32)$$

and where M is the standardized traffic flow according to whether the road is a Federal autobahn; a Federal road; State, District or Municipal connecting roads; Municipal roads.

And p is the corresponding percent heavies (over 2.8T). The value of each depends upon whether day (6.00±22.00 h) or night (22.00±6.00 h) is under consideration.

$$D_V = L_{PKW} - 37.3 + 10. \log\left\{\frac{100+(10^{0.1D}-1).p}{100+8.23p}\right\} \quad (2.33)$$

$$L_{PKW} = 27.7 + 10 \cdot \log[1 + (0.02v_{PKW})^3] \quad (2.34)$$

$$L_{LKW} = 23.1 + 12.5 \cdot \log v_{LKW} \quad (2.35)$$

$$D = L_{LKW} - L_{PKW} \quad (2.36)$$

v_{PKW} is the speed limit in the range of 30 to 130 km/h for light vehicles,

v_{LKW} is the speed limit in the range of 30 to 80 km/h for heavy vehicles,

$L_{LKW}; L_{PKW}$ are the corresponding mean levels, $L_m^{(25)}$.

D_{Stro} , the correction for road surface is given in a table and depends upon the kind of surface and the vehicle speed. It ranges from 0 to 6 dB.

$$D_{Stg} = 0.6 \cdot |g| - 0.3 \quad \text{for } |g| > 5\%,$$

$$D_{Stg} = 0 \quad \text{for } |g| \leq 5\%,$$

RSL-90 is unique, among the programs considered here, in having an algorithm for parking lots [111]. The calculations are similar to those for roads. The sound emission level is calculated from Eq. (2.37).

$$L_{m,E}^* = 37 + 10 \cdot \log(N, n) + D_p \quad (2.37)$$

where

N is the number of vehicle movements per hour, by parking spot,

n is the number of such parking spots,

D_p is a correction for the type of car park.

Attenuation is calculated with usual ray tracing methods. Barriers, elevated and depressed roads are treated in the usual way for incoherent line sources [111].

Garg and Maji [109] have given an account of RLS 90 for standard condition of the parameter $L_{m,E}$ being a function of the number of vehicles per hour Q and of percentage of heavy trucks p (weight >2.8 tons) under idealized conditions i.e. speed of 100 km/h, a road gradient below 5% and a special road surface which was expressed analytically in Eq. (2.35) as similar to Eq. (2.38) [101].

$$L_{m,E} = 37.3 + 10 \cdot \log\{Q \cdot (1 + 0.082p)\} \quad (2.38)$$

where L_m is A-weighted mean level, Q is the standardized traffic flow according to whether the road is a Federal autobahn; a Federal road; State, District or Municipal connecting roads; Municipal roads and p is corresponding percent heavies (over 2.8 t). The next step is to quantify the various deviations from these idealized conditions for the real speed, the actual road gradient or the actual surface etc. The mean level L_m in dBA is calculated as shown in Eq. (2.39) [109].

$$L_m = L_{m,E} + R_{SL} + R_{RS} + R_{RF} + R_E + R_{DA} + R_{GA} + R_{TB} \quad (2.39)$$

where R_{SL} is correction for speed limit, R_{RS} is correction for road surfaces, R_{RF} is correction for rises and falls along the streets, R_E is correction for the absorption characteristics of building surfaces, R_{DA} is attenuation's coefficient that takes into account the distance from receiver and air absorption, R_{GA} is attenuation's coefficient due to ground and atmospheric conditions and R_{TB} is attenuation coefficient due to topography and building dimensions. The $L_{m,E}$ for each lane is described as per Eq. (2.37) similar to Eq. (2.40) [109].

$$L_{m,E} = 10 \log[10^{0.1L_{m,n}} + 10^{0.1L_{m,f}}] \quad (2.40)$$

wherein n represents the nearer and f the farther lane respectively.

(d) Italian CNR model

The Italian legislation does not suggest any TNM of reference, but the most used by a technician is the one developed by the Italian “Consiglio Nazionale delle Ricerche” (CNR) [144] and then improved by Cocchi et al. [145]. This model represents a modification of the German standard RLS 90, adapted to the Italian framework; a relation between the traffic parameters and the mean sound energy level is supposed and the traffic

flow is modeled as a linear source placed in the center of the road. So the equivalent sound level in dBA is given by the Equation (2.41) [101].

$$L_{Aeq} = \alpha + 10 \log(Q_L + \beta Q_P) - 10 \log\left(\frac{d}{d_0}\right) + \Delta L_V + \Delta L_F + \Delta L_B + \Delta L_S + \Delta L_G + \Delta L_{VB} \quad (2.41)$$

where Q_L and Q_P are the traffic flow in one hour, related to light and heavy vehicles respectively, d_0 is a reference distance of 25 meters and d the distance between the lane center and observation point on the road's edge. Then, ΔL_V is the correction due to mean flux velocity defined in Table 2.2. ΔL_F and ΔL_B are the correction for the presence of reflective façade near the observation point (+2.5 dBA) or in opposite direction (+1.5 dBA) respectively; ΔL_S is the correction for the road's pavement as shown in Table 2.3.

Table 2.2. Correction due to mean flux velocity [101]

| Flux mean speed, (km/h) | ΔL_V , (dBA) |
|-------------------------|----------------------|
| 30-50 | +0 |
| 60 | +1 |
| 70 | +2 |
| 80 | +3 |
| 100 | +4 |

Table 2.3 Correction for road pavement type [101]

| Road's pavement | ΔL_S , (dBA) |
|-----------------|----------------------|
| Smooth asphalt | -0.5 |
| Rough asphalt | 0 |
| Cement | +1.5 |
| Rough pavement | +4 |

ΔL_G is the correction for a road's gradient greater than 5%. The correction value is +0.6 dBA for each % gradient over 5%. ΔL_{VB} is a coefficient that takes into account the presence of traffic lights (+1.0 dBA) or slow traffic (-1.5 dBA).

Whilst all the cited parameters have a general validity, independent by countries (because related just to physical or urban parameters), the α e β parameters are influenced by characteristics of countries roads and vehicles. In particular, α is related to noise emission from the single vehicles and β is the weighting factor that takes into account the greater emission of heavy vehicles (very frequently for Italian roads $\alpha = 35.1$ dBA and $\beta = 6$ are assumed) [101].

(e) French model: NMPB-Routes-2008

The European directive 2002/49/CE [146] for what concern the traffic noise prevision model suggest to use the official interim French standard model “Nouvelle Methode de Prevision de Bruit” or simply NMPB-Routes-96 [101, 147]. This method was developed by different French Institutes of Ministère de l’Equipement (CSTB, SETRA, LCPC, LRPC) and represents an improvement of an oldest one defined in the “Guide de Bruit” of 1980 [148], that takes into account the meteorological conditions and the long distance ($d > 250\text{m}$) prevision, as suggested in the ISO 9613. Nowadays it represents one of the most used TNM, being also integrated with some commercial software such as CadnaA™ by 01dB. In 2000, under the request of SETRA, a revision of NMPB-Routes-96 started, bringing to the NMPBRoutes-2008. The method is based on the concept of the propagation path. Several paths between a source and a receiver can exist, depending on topography and obstacles and, at each of them, a long-term sound level $L_{Ai,LT}$ may be associated. NMPB takes into account the standard meteorological conditions, as suggested by the ISO 9613, to adjust the prevision on long-period. They are classified in two types: meteorological conditions “favorable to the propagation” (as defined in ISO 9613) and “homogeneous acoustical conditions” (corresponding to the conditions used in the older

French model). So, the long-period prediction level for each path $L_{Ai,LT}$ is evaluated adding the terms corresponding to this two conditions as shown in Eq. (2.42) [101].

$$L_{Ai,LT} = 10 \log(p_i 10^{L_{Ai,F}} + (1 - p_i) 10^{L_{Ai,H}}) \quad (2.42)$$

where $L_{Ai,F}$ and $L_{Ai,H}$ are the global levels evaluated respectively for **F**avorable and **H**omogeneous conditions and p_i represent the probability of occurrence of favorable conditions. These levels are calculated for each octave band and for each path from the source on the premise that A-weighted sound pressure level generated by source S at a distance d of receiver R in propagation condition F or H is defined by Eq. (2.43 and (2.44) [109, 149-151].

$$L_{Ai,F} = L_{A,w} - A_{dlv} - A_{atm} - A_{grd,F} - A_{diff,F} \quad (2.43)$$

$$L_{Ai,H} = L_{A,w} - A_{dlv} - A_{atm} - A_{grd,H} - A_{diff,H} \quad (2.44)$$

where $L_{A,w}$ is sound power level of S . For each path the algorithm computes three different attenuations: the geometrical spreading A_{dlv} and the atmospheric absorption A_{atm} , that are the same in both formulas, and the boundary attenuations A_{bnd} , which depends on the propagation conditions and are determined by ground effect (A_{grd}) and diffraction (A_{diff}) [101]. A_{atm} is computed in ISO 9613-1 standard [152] for T-15 °C and 70% RH. A_{bnd} is propagation-condition dependent whereby the class of metrological condition F or H can be either homogenous or downward refraction. The sound level in the homogeneous atmosphere is essentially a safe side estimate of the level in upward refraction conditions, while downward refraction level is obtained assuming a standard atmosphere with time- and range-independent sound speed gradient. The source spectrum is provided in third-octave bands in the NMPB-Routes-2008 model. A source height of 0.05 m is set that corresponds to the dominance of tyre/road noise and also to the fact that other noise sources like engine can't be seen as point sources. The probabilities of downward refraction

conditions are based on the qualitative analysis in NMPB-Routes-2008 instead of qualitative one. For each vehicle category, the sound power level per metre of line source for unit flow rate is calculated by addition of rolling noise component and engine component. The model categorizes vehicles into two types viz., light vehicles with gross vehicle weight rating less than 3.5 tonnes and heavy goods vehicles (HGV) with gross vehicle weight rating larger than or equal to 3.5 tonnes. Three road surface categories namely R1 to R3 are defined with each category grouping several surfacing techniques. The engine component is based on traffic flow type and speed of vehicles and for HGV, the road gradient [109].

