

**PHYSICAL SIMULATION OF VEHICULAR POLLUTION
DISPERSION IN AN ISOLATED URBAN STREET
CANYON UNDER HETEROGENEOUS TRAFFIC
CONDITIONS**

by

**NIRAJ SHARMA
DEPARTMENT OF APPLIED MECHANICS**

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY, DELHI

August, 2004

Dedicated
to
My Parents

CERTIFICATE

This is to certify that the thesis entitled “**Physical Simulation of Vehicular Pollution Dispersion in an Isolated Urban Street Canyon Under Heterogeneous Traffic Conditions**” being submitted by **Mr. Niraj Sharma**, has been prepared under my supervision in conformity with the rules and regulations of the **Indian Institute of Technology, Delhi**. I further certify that the thesis has attained a standard required for the award of a degree of **Doctor of Philosophy** of the institute. This work, or any part thereof, has not been submitted elsewhere for the award of any other degree or diploma.



(Dr. K.K. CHAUDHRY)

Professor

Department of Applied Mechanics

Indian Institute of Technology, Delhi

New Delhi - 110016, India

ACKNOWLEDGEMENTS

At the outset, I express my sense of gratefulness to my supervisor Professor K. K. Chaudhry, Department of Applied Mechanics, Indian Institute of Technology (IIT), Delhi for introducing me to the world of physical modelling. His sympathetic hearing, constant inspiration and excellent guidance have immensely helped me in completing the present research work. I am thankful to him for giving me a lot of independence in carrying out the research work. I am also thankful to him for advising and guiding me as a parent at the time of emotional and mental stress.

I also wish to thank Professors V. Sheshadri and S.N. Singh both at the Department of Applied Mechanics and Professor M. Khare, Department of Civil Engineering, IIT, Delhi for their valuable suggestions and comments at various stages of this work.

I am thankful to Dr. Michel Pavageau, Ecole Des Mines De Nantes, Department Systems Energetiques et Environment, France for providing valuable suggestions during his visit to India . I also wish to thank Prof. E.J.Platt, University of Karlsruhe Germany, Prof. K.J. Schaudt, University of Arizona, USA and Prof. Robert N. Meroney, Colorado State University, USA for readily obliging to our request by providing relevant literature.

I am grateful to Professor P.K. Sikdar, Director, Central Road Research Institute (CRRI), New Delhi, for kindly permitting and facilitating me to pursue Ph.D. work as a part-time candidate at the IIT, Delhi. I am also thankful to Dr. T. S. Reddy, Area Coordinator and Dr. S. Gangopadhyaya, Group Leader, Traffic Engineering and Transportation Planning (TTP) area for facilitating and encouraging me to carry out doctoral research work at IIT, Delhi.

I am deeply indebted to Dr. C.V. Chalapati Rao, Deputy Director National Environmental Research Institute (NEERI), Nagpur for constantly encouraging and guiding me to carry out research work at IIT, Delhi. He was always available to me for the guidance and advice related to my research work.

My thanks are due to the staff members of the Gas Dynamics Laboratory, Department of Applied Mechanics for their help and co - operation during the experimental studies of the present work.

I also thank my colleagues Dr. V. V. L K. Rao, Mr. I.P. Rao, Dr. A. Singh, Dr. D. Tiwari, Ms. A. Shukla, Mr. C. Bhan and Mr. M. Rao at CRRI, for their support and encouragement during various stages of my research work. I also acknowledge the help of Mr. K. Ahmad and Mr. P. Gupta for their help during the course of the present study.

No words can express my deep sense of gratitude to my family members including my parents (Dr. S. M. Sharma and late Mrs. Savitri Sharma), elder brothers (Dr. Navin Sharma and Dr. Pravin Sharma), sisters - in - law (Asita Sharma and Kavita Sharma), nephews (Annanya and Ujjwal), niece (Isha) and entire family of parents - in - law (Dr. T. P. Ojha/Mrs. Kamla Devi, Mr. Ravindra Ojha/Mrs. Kanchan Ojha, Dr. Rahul Ojha/Dr. Sujata Ojha, Dr. B. D. Shukla/Mrs. Kiran Shukla and their sons Ankit, Aditya, Devyansh, Atul and Ankur) for their emotional back - up and unfading encouragement enabling me to complete the research work.

I also remember my mother Savitri Sharma with tearful eyes who always wanted me to carry out doctoral research work at IIT Delhi. Although she is no more with us , but I can always feel her presence and can sense her blessings for me from the heaven.

My heart - felt thanks are due to my wife Dr. Supriya Sharma for always encouraging and providing moral and emotional support to me. I also remember many occasions when I wanted to quit, but she gave me strength to withstand and overcome the hurdles during the whole research work. I also remember the loving faces my daughter Natasha and son Sukrit who were always my source of inspiration and never complained for my occasional irritating behavior. I hope they will always remember me as a loving and caring father.

Lastly, but definitely not the least, I am grateful to my alma - mater, IIT Delhi, for always motivating me to excel in my research field.


