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MODELING AND QUANTIFICATION OF TEMPORAL RISK GRADIENTS (TRG) FOR TRAFFIC ZONES OF DELHI CITY IN INDIA

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ABSTRACT

Vehicular density in Delhi has increased by more than 100 percent in the last decade. Moreover, 67 percent of the total vehicular population is of the most polluting kind, mainly two- and three-wheelers. On the other hand, vegetation, which serves as an important sink for vehicular emission, helps in assimilation of gaseous pollutants. For study purposes, the city of Delhi was divided into three grids of 6, 12, and 18 km radii. Leaf samples from twelve important traffic zones were collected and microscopically analyzed for measuring relevant stomatal parameters. This data was subsequently used as the input for the EHER (Ecosystem-Health Exposure-Risk) Model [1] for quantifying risks due to vehicular emissions, viz. CO, NO_x, and HC. Future projections have been made for different categories of vehicles on the basis of models developed for them and calibrated with the help of available data. Subsequently, these temporal-models for different vehicular categories have been interfaced with the EHER-model for deriving the expression for the temporal risk gradient (TRG), which represents time-derivative of this interfaced model and helps in analyzing dynamics of risk to the roadside environment due to vehicular emissions. Analysis of modeling results indicates which major roads are the most environmentally risky traffic zones.

1. INTRODUCTION

Urban planning can influence air pollution through reduced traffic events [2] and site-specific tree-plantation schemes designed to maximize the “plant-sink” effect of the trees [3]. Vegetation happens to be an important sink [4-6] for air pollution emanating from several natural and anthropogenic sources, as canopy stomatal resistance [1, 7] happens to be the most important pathway for assimilating these air pollutants. Vehicular emissions in India outrank emissions from thermal power plants and various other industrial units. It has been estimated that the transport sector contributes about 60 percent of the total air pollution load. Thermal power plants rank second with a 16 percent contribution. Industry’s share is 12 percent, the domestic sector’s is merely 7 percent [8]. Moreover, about 97 percent of hydrocarbon-emissions, 48 percent of NO_x-emissions, and 76 percent of CO-emissions are generated by transport sector, while most of the suspended particulate matter (SPM) and SO_2 emissions are from the industry and the power sector. Industry’s contribution to SPM emission is 44 percent and that of the power sector is 37 percent. As far as SO_2 is concerned, some 76 percent of emissions come from the power sector, and some 19 percent from industry [8].

Section 2 of this analysis elaborates vehicle pollution characteristics. Section 3 delineates the role of stomata in air pollution mitigation, and discusses the advantages of the Ecosystem-Health Exposure-Risk (EHER) Model. Section 4 explains the methodology for deriving, computing and applying the Temporal Risk Gradient (TRG) Model to sensitive traffic zones of Delhi. TRG couples the time-derivative from the EHER Model [1] with temporal models for vehicles in different categories. The relevant parameters for these models have been estimated on the basis of available Indian data [8]. Categorization of vehicles assumes special significance. Private vehicles constitute about 80 percent of the total vehicles in Indian metropolises today. Although the number of cars and two- wheelers manufactured has increased by 20 percent per annum, the number of buses has risen just 3 percent annually [8].

Section 5 presents results that are discussed in Section 6 in light of air pollution control and mitigation measures required for sensitive Indian traffic zones. The roadside environment continuously experiences strong wind conditions. Therefore, the role of stomatal resistance in gaseous exchange is much more important [1] than that of other resistance (e.g., aerodynamic or cuticular). To estimate stomatal resistance, dominant plant-species found on different traffic zones of Delhi were microscopically analyzed [3] to determine stomatal density and the dimensions of stomatal openings. The EHER and TRG analyses then calculate the risks for various traffic zones from two-wheelers and other kinds of fuel-powered vehicles.

2. CONTRIBUTION BY TRANSPORT SECTOR [8] AND AIR POLLUTION IN IMPORTANT INDIAN CITIES [9]

Vehicular pollution is responsible for a shocking 64 percent of the total air pollution load from various sources in Delhi, the fourth most polluted city in the world, 52 percent in Mumbai, and 30 percent in Calcutta. Vehicles presently emit about 1300 metric tons of pollutants into Delhi's air every day, which is more than the sum of the vehicular pollutants generated in Mumbai (659 tpd), Calcutta (310 tpd), and Bangalore (253 tpd).