The sound power level, $L_{A,w}$, is evaluated considering the hourly flux Q , reported in [148], and directly obtaining the equivalent hourly level in dBA, E , associated to a single light or heavy vehicle. By this procedure, the point like source acoustical power representing the road is given by Eq. (2.45) [101].

$$L_{Awi} = [(E_L + 10 \log Q_L)(E_P + 10 \log Q_P)] + 20 + 10 \log(I_i) + R(j) \quad (2.45)$$

where E_L and E_P are the emission levels obtained from [148] for light and heavy vehicle, I_i the length in meter of considered road and $R(j)$ is the value of normalized noise spectra from CEN 1793-3(1995) that take into account the frequency behavior of propagation. The predictions of NMPB-Routes-96 have been validated on a great number of experimental campaign with various topography and meteorological conditions, found a very good agreement with the noise data but generally, an overestimate level is found in downward propagation conditions. That's why SETRA required the revision of the model. The NMPBRoutes-2008 presents a better estimation of the noise level in downward condition, takes into account reflections on embankments, is able to evaluate the correction due to diffraction by low barriers and has implemented other minor corrections [101].

(f) Japan model: ASJ RTN-Model 2008

In Japan, a prediction model called ASJ Model 1975 was published in 1975, which provided a method of calculating the 50 percentile A-weighted sound pressure level (L_{A50}) [153, 154]. Later, ASJ Model 1993 was published in 1994 [155]. This model proposed for the calculation of L_{Aeq} at roads with a uniform cross-sectional structure. This was further modified in ASJ Model 1998 (published in April 1999) as a new model based on L_{Aeq} assessment [156] which had a wider scope of application to cover almost all types of roads and structures, including general roads and special road sections such as interchanges, road tunnels, semi-underground roads and overhead/double deck viaducts. In addition, the structure-borne noise of viaduct roads was newly included in this model. Soon later, further research activity with the aims of expanding the field of application, introducing the wave-based computational method for sound propagation and improving the prediction accuracy resulted in the ASJ RTN-Model 2003 was completed and published in April 2004 [157].

On basis of the fact that the prediction model is used for not only the “prediction of future environments” but also the “estimations of present environments” and the “design of noise mitigation measures,” the research committee has been working on finding solutions to the problems remaining unsolved in ASJ RTN-Model 2003. After five years of research and investigations, the new model “ASJ RTN-Model 2008” was completed [157].

The ASJ RTN-Model 2008 includes 2-wheelers apart from other vehicles, junction and signalized intersections for various running conditions, correction for sound attenuation by barriers, correction for structural borne noise, correction for depressed roads etc. were added. Conditions governing the validity of ASJ RTN-Model 2008 are as follows:

Types of road: General roads (flat, bank, cut and viaduct) and special road sections (interchanges, junctions, signalized intersections, road tunnels, depressed/semi-underground roads, flat roads with overhead viaducts and double-deck viaducts).

Traffic volume: No limitation.

Running speed of vehicles: 40 to 140 km/h for sections of steady traffic flow on expressways and general roads, 0 to 60 km/h for sections of non-steady traffic flow section on general roads, 0 to 80 km/h for acceleration/deceleration sections on expressways such as interchanges, 0 to 60 km/h for acceleration/deceleration sections on general roads such as in the vicinity of signalized intersections.

Prediction range: The validity of the model has been examined for prediction range up to a horizontal distance of 200m from the road under consideration and up to a height of 12m above the ground. However, the model is applicable without any limitation on the calculation range.

Meteorological conditions: No wind or strong temperature profile is assumed as the standard condition.

In ASJ RTN-Model 2008, road vehicles are classified into two or four categories [109]. The sound power level is a function of the vehicle speed and change in noise generated due to pavement type, road gradient, and noise directivity is considered as a correction term. The A-weighted sound power level of a vehicle is calculated as per Eq. (2.46) [157].

$$L_{WA} = a + b \log(v) + C \quad (2.46)$$

The correction term C is calculated as shown in Eq. (2.47).

$$C = \Delta L_{surf} + \Delta L_{grad} + \Delta L_{dir} + \Delta L_{etc} \quad (2.47)$$

where ΔL_{surf} is a correction term for a drainage asphalt pavement (dB), ΔL_{grad} is the correction for road gradient (dB), ΔL_{dir} is the correction for sound radiation directivity

and ΔL_{etc} is the correction for other factors (dB). The values of coefficients a and b are provided separately for steady and non-steady flow. An engineering method of calculating outdoor noise propagation considering the decay by distance due to geometrical spreading, diffraction effect, ground absorption and attenuation due to atmospheric absorption is defined. The methods of calculating the fluctuation in A-weighted sound pressure level due to meteorological factors such as wind, and of calculating the reflection and transmission of sound are also described. The method of calculating the propagation for each frequency component is explicitly defined. For complicated boundary shapes or absorption characteristics, the two-dimensional wave-based numerical analyses or scale model experiments are also defined in the model.

The model included practical method of calculating noise at road junctions and signalized intersections, noise calculation method for road tunnels, depressed/semi-underground road, structure-borne noise of viaducts, effects of individual buildings and built-up areas and correction related to the noise reduction effect of a drainage asphalt pavement in terms of running speed of vehicle, running mode including acceleration and deceleration and number of years after pavement is laid [109].

(g) HARMONOISE model of Europe

The project HARMONOISE (Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise) is to be used by member states of the European Union for developing a HARMONOISE, accurate and reliable model for strategic noise mapping [158]. The model defines the main categories of vehicles corresponding to light (category 1), medium heavy (category 2) and heavy vehicles (category 3). Two other categories viz. other heavy vehicles and two-wheelers is also defined in the model. Each vehicle category is represented by two point sources, each having a specified sound power having contributions from tyre/road (rolling) and

propulsion noise [109]. The rolling noise L_{WR} and propulsion noise L_{WP} is given by Eq. (2.48) and (2.49) [159].

$$L_{WR}(f) = a_R(f) + b_R(f) \log\left(\frac{v}{v_{ref}}\right) \quad (2.48)$$

$$L_{WP}(f) = a_P(f) + b_P(f) \log\left(\frac{v-v_{ref}}{v_{ref}}\right) \quad (2.49)$$

where v_{ref} is 70 km/h. The coefficients a_R , b_R , a_P and b_P are given in 1/3rd-octave bands in the frequency range 25 to 10 kHz.

The model considers two sources for light vehicles to represent both rolling and propulsion noise: the lowest source is located at 0.01m above the ground and the highest source is located at 0.3 m. 80% of rolling noise is attributed to the lowest source, 20% to the higher source and vice-versa for the propulsion noise. The HARMONOISE reference model has been developed in order to predict long-term average sound levels in road situations that are geometrically relatively simple but physically complex. HARMONOISE calculates “excess” attenuation in 1/3rd-octave frequency bands by considering the combined effects of air absorption, the ground effect, shielding by topography (which may include barriers or buildings), atmospheric refraction and atmospheric scattering. The reference model employs a statistical description of the atmosphere, based on local meteorological data, as well as various impedance models for ground surfaces and other absorbing surfaces. An advanced numerical model has been developed within the framework of European HARMONOISE project with the reference model comprising of three families of sound propagation methods that may be coupled together: the PE model, the straight-ray approach, and the BEM [109, 160].

(h) Son Road model of Switzerland

The model considers two types of vehicles viz., passenger cars and trucks and the description of source strength is based on the A-weighted maximum pass-by level of a

single vehicle at a distance of 7.5 m and at a height of 1.2 m above ground as shown in Eq. (2.50) and (2.51) [109, 161].

$$L_{W,A,passenger} = 28.5 + 10 \log \left(10^{0.1(7.3+35 \log v)} + 10^{0.1 \left(60.5 + 10 \log \left(1 + \left(\frac{v}{44} \right)^{3.5} + \Delta_s \right) \right)} \right) + \Delta_{BG} \quad (2.50)$$

$$L_{W,A,truck} = 28.5 + 10 \log \left(10^{0.1(16.3+35 \log v)} + 10^{0.1 \left(74.7 + 10 \log \left(1 + \left(\frac{v}{56} \right)^{3.5} + \Delta_s \right) \right)} \right) + \Delta_{BG} \quad (2.51)$$

where v is the vehicle speed in km/h, Δ_{BG} is the correction for road surface type and Δ_s is the correction for uphill grade g [%] where $\Delta_s = 0.8 g$. The propagation model is specified in third octaves and is based essentially on ISO 9613. However, the model deviates from ISO 9613 standard in the calculation of ground effect. The calculation of the ground effect follows a numerical solution of the sound field of a point source over flat homogenous ground whereby the solution is extended to arbitrary ground by a Fresnel zone approach. The model has replaced the earlier model StL-86 used previously in Switzerland [109].

(i) Nord 2000 model of Scandinavian

The sound pressure level at receiver is predicted by equation [162] as shown in Eq. (2.52) [109].

$$L_R = L_w + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r \quad (2.52)$$

where L_w is sound power level within the considered frequency band, ΔL_d is propagation effect of spherical divergence of sound energy, ΔL_a is propagation effect of air absorption, ΔL_t is the propagation effect of the terrain (ground and barriers), ΔL_s is propagation effect of scattering zones and ΔL_r is propagation effect of obstacle dimensions and surface properties when calculating a contribution from sound reflected by an obstacle.

In road traffic noise model, vehicles are divided into 5 main categories: light vehicles (cars), dual-axle heavy vehicles, multi-axle heavy vehicles, motorcycles, and mopeds. Road surfaces are divided into 8 main categories, most of them containing sub-categories and driving conditions are divided into 6 categories. The source data is expressed by L_{AE} at 10 m from the road (Kragh and Jessen, 2001). The method provides one third octave frequency band results from 25 Hz to 10 kHz. The model allows calculation for specified weather conditions including rapid turbulent motions of the atmosphere. Meteorological parameters such as wind and temperature gradient are used to approximate the vertical effective sound speed profile. The refraction is modelled using curved sound rays, whereby the curvature of rays depends on the vertical sound speed profile and is determined using a semi-analytical approach. The sound propagation model is based on geometrical ray theory and gives algorithms for computing 1/3rd-octave band sound attenuation along the path from source to receiver taking into account the terrain shape and ground type [109].