(MIRAJ SHARMA)

ABSTRACT

Air pollution from motor vehicles is one of the most serious and rapidly growing problems in various urban centers of the world. Predicting the distribution of pollutants under various urban conditions such as urban street canyon is extremely complex involving a variety of physical and meteorological factors including vehicle emissions, wake effects, canyon wind flows and turbulent dispersion.

Over the past two decades, significant progress has been made in understanding and modelling vehicular pollution dispersion phenomena under these urban environmental conditions by using Environmental Wind Tunnel (EWT) technique. In the EWT, the emission conditions, different meteorological situations, terrain and topographical features can be changed at will and useful data translatable to the real - life situations can be obtained. These EWT studies carried out over the last ten years have greatly helped in determining the pollutant concentrations under various urban street canyon conditions as a function of building dimensions, upwind building configuration, wind direction with respect to building configuration and roof geometry. These studies have further shown that the vehicle- induced turbulence (or mixing) is an important factor influencing pollutant dispersion in urban areas particularly under low wind conditions, which are typical of street canyons. Most of the models do not adequately account for the vehicle - induced mixing leading to inaccurate and unreliable predictions, and sometimes even misleading conclusions.

In the present study, experimental data have been obtained at the EWT (2mx2mx16m) facility at the Indian Institute of Technology (IIT) Delhi to evaluate the effects of traffic parameters (traffic volume, traffic speed, traffic composition) on the pollutant concentrations in an isolated urban street canyon under heterogeneous (i.e., mixed) traffic condition(s). Tracer studies were carried by using 5% Acetylene and 95% Grade I Nitrogen and Flame Ionisation Detection (FID) technique. The tracer concentrations were non- dimensionalised to assess the effects of traffic - induced mixing on the pollutant concentrations at different heights in a simulated urban street canyon.

The study has indicated that at low wind speeds ($U_{ref} \leq 1.5$ m/s) and under perpendicular and oblique wind directions, pollution distribution in the urban street canyon

is affected by the weak central vortex whereas during parallel wind flow, the pollution gets dispersed due to channelling of the flow. However, under the heterogeneous traffic conditions, the effect of vehicle-induced mixing on the pollutant concentrations was found to be minimal at low traffic speeds (less than 10kmph) and low traffic volume (less than 1500 vehicles/ h) conditions, implying the need for maintaining a minimum traffic speed in the street canyons. Thus, while increase in traffic results in an increase in the pollutant levels in the street canyon, the effect of increased pollution level is, to a certain extent is offset by the increased vehicle - induced mixing generated by these vehicles.

The effect of vehicle-induced turbulence is significantly reduced with height (Z/H). The effect of the vehicle - induced mixing was found to be maximum at the breathing level, while at sampling locations close to the top edge, the effect of vehicle-induced mixing of pollution was found to be almost negligible. Further, the pollution level in street canyon has also been found to be affected by aspect ratio(s) and traffic volume(s).

Artificial Neural Networks (ANN) are being increasingly used for vehicular exhaust emissions modelling under the complex urban conditions. The present investigation also demonstrates the ability of these ANN models to simulate, the complex non - linear interaction between various variables, and predict the pollutant concentrations in an urban street canyon under mixed traffic conditions dominated by vehicle - induced effects.

TABLE OF CONTENTS

	Page No.
Certificate	(i)
Acknowledgements	(ii)
Abstract	(iv)
Table of Contents	(vi)
List of Figures	(xii)
List of Tables	(xvii)
List of Plates	(xviii)
List of Abbreviations	(xix)
Notations	(xxiii)
1. INTRODUCTION	1-11
1.1 General	1
1.2 Statement of problem	3
1.3 Motivation for the present study	5
1.4 Scope of the present study	6
1.5 Objectives of the present study	8
1.6 Brief description of the thesis	9
2. REVIEW OF THE LITERATURE	13-102
2.1 Air pollution dispersion modelling	13
2.1.1 Modelling of photochemical oxidants	23
2.2 Vehicular pollution modeling	26
2.2.1 Integrated modelling approach	28
2.2.2 Vehicular pollution modelling in India	31
2.2.3 Inadequacies of vehicular pollution modeling	34
2.3 Air pollution dispersion studies through Wind Tunnel investigations	39
2.3.1 Development of atmospheric boundary layer in the EWT	42

2.3.2	Generation of different terrain categories in the EWT	48
2.3.3	Design philosophy	50
2.3.4	Similarity considerations	51
2.3.5	Importance and relevance of EWT experiments in India	53
2.3.6	Limitations of the EWT technique	55
2.4	Artificial Neural Networks (ANNs)	57
2.4.1	Basic features of ANN	60
2.4.1.1	The biological neuron	60
2.4.1.2	The Multilayer Perceptron (MLP)	61
2.4.1.3	Transfer function	62
2.4.1.4	Training a multilayer perceptron - the back - propagation algorithm	63
2.4.1.4.1	Feed forward computation	67
2.4.1.4.2	Error back-propagation	69
2.4.1.5	Selection of learning rate parameter	71
2.4.1.6	Selection of initial weights	72
2.4.1.7	Normalization of the training data set	72
2.4.1.8	Criteria for selection of neural network architecture	73
2.4.2	Application of ANN in vehicular emission modeling	74
2.4.3	Summary	74
2.5	Air pollution dispersion in urban street canyon	77
2.5.1	Pollution dispersion modelling in the street canyon	89
2.6	Performance evaluation of models	95
2.6.1	Statistical analysis	98
3	EXPERIMENTAL SETUP AND METHODOLOGY	103-138
3.1	General	103
3.2	Simulation of the Atmospheric Boundary Layer (ABL) in the EWT	104
3.2.1	Log -law profile – estimation of surface layer parameters	111
3.2.2	Reynolds number independence	113