The number of vehicles in Delhi rose from 1 million in 1986 to 2.2 million in 1994; population grew from 766.1 million to 891.0 million in the same period. Sixty-seven percent of the total vehicular population of Delhi is two- and three-wheeled motorized vehicles, the most polluting kind. The situation in other metropolises is no different. The 20 percent of vehicles in Mumbai that are diesel powered are its main source of particulate emissions. Particulates less than 10 microns in size result in a significantly high morbidity rate—and more than 90 percent of the particulate matter emitted in Mumbai is under 2.5 microns in size and is respirable, thus causing serious adverse effects on human health [10]. In Calcutta, the area covered by roads is only 6 percent of the total city area, compared to about 10 to 15 percent in other Indian cities. Since average speed is the major determinant of fuel consumption and resultant emissions [2], traffic jams and slow moving traffic due to insufficient and unfit road space further aggravate the problem of vehicular emissions in this city.

3. STOMATA AND ITS ROLE IN AIR POLLUTION MITIGATION

Stomata are the primary pathway for gaseous exchange [5, 6] at the atmosphere-vegetation interface. Stomatal diversity (density, lengths of major and minor axes, and the effective opening of stomata) is species-specific [3]. Wide inter-specific variations have been observed during our monitoring programs [11] and ecological studies, conducted as part of projects for quantifying regional environmental impact due to various industrial activities in and around Jamshedpur, Doon Valley Region, and the National Capital Region in India [9, 12].

Moreover, even for the same species, stomatal features have been found to vary under different pollution scenario [12-14]. The damaging effects of air pollution on foliar characteristics have been well recognized. Foliar epidermal aberrations were first quantified through Salisbury's Stomatal Index [15]. Subsequently, in order to evaluate the susceptibility of plants to air pollutants, such indices as the Air Pollution Tolerance Index (APTI) of plants have also been used [16].

Although these indices help in ranking various tolerant and sensitive Indian species, they do not explicitly represent process-dependent models [17, 18]. For example, none of these indices throws light on gaseous exchange or on a possible ranking on the basis of stomatal uptake, which is dependent on stomatal density, length of stomatal opening, PAR (Photosynthetically Active Radiation), and the lengths of major and minor axes of the elliptical stomata. The EHER Model [1], was chosen as a process-dependent model mainly because of its dependence on species-specific stomatal resistance (R_{sm}) for quantifying pollutant assimilation.

4. METHODOLOGY

Delhi city vegetation is mainly in the form of roadside plantations, parks, and gardens. Delhi today has twenty major district parks with some 1000 species of flowering plants; 60 percent are either indigenous or naturalized, and the rest are introduced. More than 50 percent of the indigenous species are of tropical varieties. Tree species commonly planted along major roads include neem, amaltas, jamun, peepul, arjun, shishum, devil's tree, gulmohar, kijelia, kabuli kikar, and acacia.

For study purposes, the city of Delhi was divided into grids of 6, 12, and 18-km radii. Identified pollution hotspots were Southern Ridge forest, various industrial zones of the city, and major traffic intersections. Leaf samples from twelve traffic zones (Figure 1) were collected and microscopically analyzed for the relevant stomatal parameters (Table 1). Fluxes of CO, HC, and NO_x (Table 2) were computed on the basis of models developed for them earlier [1]. Temporal Risk Gradients (see Figure 2) were computed as time-derivatives of the interfaced model incorporating three functionalities, dependent on a) emission-factors, b) air-vegetation interface properties, and c) the temporal rise in vehicular density. The first component represented NO_x CO, and HC vehicular emissions [1] as functions of vehicular speed and the air-gas diffusion coefficient. The second component represented a function of various stomatal parameters [1], and the third represented models for temporal variations under different vehicular categories, as shown in Tables 3 and 4.