(j) CNOSSOS-EU model

In 2009, The European Commission decided to develop CNOSSOS-EU (Common Noise Assessment Methods in Europe) for noise mapping of road traffic, railway traffic, aircraft and industrial noise with an objective of development of a harmonized methodological framework for noise assessment [163-165] The CNOSSOS-EU method is valid for determining noise in frequency range from 125 Hz to 4 kHz for road traffic noise. The vehicles are grouped into four separate categories (1-light motor vehicles, 2-medium heavy vehicles, 3-heavy vehicles and 4-powered 2-wheelers) with regard to their characterization of noise emission, while the fifth category is foreseen as an open class for new vehicles that may be developed in future [109]. For the calculation of noise propagation and for the determination of sound power emission, the source was described

with one or several point sources. In this method, each vehicle (category 1, 2, 3 and 4) was represented by one single point source which was placed at 0.05 m above the road surface. The sound power of the source was defined in ‘semi-free field’, with no disturbing objects in its surroundings except for the reflection on the road surface [164].

The noise emission of a traffic flow is represented by a source line characterized by its directional sound power per meter per frequency. This corresponds to the sum of the sound emission of the individual vehicles in the traffic flow, taking into account the time spent by the vehicles in the road section considered. The implementation of the individual vehicle in the flow requires the application of a traffic flow model. If a steady traffic flow of Q_m vehicles of category m per hour is assumed, with an average speed of v_m (in km/h), the directional sound power per metre per frequency band of the source line $L_{w',eq.line,i,m}$, determined by the vehicle flow, is defined by Eq. (2.53) [164].

$$L_{w',eq.line,i,m} = L_{w,i,m} + 10 \log \left(\frac{Q_m}{1000 \times v_m} \right) \quad (2.53)$$

where $L_{w,i,m}$ is the instantaneous directional sound power in ‘semi free-field’ of a single vehicle. $L_{w',eq.line,i,m}$ is expressed in dB (ref. 10^{-12} W/m). These sound power levels are calculated for each octave band i from 125 Hz to 4 kHz. In Eq. (2.50), individual road traffic noise sources are modelled as omnidirectional sources. Traffic flow data Q_m should be expressed as a yearly average per time period (day-evening-night), per vehicle class and per source line. For all categories, input traffic flow data derived from traffic counting or from traffic models should be used. However, if input data are missing, default values can be used. Average speed data v_m is a representative speed per vehicle category: in most cases, the maximum legal speed for the vehicle category [164].

For each road vehicle category, the emission model consists of a set of mathematical Equation representing two main sources viz., rolling noise and propulsion

noise [109]. The general form of the mathematical expression for the sound power level emitted by one of the sources (rolling or propulsion) as a function of the vehicle speed v_m ($20 \text{ km/h} \leq v_m \leq 130 \text{ km/h}$) is given in Eq. (2.54) [164].

$$L_{w,i,m}(v_m) = A_{t,m} + B_{t,m} \cdot f(v_m) \quad (2.54)$$

with $f(v_m)$ being a logarithmic function of (v_m) in the case of rolling and aerodynamic noise, and a linear function of (v_m) in the case of propulsion noise. For light, medium and heavy motor vehicles (categories 1, 2 and 3), the sound power corresponds to the energetic summation of the rolling and the propulsion noise. Thus, the sound power level of the source lines ($L_{w,i,m}$) for $m=1, 2$ or 3 is defined by Eq. (2.55).

$$L_{w,i,m}(v_m) = 10 \log(10^{L_{WR,i,m}(v_m)/10} + 10^{L_{WP,i,m}(v_m)/10}) \quad (2.55)$$

where $L_{WR,i,m}$ is the sound power level for rolling noise and $L_{WP,i,m}$ is the sound power level for propulsion noise.

For two-wheelers (category 4), only propulsion noise is considered for the source line as per Eq. (2.56) [164].

$$L_{w,i,m-4}(v_{m-4}) = L_{WP,i,m-4}(v_{m-4}) \quad (2.56)$$

The source Equation and coefficients were derived to be valid under reference conditions in terms of meteorology and traffic. These reference conditions are a constant vehicle speed; a flat road, an air temperature of $\tau_{ref} = 20 \text{ }^\circ\text{C}$; a virtual reference road surface, consisting of an average of dense asphalt concrete and stone mastic asphalt, between 2 and 7 years old and in a representative maintenance condition; a dry road surface; a vehicle fleet for which the characteristics correspond to the values found for the European average; and no studded tyres [164].

The coefficients are given in octave bands for each vehicle category and for a reference speed $v_{ref} = 70 \text{ km/h}$ and virtual reference road surface consisting of an average of dense asphalt concrete and stone mastic asphalt. For road surfaces with other acoustic

properties, the recommendation is to apply a spectral correction factor on rolling noise, and in case of a porous surface, to apply spectral correction factors on both rolling noise and propulsion noise. The equivalent continuous sound pressure level at a receiver point is calculated corresponding to two types of atmospheric conditions viz., downward refraction and homogenous atmospheric conditions. NMPB 2008 is currently the base for the definition of propagation part of CNOSSOS-EU harmonized framework for implementation of Environmental Noise Directive 2001/49/EC [109, 164]. The model has superseded Hamonoise model with an objective of enhancing reliability and comparability of noise exposure data across the EU Member states. However, the performance of sound propagation module has to be thoroughly tested and validated for accuracy requirements [109, 165].

2.6.3 Brief summary of models

The FHWA TN Model is an example of the trends towards more accurate physics in models and towards more realistic representations of the actual traffic flows. Another approach, by Cammarata et al. [166], was to use a neural network scheme as a substitute for the linear regression in earlier models. He compared his results with Burgess [167], Josse [168] and Bertoni et al. [169], and found significant improvements for the neural network. In 1982, Samuels [170] developed an air pumping theory of tyre/road noise. His model comprised four simple sources at both front and back of every tyre (32 sources for an automobile).

Steele [111] was of the opinion that there is a practical need for a model which may be ideal for meeting a range of needs. All the models discussed in his paper have acoustic energy descriptors usually explicit as L_{eq} or as a pseudo- L_{10} . The L_{eq} models admit of easy corrections for interrupted flow, multiple streams, and multiple roads. For

architectural and more general applications, one would wish, in addition to L_{eq} , predictions of, say, L_{max} , L_1 , L_5 , L_{10} , and L_{90} could be had conveniently. Capability is especially wanted for interrupted and complex flow, for predicting the effects of various traffic light cycles, traffic routings, pedestrian crossing locations and other controls.

Quartieri et al. [101] were of the view that a stable model would not diverge for any value of the traffic flux and that the general slope of the various curves is more or less similar for all the models, once one has neglected the corrective factors which usually strongly influence the behavior of the prediction in some particular conditions. Therefore, the adopted procedure is to fix some parameters, such as the percentage of heavy vehicles, the distance from the lane, the average speed and limit, and then to plot each model versus the traffic flux, adopting the “normalized” traffic flux (Q_{eq}) whenever is needed, i.e. CSTB model formulated by the French [120]. The results of these plots are shown in Figure 2.2 [101].

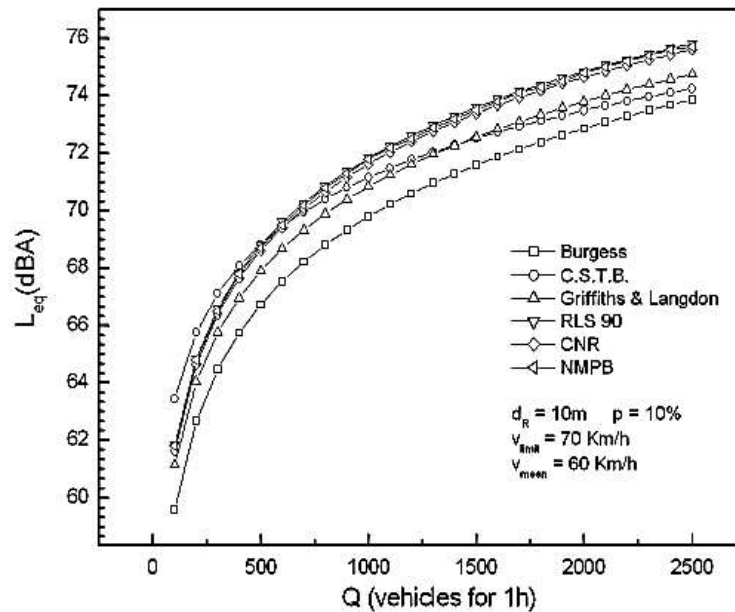


Figure 2.2 Comparison between different Traffic Noise Models with fixed parameters

The NMPB Routes-96 represents the official standard TNM adopted by the European community. Almost all models distinguish between vehicle types such as light

passenger cars, light and heavy trucks, motorcycles, buses, etc; one of these models (RLS90) can simulate also the noise emitted by a parking lot. All the TNMs adopt an acoustic energy descriptor, usually, the equivalent sound level L_{eq} ; in some cases, the percentile levels L_{10} or L_{50} were considered. Afterward, the calculated sound level was generally corrected by means of various parameters, such as ground absorption, meteorological conditions, road's gradient, mean speed, flow type, etc. [101].

The main limitation of the statistical models is that they don't take into account the intrinsic random nature of traffic flow, in the sense that they don't take care of how vehicles really run, considering only how many they are. This result gives motivation to the development of dynamic TNMs, able to consider vehicle speed distributions, traffic flow conditions, etc. Such an attempt is made in their work by Quartieri et al. [171], where the authors proposed a TNM that integrates into noise predictions, a Cellular Automata model, able to furnish dynamical parameters [107].

2.7 TRAFFIC NOISE MODEL FOR INTERRUPTED AND COMPLEX FLOW

The traffic noise prediction models are commonly designed to assist in the conception of new roads or for taking into account changes in traffic noise conditions. Usually, the traffic is represented as a steady flow. Therefore, the “static” models are only able to predict average noise levels generated at the roadside [172]. In Section 2.6.3, it was mentioned about Steele [111] of his review of some traffic noise prediction models has mentioned that a model able to represent interrupted and complex flow was needed [172]. Such a model would be a dynamic traffic model, a macroscopic one based on Lighthill and Whitham [173] and Richards [174] theory [172]. This model represents the traffic flow as a continuous stream characterised by three variables: the flow Q , the density K and the

flow speed V . The flow is considered to be at any time in a state of equilibrium, described by a fundamental relationship between the flow Q and the density K as shown in Figure 2.3. This relationship represents the possible traffic states depending on the network where vehicles drive.

In this traffic model, each link of the network is divided into cells whose length is Δx (roughly a few ten meters) and where the traffic density K is supposed to be constant. Thus, each cell contains $K\Delta x$ vehicles at each time step of the simulation. These vehicles are supposed to have the same kinematics characteristics. At each time step Δt (we usually use $\Delta t = 1s$), the traffic characteristics (density, speed...) are calculated for each cell of the network. Then it is possible to deduce every second the acoustic power emitted by each cell and for each third-octave band. To evaluate the noise received around the road network, this information has to be coupled with a propagation model. The author advocates for French CSTB propagation model which takes into account the influences of the atmospheric conditions (wind, temperature) as well as the topography (hills, noise barriers, buildings etc.) [172].

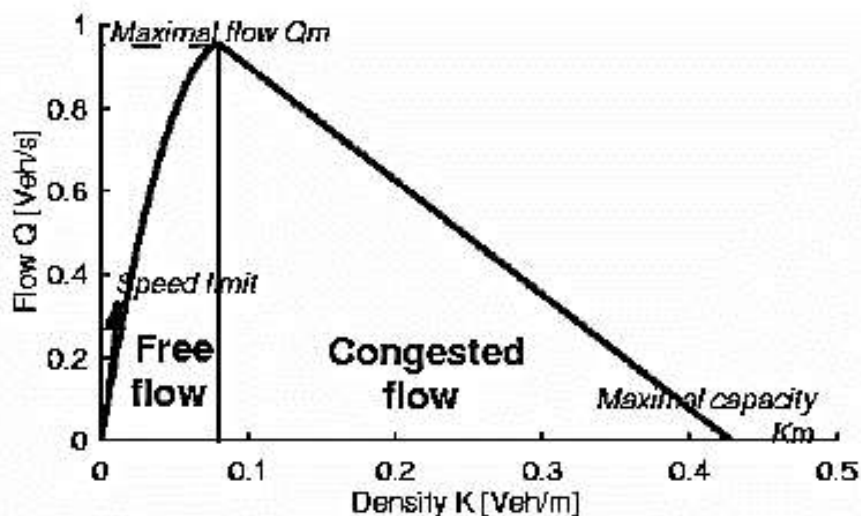


Figure 2.3. Equilibrium flow-density relationship

Another important study was made by Pamanikabud and Tharasawtpipat (1999) for the stop-and-go or interrupted traffic flow in an urban area of the central part of Bangkok [74]. They mention that the stop-and-go or interrupted traffic flow in urban areas generates traffic noise, which is characteristically different from that of uninterrupted or free-flow traffic conditions normally occurring on highways and expressways [175-177]. This characteristic difference in traffic noise requires a different modeling technique from the one used for free-flow traffic conditions [74]. Stop-and-go conditions caused by changing traffic signals result in deceleration and acceleration noises as vehicles approach and depart from road intersections. These deceleration and acceleration noises not only differ from each other but also differ from the cruising traffic noise that occurs in the middle of a green light period [177, 178]. Different characteristics that are apparent throughout the noise measurement period of interrupted traffic flow conditions in urban areas make formulating a theoretical traffic noise model difficult and complex for this kind of condition. Therefore, most of the research efforts in this area were focused previously toward building empirical or semi-empirical interrupted traffic flow noise models [74] [175, 179, 180].

Data was collected at 60 uniformly distributed locations within the study area on traffic characteristics, traffic noise levels, and geometrical dimensions of road cross sections. Three-time periods, specifically, the morning peak-hour period (6:00 a.m.–9:00 a.m.), the afternoon peak-hour period (3:30 p.m.–6:30 p.m.), and the daytime off-peak period (9:00 am–3:30 p.m.) were used for data collection at each location. Traffic characteristics and noise level were collected simultaneously for 1 h during each of these three time periods at each location [176, 181]. Traffic characteristic data comprised of traffic volume, traffic composition, and average spot speed of vehicles using the roadway during measurement periods [176]. Traffic noise data were collected simultaneously with

that of traffic characteristics, traffic volumes, and spot speeds by using integrated precision sound level meters. Traffic noise was measured in *Leq* index with an A-weighting scale of decibel unit for a 1-h period at each selected location. These meters were set back at the distance of 1 m from the curb on the sidewalk at a height of 1.20 m from the ground level [176, 181, 182]. Measurement of geometrical dimensions of each location's involved identifying the number of lanes and their width, the width of median, and sidewalk, and the curb to facade width [177]. The sound level meter's distance from the nearest intersection was measured in addition to recording the direction of traffic flow on each side of the road's median [74].

Noise level from different vehicle types

The difference in noise levels of eight types of in relation to their spot speeds on roads was evident on the roads of Bangkok and the noise level data in *Leq* was collected randomly from the real road running condition of a single vehicle passing by a noise level meter set at the reference distance of 15 m from the centerline of the traffic lane. The spot speed of that particular vehicle also was collected on a simultaneous basis by setting the noise meter in the middle of the course length for spot speed study. Individual noise characteristics at an overall mean vehicle speed were used to identify the proportional weighting scale of the noise levels generated per unit of each vehicle type in relation to an automobile unit. Vehicle types were classified into groups based on similarities in their noise level characteristic within the speed range observed. Based on the overall mean vehicle speed of 33 km/h, the noise generating ratio of each vehicle type in comparison with automobiles in Bangkok's urban traffic was obtained to get the equation for traffic volume [74] as shown in Eq. (2.57).

$$\text{Volume of traffic} = (AU) + 1.04(LT) + 1.12(MT + TT) + 1.14(HT) + 1.09(MC + BU + MB) \quad (2.57)$$

where AU = automobile; HT = heavy truck; LT = light truck; MC = motorcycles; MT = medium truck; BU = bus; TT = Tuk-Tuk; and MB = minibuses.

Single model analysis

They proposed a single stop-and-go traffic flow noise model that can be applied to both sides of an urban roadway as shown in Eq. (2.58).

$$L_{eq} = 71.05 + 0.10S_n + 0.95 \log V_n + 0.04S_f + 0.015 \log V_f - 0.111D_g \quad (2.58)$$

Coefficient of multiple determination (R^2) = 0.534.

where L_{eq} = equivalent traffic noise level in 1 h (dBA); S_n = mean speed of traffic on nearside of observer (both sides of road)(km/h); S_f = mean speed of traffic on far-side of observer (both sides of road)(km/h); V_n = volume of traffic for nearside of observer (both sides of road)(vehicles/h); V_f = volume of traffic for far-side of observer (both sides of road)(vehicles/h); D_g = geometric mean of road section (m); $= \sqrt{D_f \times D_n}$; d_f = distance from observer to centerline of far-side roadway (m); and d_n = distance from observer to nearside roadway curb (m).

The R^2 obtained in this case was considered to be low and hence is not acceptable statistically [74].

Separated lane model analysis

Definition of the parameters are A = location of sound level meter on acceleration side (A); B = location of sound level meter on deceleration side (B); $d_f(a)$ = distance from observer (A) to centerline of roadway on far-side (m); $d_n(a)$ = distance from observer (A) to roadway curb on nearside (m); $d_f(b)$ = distance from observer (B) to centerline of roadway on far-side (m); $d_n(b)$ = distance from observer (B) to roadway curve on nearside (m); J = distance from observer to the nearest junction (m); $S_f(a)$ = mean speed of traffic on far-side

of observer (*A*) (km/h); $S_f(b)$ = mean speed of traffic on farside of observer (*B*) km/h); $S_n(a)$ = mean speed of traffic on nearside of observer (*A*) (km/h); $S_n(b)$ = mean speed of traffic on nearside of observer (*B*) (km/h); $V_f(a)$ = volume of traffic for farside of observer (*A*) (vehicles/h); $V_f(b)$ = volume of traffic for farside of observer (*B*) (vehicles/h); $V_n(a)$ = volume of traffic for nearside of observer (*A*) (vehicles/h); and $V_n(b)$ = volume of traffic for nearside of observer (*B*) (vehicles/h).

The acceleration lane and deceleration lane models obtained from the analysis are described mathematically in equation (2.59) and (2.60), respectively.

$$L_{eq} = 56.91 + 0.09S_n(a) + 5.22 \log V_n(a) + 0.04 V_n(a) + 0.04S_f(a) + 0.02 \log V(a) - 0.006D_g(a) \quad (2.59)$$

Coefficient of multiple determination (R^2) = 0.726.

$$L_{eq} = 71.12 + 0.07S_n(b) + 0.42 \log V_n(b) + 0.08S_f(b) + 0.44 \log V_f(b) - 0.061D_g(b) \quad (2.60)$$

Coefficient of multiple determination (R^2) = 0.640.

These R^2 were higher than the R^2 obtained for the single model, which implied that the independent variables or noise generating parameters used in the two separated models provided a better explanation of the dependent variable or L_{eq} than the parameters used in the single model [74].

Another important study was conducted for the city of Bangalore by Rajakumara and Mahalinge Gowda (2009) for developing an empirical traffic noise prediction model under interrupted traffic flow conditions using the analytical approaches of acceleration lane approach, and deceleration approach. Data were collected at 16 selected study locations at major traffic junctions and were analyzed separately for both acceleration and

deceleration lanes when vehicles leave an intersection on a green traffic light and come to a stop on red traffic light [183].