5. RESULTS

As the values of k, PAR, and D are not expected to show significant variations within one particular city, especially in roadside environments, they have been assumed to be constant throughout the model computations. Accordingly, k/PAR has been fixed at the value of 0.5 and D has been taken as 2.0×10^{-5} (m^2/s), while the average vehicular speed has been taken as 15 (m/s) in line with the prior studies of congestion and stagnation on Indian roads, especially in Delhi [8].

Figure 3 compares the model results and actual values for buses and for total vehicular density between 1951 and 1991. Model-predicted values are found to be

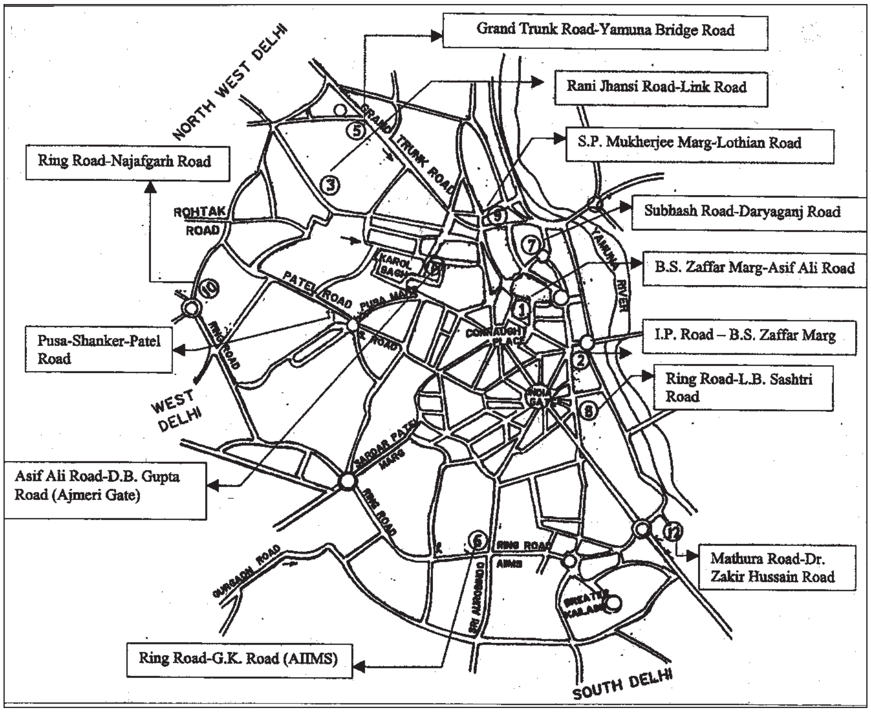

Figure 1.

quite close to the actual values. In Figure 4, similar comparisons are portrayed for two wheelers and for cars, jeeps, and taxis (treated together). TRG-model results show which areas—here Mathura road, B. S. Zaffar Marg and Pusa road, with their respective TRG values of 0.100, 0.110, and 0.111 with respect to air pollution risk posed by two wheelers (Figure 2)—are the most environmentally-risky traffic zones.

6. DISCUSSION

In slow city traffic in Delhi, fuel consumption increases by 20 percent and (in diesel vehicles) emissions increase twenty-five to fifty times [8]. As is well known, vehicular emissions cannot be controlled unless the frequent stoppages caused by too many intersections and congested traffic are reduced in number and severity. The alarming rise in air pollution in India is mainly due to the sharp and equally alarming rise in the number of vehicles, which exploded from 9.17 million in 1986 to 25.3 million in 1993. Moreover, Indian cities have highly inadequate road space, which does not expand at the same rate at which the vehicular number

Table 1. Dominant Species on Various Traffic Zones (Delhi) and Their Stomatal Characteristics

S. No.	Sampling Zones	Stomatal Characteristics				
		Species	$N(cm^{-2})$	$a(\mu m)$	$b(\mu m)$	$L(\mu m)$
1.	B.S. Zaffar Marg-Asif Ali Road	Jamun	4.90	27.89	17.12	16.11
2.	I.P. Road-B.S. Zaffar Marg	Peepal	1.70	26.21	19.48	20.16
3.	R.J. Road-Link Road	Peepal	2.00	23.86	13.10	17.14
4.	Asif Ali Road-D.B. Gupta Road (Ajmeri Gate)	Peepal	1.10	32.59	23.52	25.87
5.	G.T. Road-Yamuna Bridge Road	Peepal	2.00	26.21	19.15	19.82
6.	Ring Road-G.K. Road (AIIMS)	Pitrunjia	2.10	20.16	10.75	12.10
7.	Subhash Road-Daryaganj Road	Peepal	1.25	34.27	21.50	27.22
8.	Ring Road-L.B. Sashtri Road	Peepal	1.60	31.92	21.50	26.21
9.	S.P. Mukherjee-Lothian Road	Peepal	1.95	28.24	18.81	20.83
10.	Ring Road-Najafgarh Road	Jamun	4.55	26.21	15.79	16.13
11.	Pusa-Shanker-Patel Road	Siris	3.75	24.86	16.80	10.75
12.	Mathura Road-Zakir Hussain Road	Neem	4.25	28.54	18.14	16.80

Table 2. Flux Contributions by the Pollutants

S. No.	Sampling Zones	Flux Gas ($gkm^{-1}veh^{-1}$) CO	HC	NOx
1.	Bahadur Shah Marg-Asif Ali Road	79.72	9.70	4.52
2.	Indraprastha Road-Bahadur Shah Zaffar Marg	23.63	2.88	1.34
3.	Rani Jhansi Road-Link Road	20.02	2.44	1.14
4.	Asif Ali Road-D.B. Gupta Road (Ajmeri Gate)	17.90	2.18	1.01
5.	Grand Trunk Road-Yamuna Bridge Road	27.80	3.38	1.57
6.	Ring Road-Greater Kailash Road (AIIMS)	20.65	2.51	1.17
7.	Subhash Road-Daryaganj Road	18.57	2.26	1.05
8.	Ring Road-Lal Bahadur Sashtri Road	23.00	2.80	1.38
9.	S.P. Mukherjee-Lothian Road	27.29	3.32	1.55
10.	Ring Road-Najafgarh Road	64.08	7.80	3.63
11.	Pusa-Shanker-Patel Road	79.97	9.73	4.53
12.	Mathura Road-Dr. Zakir Hussain Road	71.89	8.74	4.07