They mention that the transportation sector is growing rapidly in India, and the number of vehicles on Indian roads is increasing at a rate of more than 7% per annum. The environmental quality of Indian cities is gradually degrading by an incessant growth in the number of vehicles and the ever-expanding road work, resulting in the increase in traffic noise. Managing of road traffic noise is a challenging task for environmental managers and urban planners. Urban planners often have to rely on the road traffic noise prediction models for their assessment. In India, the research studies on traffic noise pollution are limited when compared to other developed countries. India does not have its own traffic noise prediction model that encompasses the Indian traffic characteristics and prevailing environmental conditions. In view of this, to develop a road traffic noise prediction model relating to the current road traffic conditions in India was essential [184].

In urban areas, most of the traffic flow is often interrupted by traffic signals frequently. The traffic noise resulting from interrupted traffic flow conditions on urban roads create substantially different noise characteristics from free or uninterrupted traffic flow, normally found on highways and expressways [185]. Interrupted conditions are caused by changing signals resulting in deceleration and acceleration noises as vehicles approach and depart from each other. Different characteristics that are apparent throughout the noise measurement period of interrupted traffic flow conditions in urban areas make formulating a theoretical noise prediction model difficult and complex. Therefore, to develop an empirical interrupted traffic noise prediction model, the following assumptions were made within the practical limit without any loss of generality [183]:

- Mode of vehicle motion is of two types: cruising with steady uniform speed, and stopping.

- Road stretch is straight and level with a reasonably good road surface condition and therefore the influence of variation in road interface is negligible.
- There is no noise barrier either natural or artificial between the observer and the noise source (i.e., traffic flow).
- Acoustic condition of the site is neglected.
- Traffic noise is quantifiable by the equivalent noise, L_{Eq} .
- Model applies to normal weather/meteorological conditions.
- Vehicles under motion satisfy the requirements of the Indian Motor Vehicles Act.
- The background noise in the study locations does not exceed 10 dB (A).

Field data such as traffic noise levels, traffic composition, traffic volume, vehicle spot speed, geometrical dimensions of roadway sections, and the position of sound level meters from the roadway during interrupted traffic flow conditions were obtained. They represented different zones within an urban area-like residential zone, commercial zone, silent zone, and heavy traffic zone. At each location, integrated precision sound level meters were set up on both sides of the road under for acceleration and deceleration conditions of interrupted traffic flow are shown in Figure 2.4. Traffic noise (measured in the L_{eq} index with an A-weighted scale of decibel [dB (A)] unit) was recorded when vehicles leave an intersection on a green traffic light and come to a stop on a red traffic light. The sound level meters are set back at a distance of 1 m from the curb on the pedestrian sidewalk at a height of 1.2 m from the local ground level [183].

Traffic composition included two-wheelers, cars, jeeps, vans, buses, minibuses (MB), light commercial vehicles (LCV), autorickshaws, and trucks. The average spot speed of vehicles is measured using a radar gun [183]. The measurement of geometrical dimensions of the road section involves identifying the number of lanes and their width,

width of the median, width of the pedestrian sidewalk, and the position of the sound level meters from the nearest intersection in locations of interrupted traffic flow conditions.

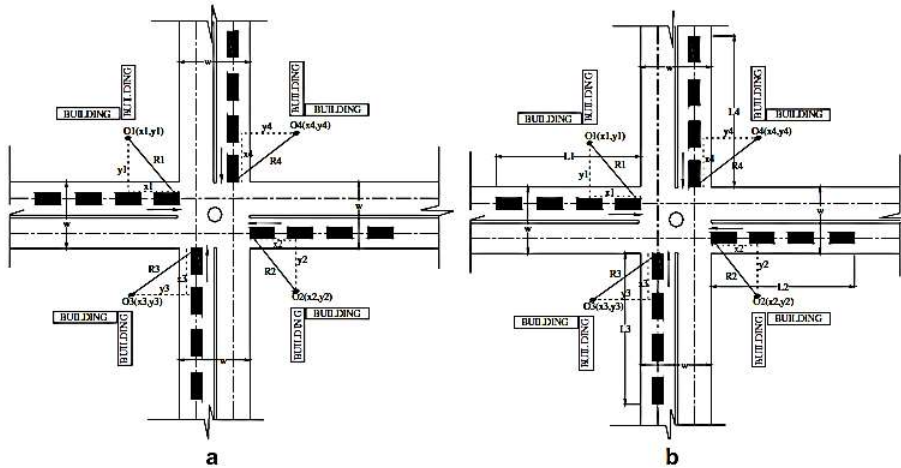


Figure 2.4. Traffic noise measurement during **a** acceleration condition and **b** deceleration condition [183]

All vehicle types were converted into some equivalence based on their noise generation characteristics. The acoustic equivalence (E) of particular vehicles represents how many times the vehicle is noisier than the reference vehicle [183]. In their study, the car/jeep/van was taken as a reference vehicle and acoustic equivalence value was used to quantify the noise produced by different types of vehicles into a common unit. The measurement results from 2,249 data sets, which were collected from approximately 375 vehicles per type during both acceleration and deceleration conditions, as given in Table 2.4.

Table 2.4. Reference equivalent noise emission levels for vehicle classes [183]

| Vehicle | | L_{eq} (1 h) (dB [A]) | | | |
|--------------|--------|-------------------------|-------|-------|------|
| Type | Number | Max | Min | Mean | SD |
| Car/jeep/van | 423 | 78.34 | 56.62 | 71.40 | 1.84 |
| Two-wheelers | 550 | 86.73 | 62.54 | 73.12 | 1.92 |
| Lcv/MB | 301 | 88.22 | 64.13 | 75.20 | 2.10 |
| Autorickshaw | 327 | 91.72 | 61.34 | 78.82 | 2.43 |
| Bus | 451 | 95.57 | 65.35 | 80.32 | 2.70 |
| Trucks | 197 | 96.44 | 66.72 | 81.24 | 3.12 |

$$E_{\text{Tru}} = 10^{(81.24-71.40)/10} = 9.63 \quad (2.61)$$

$$E_{\text{Bus}} = 10^{(80.13-71.40)/10} = 7.80 \quad (2.62)$$

$$E_{\text{Auto}} = 10^{(78.82-71.40)/10} = 5.60 \quad (2.63)$$

$$E_{\text{LCV/MB}} = 10^{(80.13-71.40)/10} = 2.39 \quad (2.64)$$

$$E_{\text{Tw}} = 10^{(73.12-71.40)/10} = 1.48 \quad (2.65)$$

In these equations, E_{Tru} indicates that the noise level produced by one truck is equivalent to the noise emitted by 9.63 car/jeep/van. Similarly, E_{Bus} , E_{Auto} , $E_{\text{LCV/MB}}$, and E_{Tw} indicate that the noise level produced by one bus, auto, car/jeep/van and two-wheeler is equivalent to 7.80, 5.60, 2.39, and 1.48 car/jeep/van, respectively. The total equivalent road traffic flow is then calculated using Eq. (2.66) and (2.67).

$$Q_E = Q_{\text{Car/Jeep/Van}} + E_{\text{Tru}}Q_{\text{Tru}} + E_{\text{Bus}}Q_{\text{Bus}} + E_{\text{Auto}}Q_{\text{Auto}} + E_{\text{LCV/MB}}Q_{\text{LCV/MB}} + E_{\text{Tw}}Q_{\text{Tw}} \quad (2.66)$$

$$= Q_{\text{Car/Jeep/Van}} + 9.6Q_{\text{Tru}} + 7.8Q_{\text{Bus}} + 5.6Q_{\text{Auto}} + 2.39Q_{\text{LCV/MB}} + 1.48Q_{\text{Tw}} \quad (2.67)$$

in which Q_E is the total hourly equivalent traffic flow in vehicles per hour, Q_{Tru} is the hourly traffic flow for trucks in vehicles per hour, Q_{Bus} is the hourly traffic flow for bus in vehicles per hour, Q_{Tw} is the hourly traffic flow for two-wheelers in vehicles per hour, $Q_{\text{LCV/MB}}$ is the hourly traffic flow for LCV/MB in vehicles per hour, Q_{Auto} is the hourly traffic flow for autorickshaw in vehicles per hour, and Q_{Car} is the hourly traffic flow for car/jeep/van in vehicles per hour. Similarly, the equivalent traffic speed can be calculated according to Eq. (2.68).

$$S_E = (9.6Q_{\text{Tru}}S_{\text{Tru}} + 7.8Q_{\text{Bus}}S_{\text{Bus}} + 5.6Q_{\text{Auto}}S_{\text{Auto}} + 2.39Q_{\text{LCV/MB}}S_{\text{LCV/MB}} + 1.48Q_{\text{Tw}}S_{\text{Tw}} + Q_{\text{Car}}S_{\text{Car}})Q_E \quad (2.68)$$

in which S_E is equivalent speed of traffic flow in kilometers per hour, S_{Tru} is the mean speed of trucks in km per hour, S_{Bus} is the mean speed of bus in kilometers per hour, $S_{\text{LCV/MB}}$ is the mean speed of LCV/MB in kilometers per hour, S_{Auto} is the mean speed of autorickshaw in kilometers per hour, S_{Tw} is the mean speed of two-wheelers in kilometers per hour, and S_{Car} is the mean speed of car/jeep/van in kilometers per hour [183].

Generalized model

The basic concept used for model development was according to Eq. (2.69):

$$L_{cq} = a_{a0} + a_{a1}Q_E + a_2S_E + a_3R + a_4L \quad (2.69)$$

in which L_{cq} is equivalent traffic in dB(A), a_0 , a_1 , a_2 , a_3 , and a_4 are the coefficients to be determined by the multiple regression analysis of data, Q_E is the equivalent traffic flow in vehicles per hour, S_E is the equivalent traffic speed in km per hour, R is the position of sound level meters in meters = $\sqrt{(x^2 + y^2)}$, x and y are the coordinates of the sound level meter from the nearby intersection in meters, and L is the queue of waiting vehicles on the deceleration lane in meters [183].