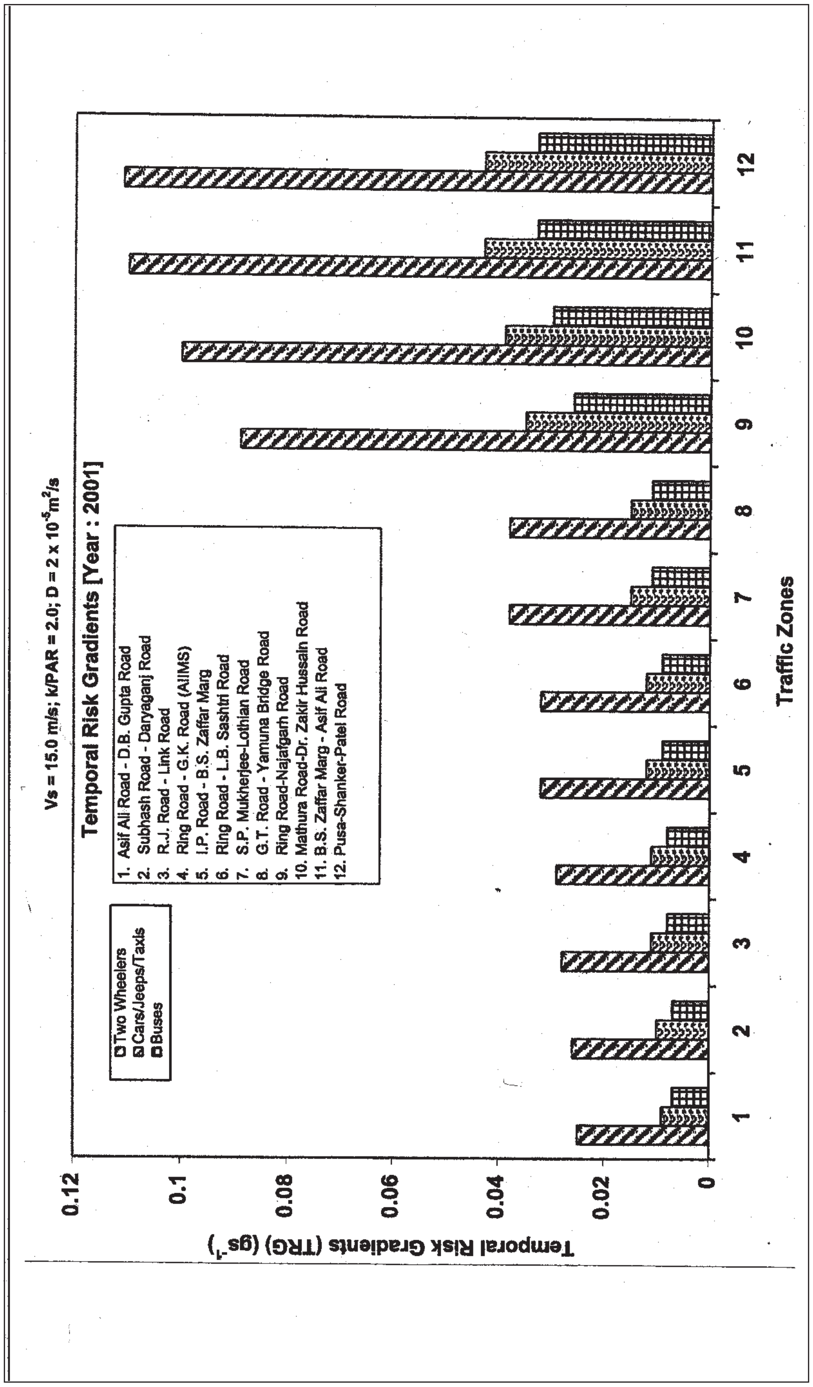
Vs = 15.0 m/s; k/PAR = 2.0; D = 2 x 10-5m2/s
Temporal Risk Gradients [Year : 2001]
▢ Two Wheelers
▨ Cars/Jeeps/Taxis
▦ Buses
1. Asif Ali Road - D.B. Gupta Road
2. Subhash Road - Daryaganj Road
3. R.J. Road - Link Road
4. Ring Road - G.K. Road (AIIMS)
5. I.P. Road - B.S. Zaffar Marg
6. Ring Road - L.B. Sashtri Road
7. S.P. Mukherjee-Lothian Road
8. G.T. Road - Yamuna Bridge Road
9. Ring Road-Najafgarh Road
10. Mathura Road-Dr. Zakir Hussain Road
11. B.S. Zaffar Marg - Asif Ali Road
12. Pusa-Shanker-Patel Road
Temporal Risk Gradients (TRG) (gs-1)
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
8
9
10
11
12
Traffic Zones

Figure 2.

Table 3.

Temporal Risk Gradient (TRG)

$= f_1$ (Pollutant) × f_2 (Vegetation) × f_3 (Traffic Density) .... (1)

Where,

f_1 (Pollutant) = D × Emission .... (2)

D = Air-gas diffusivity ($m^2 s^{-1}$) .... (2.1)

Emission = $(E_{1\_gas}) \times Vs^2 - (E_{2\_gas}) \times Vs + E_{3\_gas}$ .... (2.2)

$E_{1\text{-NOX}} = 5.6 \times 10^{-4}$ .... (2.3)
$E_{2\text{-NOX}} = 7.1 \times 10^{-2}$ .... (2.4)
$E_{3\text{-NOX}} = 5.75$ .... (2.5)

$E_{1\text{-CO}} = 1.38 \times 10^{-2}$ .... (2.6)
$E_{2\text{-CO}} = 2.14$ .... (2.7)
$E_{3\text{-CO}} = 112.0$ .... (2.8)

$E_{1\text{-HC}} = 1.616 \times 10^{-3}$ .... (2.9)
$E_{2\text{-HC}} = 0.288$ ...... (2.10)
$E_{3\text{-HC}} = 13.98$ ...... (2.11)