Acceleration lane model

This model acknowledges the difference in traffic noise characteristics from the deceleration model on both sides of the urban road when vehicles leave an intersection on a green traffic light. The acceleration lane model was built using the data collected from the noise level meter placed on the sidewalk near the acceleration lane of the roadway when the traffic leaves the intersection. Sets of highly correlative parameters with the traffic noise level were applied to multiple regression analysis using a stepwise approach to analyze the acceleration lane traffic noise model. Several modifications are made to the set of parameters such as the application of log scale and calculation of equivalent traffic volume and speed [183].

The final form of the acceleration lane model obtained from the analysis is described mathematically in Eq (2.70).

$$L_{eq}(1h) = 59.21 + 0.043S_E + 5.71 \log Q_E - 0.197R \quad (2.70)$$

Coefficient of multiple determination (r^2) = 0.8236

Correlation coefficient (r) between observed and predicted values of traffic noise = 0.907
Standard error (SE) between observed and predicted values of traffic noise = 0.5836.

Every parameter, which was considered to generate potentially traffic noise under the acceleration condition, was tested against the observed traffic noise level for its correlation with the equivalent traffic noise index (L_{eq}) and was tested to observe whether any colinearity existed among the noise-generating parameters. The highest value of r^2 obtained for acceleration model is 0.8236 between observed and predicted values of traffic noise, which implied that the independent variables or noise-generating parameters used in the model provided a better explanation of a dependent variable, L_{eq} . All the apparent coefficients in the model also have meanings in reference to traffic and traffic noise characteristics [183].

Deceleration lane model

In case of the deceleration lane traffic noise model, the same procedure as mentioned above was adopted. The noise data and all other parameters obtained from the roadway under deceleration lane conditions were applied to build the model using multiple regression analysis. In this model, the queue length (L) of traffic is considered as an additional parameter. The final form of the deceleration lane model obtained from the analysis is described mathematically in Eq. (2.71).

$$L_{eq}(1h) = 65.12 + 0.061S_E + 2.14 \log Q_E + 0.923 \log L - 0.041R \quad (2.71)$$

Coefficient of multiple determination (r^2)= 0.7312

Correlation coefficient (r) between observed and predicted values of traffic noise = 0.856.

Standard error (SE) between observed and predicted values of traffic noise = 0.4825.

In this model, the highest value of r^2 obtained is 0.7312 between observed and predicted values of traffic noise, which implied that the independent variables or noise generating parameters used in the deceleration model provided a better explanation of the dependent variable, L_{Eq} . All the apparent coefficients in the model also have meanings in reference to traffic and traffic noise characteristics [183].

2.8 URBAN NOISE ASSESSMENT AND MODELING

Calixto et al. [43] mention in their work of statistical modeling of road traffic noise in an urban setting that in order to obtain the proper mathematical models which are able to predict, in a satisfactory manner, the equivalent and statistical noise levels, it is necessary that the models:

- Be simple enough so that they can be used by those responsible for urban planning;
- Require only easily obtained data for the noise level calculus;
- Incorporate accurate results according to the subjective perception of the noise.

The authors obtained a matrix of the correlation coefficients between various data like vehicle flow (Q), percentage of heavy vehicle (VP), L_{10} , L_{90} , L_{eq} etc. in order to determine which factors involved in the modeling process were more significant to the determination of the noise levels. They coined a term $10 \log(Q_{eq})$ which was transformed into $10 \log[Q(1 + n \times VP/100)]$, where n is a factor having value between 4 and 10 that would result in the largest correlation coefficients between the noise levels and the term $10 \log[Q(1 + n \times VP/100)]$. They obtained largest correlation coefficients for L_{eq} and L_{10} at $n = 9.5$, and for L_{90} at $n = 5$.

By utilizing the two simple parameters Q and VP , the mathematical model for estimation of L_{eq} , L_{10} and L_{90} were proposed as shown in Eq. (2.72 to 2.74) [43].

$$L_{eq} = 7.7 \log [Q (1 + 0.095 \times VP)] + 43 \quad (2.72)$$

$$L_{10} = 6.2 \log [Q (1 + 0.095 \times VP)] \quad (2.73)$$

$$L_{90} = 10.2 \log [Q (1 + 0.050 \times VP)] + 27.1 \quad (2.74)$$

Chew (1995) [186] made an assessment of noise reduction arriving at buildings in Singapore having an inclination from the main road with the intuition that effects of the multiple reflections and diffuse energy would be reduced. However, field measurements, as well as the prediction models derived, show that inclining the buildings, even by as much as 40° , has insignificant influence on the road traffic noise.

Iannone et al. (2013) [187] mention in their study that usually models parameters were obtained by a statistical data fit and thus they are related to the area where measurements have been performed. These models were suitable for standard conditions, but they generally fail when vehicle speed distribution influence such as non-free flow traffic, traffic jams, etc. was to be considered. Thus, the possibility to perform a road traffic noise prediction by means of energy based stochastic approach represents a challenge in the noise control issues. The equivalent level, in fact, depends on the acoustical energy emitted by each vehicle, which may be directly connected to its speed by some experimental relations. They presented an approach in which the speed of each vehicle was randomly generated according to specific speed distributions. The different distributions were chosen according to the contextual traffic situation (free flow, pulsed accelerated flow, intersection, mixed flow composition, etc.), resulting in a detailed microscopic description of the phenomenon, based on a stochastic core model. Once the speed is

generated according to the given distribution, the global level is obtained collecting all the energies sent to the receiver by each source.

Makarewicz and Gąluszka (2011) [52] made an analysis on road traffic noise prediction based on speed-flow diagram. He advanced a method which enables calculation of the annual average sound level of the road traffic noise, when the characteristics of the speed-flow diagram like the average speed of freely cruising vehicles, capacity of the traffic flow, traffic speed at the traffic flow capacity, and the slope of the decreasing traffic speed versus traffic flow, were available. He found that traffic congestion reduces the annual average sound level. None of the noise prediction models provides congestion correction and therefore validation of the developed model against any other model was not possible. Finally, he concluded that strong traffic congestion cannot be ignored in noise prediction.

Abo-Qudais (2007) [188] in his study for traffic noise at signalized intersections found that predicted L_{Aeq} were mainly affected by traffic volume. However, the number of heavy vehicles passing through the intersection, road slope, and BPN were also found to have a significant effect on L_{Aeq} , but to a lesser extent than that of traffic volume. The predicted maximum noise level was found to be significantly affected by the number of heavy vehicles in the traffic stream in addition to the horn effect. The predicted minimum noise level was significantly affected by pavement surface texture and lane width.

Agarwal et al. (2009) [189] developed noise prediction model for interrupted traffic flow for Jaipur city in India using the FHWA approach. A new factor tendency to blow horn (AH) was introduced in the FHWA model on data of four intersections. The developed model gave satisfactory results within a deviation of ± 3 dBA.

2.9 NOISE STUDIES OF CITY ENVIROSCAPE AT DIFFERENT FLOOR LEVELS

Mak et al. (2010) [190] made a prediction of road traffic noise at different building floor levels in Hong Kong. With a population of approximately one million people, this city has limited horizontal spread of land. The buildings are built close to the roads, thereby creating a serious noise pollution problem. This is despite efforts of the Hong Kong Government to curb excessive noise by erecting more than 30 km of barriers and screens, resurfacing roads with low noise materials, and promoting pedestrianisation schemes, the noise levels are greater than 70 dBA (L_{A10} in 1h) in many places endangering people's life by affecting sleep disturbance. The authors were of the view that effective road planning in the early stages of design, could help to reduce the adverse effects of environment in the future. The ability to accurately predict road traffic noise at different levels of a residential building during the building planning stage is also important [190].

Using the CRTN model, they measured the traffic noise levels at each floor level of a 20-story residential building in Hong Kong and predicted the vertical distribution of traffic noise level L_{A10} at different floor levels. They found that both the predicted and measured L_{A10} followed a uniform trend: like, the higher the floor level, the lower the traffic noise levels. However, the predicted L_{A10} at the building façade had a tendency of overestimation, especially at the higher floor levels, with a mean difference of +2.0dBA between the predicted and measured results. A correlation coefficient (R^2) of 0.9331 between the predicted and the measured L_{A10} indicated that the predicted levels correlate closely with the measured levels. The CRTN model was found as a useful tool for predicting traffic noise levels at different floor levels during the building planning stage [190].

The CRTN model assumes that the traffic concerned is a long line source with a constant speed (no account is taken of vehicle acceleration) and a height of 0.5m at the centre of the road shown in Figure 2.5. Additional corrections of the actual assessment point and other topographic data which are necessary for the estimation of L_{A10} generally include corrections for the road surface, distance, view angles, ground attenuation, screening/reflection effects of barriers and geometrical dispersion (use of segments). For the calculation of L_{A10} at different floor levels of a building, the distance correction in Chart 7 of the CRTN method is based on the shortest slant distance d' and the shortest horizontal distance d for a reception at a relative height h from the source line. The shortest horizontal distance d is assumed to be not less than 4m; d' is therefore the shortest slant distance from the source position given by $d' = [(d + 3.5)^2 + h^2]^{1/2}$, and the distance correction is given by $-10\log(\frac{d'}{13.5})$. The predicted L_{A10} noise level is, therefore, obtained by combining with the basic CRTN noise level equation, propagation corrections, including distance correction, and site layout corrections, including the correction for building facade reflection [190].