V_s = Speed of the vehicle (m/s) ...... (2.12)

$f_2 = (\pi NAB) / (4.0\ L\ (1.0 + k/PAR))$ .... (3)

Where,

N = Number of stomatal pores per unit leaf area (per cm^2)
A = Length of major axis of stomata (μm)
B = Length of minor axis of stomata (μm)
L = Length of effective opening (μm)
k = PAR-curvature coefficient defined as the Photosynthetically Active Radiation (PAR) at twice the minimum stomatal resistance (W/m^2)

(Table 3 *continued on next page*)

Table 3. (Cont'd.)

f_3 (traffic_density) $= f_{31} \times f_{32} \times f_{33}$ .... (4)

$f_{31} = a_{\text{vehicle\_type}} \times b_{\text{vehicle\_type}}$ .... (4.1)

$f_{32} = (\text{year})^{B}$ .... (4.2)

$f_{33} = \exp\{a_{\text{vehicle\_type}} \times (\text{year})^{B+1}\}$ .... (4.3)

Where,
$B = b_{\text{vehicle\_type} - 1.0}$ .... (4.4)
$a_{\text{two\_wheelers}} = 9.664$ .... (4.5)
$b_{\text{two\_wheelers}} = 0.311$ .... (4.6)

$a_{\text{car\_jeep\_taxi}} = 11.70$ .... (4.7)
$b_{\text{car\_jeep\_taxi}} = 0.137$ .... (4.8)

$a_{\text{bus}} = 10.193$ .... (4.9)
$b_{\text{bus}} = 0.123$ ...... (4.10)

$a_{\text{all\_vehicles}} = 12.135$ ...... (4.11)
$b_{\text{all\_vehicles}} = 0.185$ ...... (4.12)

year = Year-number (as explained in Table 4)

rises. Consequently, traffic jams and congestion impede the flow of traffic resulting in reduction of average speed and, therefore, there have been very substantial increases in emissions.

Along with lack of adequate public transport and the growth in the number of private vehicles, poor traffic planning and management are additional factors responsible for the alarming increase in vehicular air emissions. It has been estimated [8] that to carry the same number of people over the same distance, a car emits ninety times more CO than a bus, a taxi emits 113 times more, a three-wheeler sixty times, and a two-wheeler forty-nine times. Increased use of buses or other mass transit systems would alleviate the pollution threat considerably.

The main emphasis of the present modeling exercise lies in the derivation and computation of TRG values for sensitive traffic zones of Delhi city. TRG, in its present form, does not explicitly include mutual synergies of air pollutants [19, 20]. However, as far as quantification and comparison of relative magnitudes of risks under different categories of vehicles are concerned it adequately serves the purpose. Hence, it provides an appropriate planning model for suggesting the right mix for different traffic zones by quantifying the magnitude of the present risk and

Table 4. Decadal Models for Temporal Predictions in Vehicular Density

Two Whelers

$$V_{TM} = \exp\,[9.664(\text{Year})^{0.311}] \tag{1}$$

Car/Jeeps/Taxis

$$V_{CJT} = \exp\,[11.700\,(\text{Year})^{0.137}] \tag{2}$$

Buses

$$V_{B} = \exp[10.193(\text{Year})^{0.123}] \tag{3}$$

All Vehicles

$$V_{AV} = \exp[12.135(\text{Year})^{0.185}] \tag{4}$$

Where,

V_{TW} = No. of Two Wheelers
V_{CJT} = No. of Cars/Jeeps/Taxis
V_{B} = No. of Buses
V_{AV} = Total No. of Vehicles
Year = Number of year: Starting with 1951, increment for every decade has been taken as equivalent to 1. For example, for 1971, Year = 3.0; for 1981, Year = 4.0; for 1991, Year = 5.0; and for 2001 Year = 6.0, etc.

the rate at which it is likely to rise in future so as to identify the zones for traffic-diversion or expansion.

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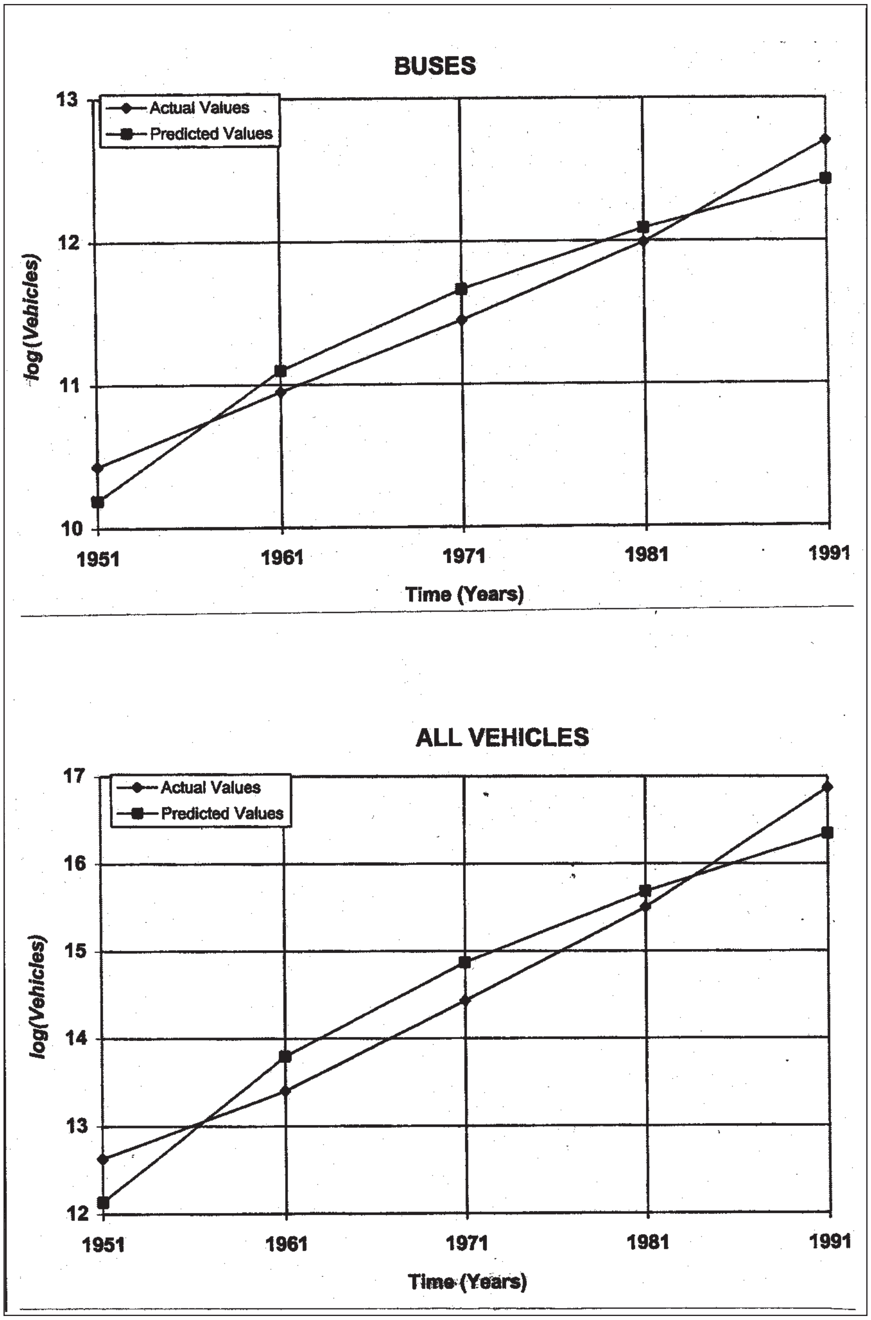
BUSES
Actual Values
Predicted Values
13
12
11
10
log(Vehicles)
1951
1961
1971
1981
1991
Time (Years)
ALL VEHICLES
Actual Values
Predicted Values
17
16
15
14
13
12
log(Vehicles)
1951
1961
1971
1981
1991
Time (Years)

Figure 3.