At every floor level of the 20-story public residential building, the sound level meter was placed 1m away from the external facade of the building. The building was adjacent to a noisy road at zero gradient, topped with impervious bituminous surface and perpendicular to the line of the straight road. No sound barrier or screen was available between the source and receiver. The observation site was located far away from multiple connected streets/roads in urban areas to avoid complex traffic conditions, various non-traffic noise sources and traffic control signals. The typical measurement settings included the use of an extended microphone connected with a sound analyzer and a digital video camera. The

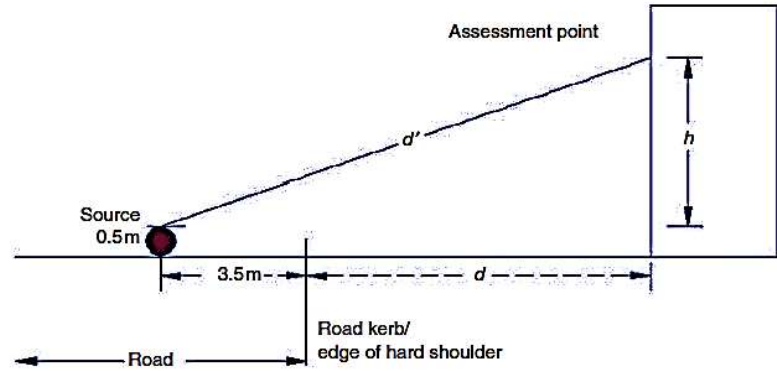


Figure 2.5. Illustration of the shortest slant distance d' and the shortest horizontal Distance d for a reception at a relative height h from the source line [190]

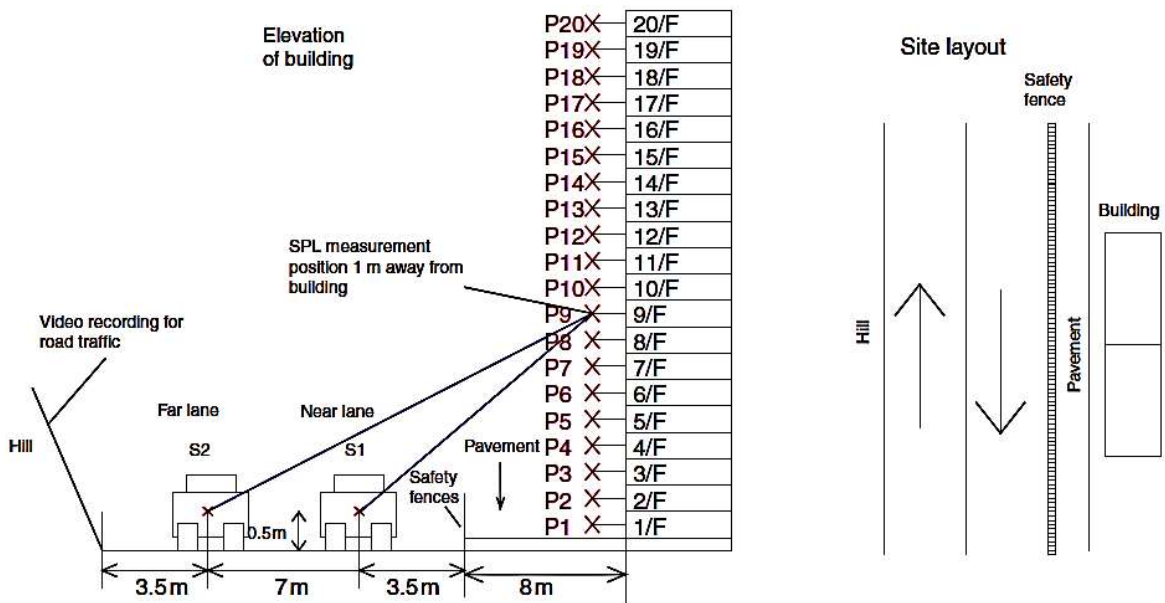


Figure 2.6. Sectional view showing the measurement and prediction of road traffic noise at different levels of a public residential building [190]

digital video camera was used to record the traffic flow so that both the total traffic flow and the number of heavy and light vehicles could be counted. 20 on-site traffic noise measurements at 20 different floor levels were followed by 20 CRTN predictions. Since the road surface was of the impervious bituminous type, a correction of -1 dB was applied to the basic noise level in the CRTN prediction. In addition to L_{A10} , L_{Aeq} , L_{A50} , L_{A90} , and

L_{Amax} were measured and used as references in the traffic noise studies. Dry- and wet-bulb temperatures were also measured. Table 2.4 shows the measured noise levels at different floor levels and the traffic count for each measurement, and Table 2.5 shows the difference between measured and predicted L_{A10} at 20 different floor levels [190].

Table 2.5 shows that the measured L_{A10} exceeded 70 dBA at the lower floor levels (1/F–11/F, 14/F, and 15/F). This suggests that it was not easy to achieve the benchmark of 70 dBA at all floor levels of existing buildings, despite the great efforts made by the government of Hong Kong to tackle road traffic noise problems. Figure 2.7 shows the variation between the measured and calculated values from floor to floor in the building. It can be seen that the measured and the predicted L_{A10} of road traffic noise decrease with increasing building height. The measured and predicted L_{A10s} shown in Table 2.6 were in reasonable agreement. The prediction has a tendency to overestimate L_{A10} . The differences between the measured and predicted L_{A10s} were higher at the higher floor levels. The maximum deviation between the measured and predicted L_{A10s} was +2.8 dBA and the mean difference was +2.0 dBA. The majority of the deviations between the measured and predicted L_{A10s} in the study did not exceed 2.5 dBA. Figure 2.8 shows that the predictions using the CRTN model correlate well with the L_{A10s} measured at the 20-floor levels of the building investigated in their study (a correlation coefficient (R^2) of 0.9331). This indicates that the predicted noise levels correlate closely with the measured levels, although the predictions may tend to overestimate L_{A10s} slightly in cases where the predictions are carried out at the higher floor levels of the building. Overestimation may be due to the fact that the CRTN model was calibrated mainly to suit the urban characteristics of the UK, while the urban characteristics of Hong Kong were different to that in the UK due to complicated and congested streets/road with multiple connectivity and may include various non-traffic noise sources and multiple noise reflections from nearby high-rise buildings [190].

Table 2.5. Measurement data for 20 floor building [190]

| Floor level | Measurement of noise level | | | | | Traffic count per hour | | | | | | | | Temperature | |
|-------------|----------------------------|------|-------|-------|-------|------------------------|-------|--------|----------|----------|-------|--------|----------|---------------|---------------|
| | LA10 | LAeq | LA50 | LA90 | LAmax | Near lane | | | | Far lane | | | | Dry bulb (°C) | Wet bulb (°C) |
| | | | | | | Light | Heavy | P (%) | V (km/h) | Light | Heavy | P (%) | V (km/h) | | |
| 1/F | 76.9 | 73.1 | 70.1 | 62.9 | 84.6 | 345 | 195 | 36.11 | 40.1 | 405 | 207 | 33.82 | 39.2 | 17 | 13 |
| 2/F | 75.8 | 72.7 | 69.85 | 62.95 | 85.8 | 396.5 | 221.5 | 35.872 | 40.05 | 456.5 | 245.5 | 34.841 | 39.1 | 20 | 18 |
| 3/F | 75 | 72.3 | 69.6 | 63 | 87 | 448 | 248 | 35.63 | 40 | 508 | 284 | 35.86 | 39 | 20 | 16 |
| 4/F | 73.6 | 69.9 | 66.2 | 60 | 84.3 | 195 | 121 | 38.29 | 40.1 | 213 | 138 | 39.32 | 39.2 | 20 | 18 |
| 5/F | 74.1 | 70.7 | 68.4 | 62.5 | 85 | 321 | 231 | 41.85 | 42.5 | 441 | 210 | 32.26 | 39.6 | 17 | 13 |
| 6/F | 73.1 | 69.3 | 66.7 | 62.4 | 82.1 | 192 | 180 | 48.39 | 40.1 | 267 | 183 | 40.67 | 40 | 20 | 18 |
| 7/F | 73.1 | 69.7 | 67.8 | 63.8 | 83.7 | 369 | 231 | 38.50 | 40.1 | 408 | 240 | 37.04 | 40.1 | 21 | 18.5 |
| 8/F | 72.5 | 68.6 | 66.5 | 62.6 | 80.2 | 261 | 228 | 46.63 | 42.5 | 336 | 195 | 36.72 | 42.5 | 21 | 18.5 |
| 9/F | 72.8 | 69.2 | 67.4 | 63.8 | 79.8 | 407 | 301 | 42.51 | 38 | 556 | 240 | 30.15 | 40.1 | 20 | 16 |
| 10/F | 70.9 | 67.7 | 66.5 | 62.6 | 75.8 | 290 | 165 | 37.08 | 39.2 | 335.00 | 210 | 38.53 | 39.3 | 22 | 20 |
| 11/F | 70.9 | 67.9 | 66.8 | 63.1 | 75.9 | 306 | 222 | 42.05 | 39.2 | 308 | 195 | 38.69 | 39.2 | 22 | 20 |
| 12/F | 70 | 67 | 65.8 | 62.3 | 78.6 | 219 | 165 | 42.97 | 39.2 | 302 | 216 | 41.70 | 39.6 | 22 | 20.5 |
| 13/F | 69.9 | 66.7 | 65.4 | 61.9 | 76.8 | 255 | 180 | 41.38 | 39.2 | 255 | 180 | 41.38 | 40 | 22 | 20.5 |
| 14/F | 70.1 | 67.2 | 65.9 | 62.8 | 76 | 288 | 200 | 40.98 | 39.2 | 400 | 188 | 31.97 | 40.1 | 18.5 | 15.5 |
| 15/F | 70.1 | 67 | 65.8 | 63.2 | 77.2 | 240 | 240 | 50.00 | 40 | 294 | 246 | 45.56 | 39.2 | 22 | 14.5 |
| 16/F | 69.4 | 66.8 | 65.9 | 63 | 77 | 216 | 224 | 50.91 | 39.5 | 352 | 192 | 35.29 | 40 | 18.5 | 15.5 |
| 17/F | 69.5 | 66.7 | 66 | 62.8 | 75.8 | 324 | 205 | 38.75 | 41 | 342 | 213 | 38.38 | 40.1 | 22 | 14.5 |
| 18/F | 69.3 | 66.5 | 65.5 | 62.2 | 77.7 | 222 | 204 | 47.89 | 42 | 324 | 246 | 43.16 | 42.5 | 18.5 | 15.5 |
| 19/F | 69.9 | 66 | 66.4 | 64.0 | 76 | 328 | 248 | 43.05 | 41 | 452 | 184 | 28.93 | 40.1 | 22 | 14.5 |
| 20/F | 68.1 | 65.7 | 65 | 63.1 | 74 | 240 | 180 | 42.86 | 41 | 291 | 201 | 40.85 | 41 | 18.5 | 15.5 |