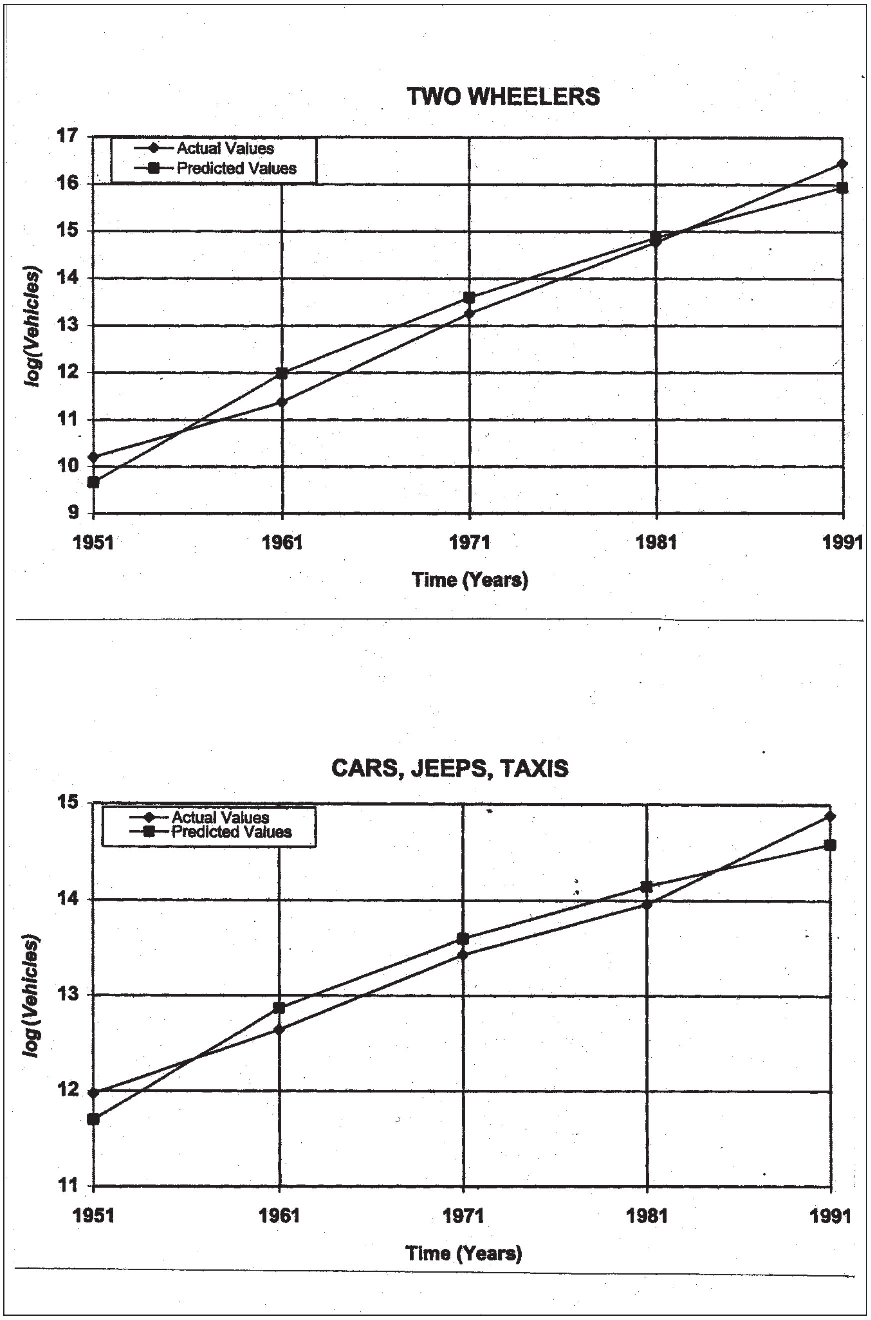
TWO WHEELERS
Actual Values
Predicted Values
log(Vehicles)
17
16
15
14
13
12
11
10
9
1951
1961
1971
1981
1991
Time (Years)
CARS, JEEPS, TAXIS
Actual Values
Predicted Values
log(Vehicles)
15
14
13
12
11
1951
1961
1971
1981
1991
Time (Years)

Figure 4.

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