Table 2.6. Difference between measure and predicted L_{A10} at 20 different floor levels [190]

| Floor level | 1/F | 2/F | 3/F | 4/F | 5/F | 6/F | 7/F | 8/F | 9/F | 10/F | 11/F | 12/F | 13/F | 14/F | 15/F | 16/F | 17/F | 18/F | 19/F | 20/F |
|---------------------------|------|------|------|------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Predicted L_{A10} (dBA) | 77.4 | 76.9 | 76.7 | 74.7 | 76.30 | 74.8 | 75.7 | 74.7 | 75.5 | 73.5 | 73.4 | 72.8 | 72.4 | 72.4 | 71.8 | 72.1 | 71.6 | 71.5 | 71.9 | 70.8 |
| Measured L_{A10} (dBA) | 76.9 | 75.8 | 75 | 73.6 | 74.1 | 73.1 | 73.1 | 72.5 | 72.8 | 70.9 | 70.9 | 70 | 69.9 | 70.1 | 70.1 | 69.4 | 69.5 | 69.3 | 69.9 | 68.1 |
| Differences (dBA) | 0.5 | 1.1 | 1.7 | 1.1 | 2.2 | 1.7 | 2.6 | 2.2 | 2.7 | 2.6 | 2.5 | 2.8 | 2.5 | 2.3 | 1.7 | 2.7 | 2.1 | 2.2 | 2 | 2.7 |
| Height (m) | 2 | 5 | 8 | 11 | 14 | 17 | 20 | 23 | 26 | 29 | 32 | 35 | 38 | 41 | 44 | 47 | 50 | 53 | 56 | 59 |

Formula used: $L_{A10} = 10 \log Q + 33 \log |V + 40 + 500/V| + 10 \log |l + 5P/V| + 0.3G - 26.6$

As required by the CRTN method, a correction of +2.5dBA was made for each of the measurements at different floor levels of the building, with the microphone set one meter in front of the building façade. The differences between the measured and predicted L_{A10s} at the lower floor levels may be due to the existence of background noise from pedestrians. As the pavement was near to the assessment location, noise from the pavement during the peak hour would have more effect on the L_{A10} measurements at the lower floor levels. Furthermore, it was possible that occasional strong winds, the noise from vehicle brakes, and personal errors in determining the data entry, especially with regard to the

definition of a heavy vehicle and to the average velocity of vehicles for the CRTN calculation, led to the deviations between the measured and predicted L_{A10s} . The authors suggest that Laser Speed Guns may be used to improve the accuracy of the measurement of vehicle speed [190].

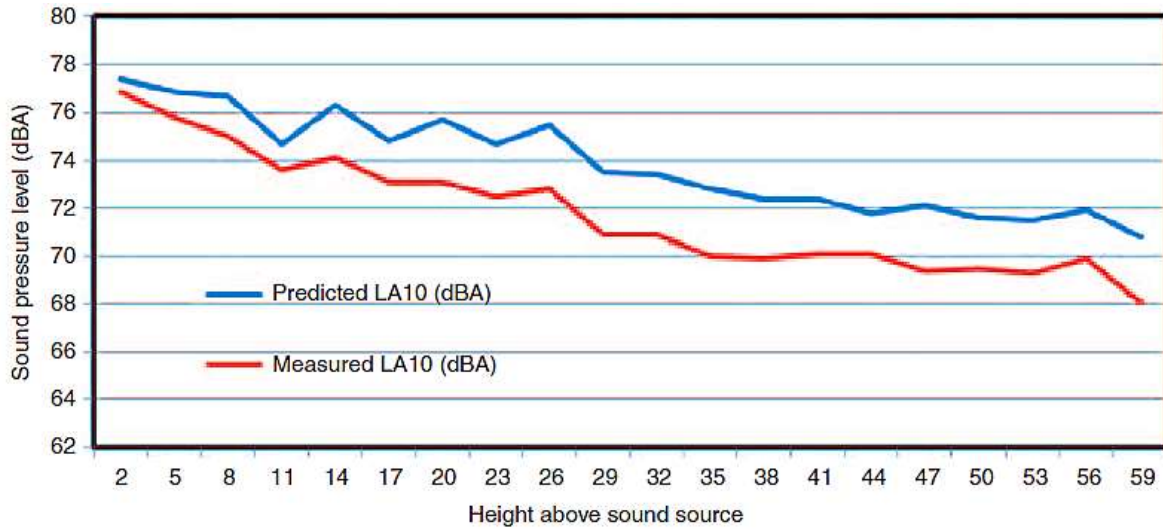


Figure 2.7. Comparison between measured and predicted L_{A10} against height of the assessment point above the source [190]

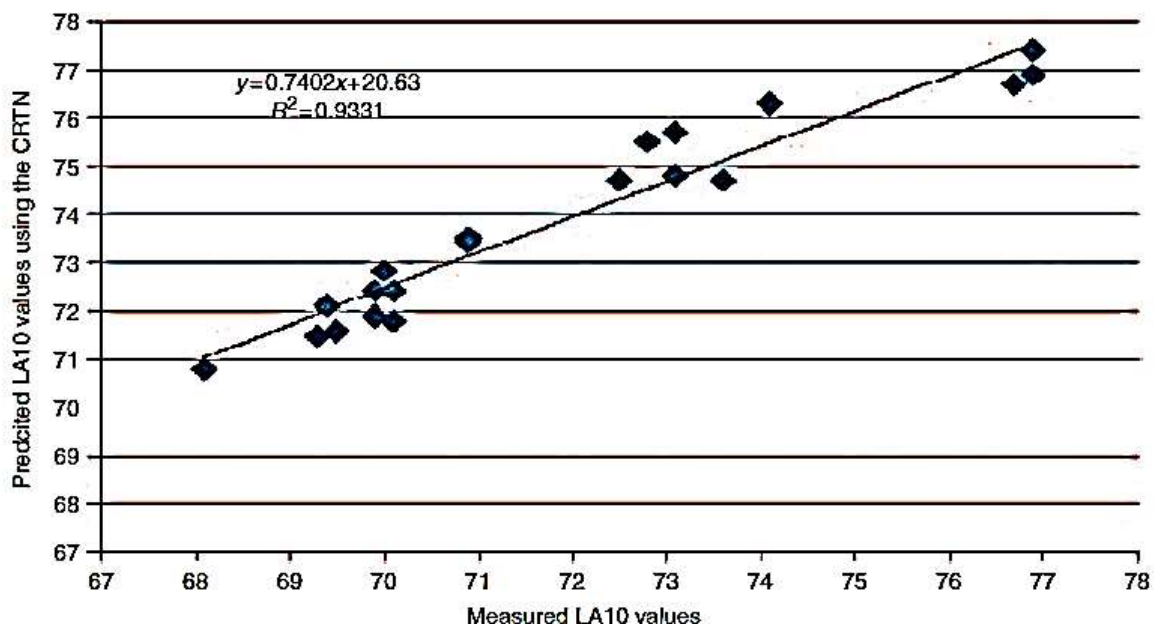


Figure 2.8. Predicted L_{A10} by the CRTN model against measured L_{A10s} [190]

2.10 RESEARCH GAP

Various models discussed in the foregoing paragraphs were for the western world or developed nations where traffic segregation and lane discipline were largely maintained. Intersections were signalized and traffic flow was maintained under controlled conditions varying from free to congested flow. Also, fewer vehicle types were using the carriageway. On the contrary, traffic composition is of mixed nature in the developing nations like India where lane discipline is often violated [83]. The cross-section of vehicle type is large ranging from non-motorised ones to motorized light, medium and heavy vehicles. There is overwhelming presence of 2-wheelers and 3-wheelers in the traffic stream. Intersections are majorly unsignalised and often characterized by traffic congestion [84]. Superintendence of the intersections are poor owing to lack of adequate personnels. Roadside friction is escalated due to roadside parking, pedestrian encroachment, temporary vending outlets, footpath encroachment, resulting in significant reduction in traffic speed. Due to the heavy pressure of vehicles, the intersections often experience interrupted flow, which may manifest to traffic jam situations during peak hours.

TNMs discussed in Section 2.6 to 2.8 may account for interrupted flow, however, their efficacy for dealing with traffic jam noise is not mentioned, while researchers on the subject have more than stressed the need for a model which may be ideal in meeting a range of needs. They had underlined the need to develop the capability for interrupted and complex flow for predicting the effects of various traffic light cycles, traffic routings, pedestrian crossing locations and other controls as mentioned in Section 2.6.3 [111]. Statistical models developed for free flow conditions were reported to fail when vehicle speed distribution influence such as non-free flow traffic, traffic jams, etc. was to be encountered [187]. Makarewicz and Gałuszka (2011) [52], who worked on road traffic noise prediction based on speed-flow diagram had mentioned that none of the noise

prediction models provides congestion correction. Finally, they concluded that strong traffic congestion cannot be ignored in noise prediction.

The aforementioned discussions bring out the fact that traffic noise studies on traffic jam conditions were not considered in TNMs developed so far in the Western and developed nations. Developing economies like India are yet to develop their TNM. Therefore, the assessment and analysis of traffic jam noise is a research gap.

Traffic jam in the urbanscape of developing economies like India is likely to persist and endure itself owing to difficulty in capacity augmentation of carriageways and escalation of roadside friction, inviting community reactions for control as stated in Section 1.2 and 1.3. Assessment models are a prelude for planning remedial measures. Towards this end, the assessment and modeling of the noise enviroscape of traffic jam is undertaken in the present research according to the objectives set out in Section 1.5 with its scope and limitations outlined in Section 1.6 for the mid-sized city of Varanasi as the study area.