3.3	Street canyon model	114
3.4	Design of moving traffic in the EWT	117
3.4.1	Description of the street canyon geometries	119
3.5	Simulation of traffic	122
3.5.1	Traffic speed	122
3.5.2	Traffic volume	122
3.6	Pollution (tracer) dispersion measurements in the EWT	123
3.7	Brief summary of experimental set up	126
3.7.1	Salient features of the EWT	126
3.7.2	Simulation of the ABL	126
3.7.3	Line source model	126
3.7.4	Street canyon model	126
3.7.5	Simulation of the traffic in the EWT	126
3.7.6	Meteorological conditions	127
3.7.7	Aspect ratio (D/H)	127
3.7.8	Tracer dispersion experiments	127
3.7.9	Non - dimensionalised mean concentration parameter	127
3.7.10	Total number of pollution (tracer) measurements at different sampling points	127
3.8	Modelling of EWT data using Artificial Neural Network (ANN) technique	128
3.9	Concluding remarks	133
3.9.1	Justification for the use of 'an isolated street canyon' for the present study	133
3.9.2	Potential interference effects by the moving traffic mechanism	136
3.9.3	Justification for simulating 55% of total vehicles as two wheelers in the EWT experimentation work as against the 70% of the total vehicles in India	138
4	RESULTS AND DISCUSSION	139 -216
4.1	General	139
4.2	Physical modelling of vehicular pollution dispersion phenomena	141

4.3	Effect of traffic - induced mixing on pollutant concentration values at different sampling locations when wind flow is parallel ($\theta = 0^0$) to the simulated urban street canyon in the EWT	142
4.3.1	Left side wall (aspect ratio 1.2)	142
4.3.2	Right side wall (aspect ratio 1.2)	146
4.3.3	Left side wall (aspect ratio 1.0)	150
4.3.4	Right side wall (aspect ratio 1.0)	150
4.3.5	Left side wall (aspect ratio 0.8)	155
4.3.6	Right side wall (aspect ratio 0.8)	155
4.4	Effect of traffic - induced mixing on pollutant concentration values at different sampling locations when wind flow is perpendicular ($\theta = 90^0$) to the simulated urban street canyon in the EWT	155
4.4.1	Leeward wall (aspect ratio 1.2)	155
4.4.2	Windward wall (aspect ratio 1.2)	162
4.4.3	Leeward wall (aspect ratio 1.0)	166
4.4.4	Windward wall (aspect ratio 1.0)	166
4.4.5	Leeward wall (aspect ratio 0.8)	171
4.4.6	Windward wall (aspect ratio 0.8)	171
4.5	Effect of traffic - induced mixing on pollutant concentration values at different sampling locations when wind flow is at $\theta = 45^0$ to the simulated urban street canyon in the EWT	171
4.5.1	Leeward wall (aspect ratio 1.2)	171
4.5.2	Windward wall (aspect ratio 1.2)	179
4.5.3	Leeward wall (aspect ratio 1.0)	179
4.5.4	Windward wall (aspect ratio 1.0)	179
4.6	Effect of traffic - induced mixing on pollutant concentration values at different sampling locations, when wind flow is at $\theta = 30^0$ to the simulated urban street canyon in the EWT	186
4.7	Effect of wind direction on pollution concentrations	191
4.8	Modelling of EWT data using Artificial Neural Network (ANN) technique	196
4.8.1	General	196
4.8.2	Input and Output parameters	197
4.8.3	Training of the neural networks with EWT data	198

4.8.3.1	Training methodology	198
4.8.4	Validation of ANN results for ($\theta = 30^0$) orientation case	201
4.8.5	Comparison of EWT data and ANN results	207
4.8.5.1	Significance of the ANN model if it were to be employed in a realistic situation	209
4.9	Concluding remarks	212
5	CONCLUSIONS AND SCOPE FOR THE FUTURE WORK	217-224
5.1	Conclusions	217
5.1.1	Conclusions based on the experimental study to investigate vehicular dispersion phenomena in a simulated urban street canyon in the EWT	217
5.1.2	Conclusions based on the ANN modeling of the Experimental data obtained in the EWT study	219
5.2	Contributions of the present study	220
5.3	Scope for the future work	221
	REFERENCES	225-258
	APPENDICES	259-283
APPENDIX –I	: Salient features of EWT at IIT Delhi	259
APPENDIX - II	: Estimation of roughness parameters in simulated ABL in EWT	261
APPENDIX - III	: Summary of the some of the recent EWT simulation studies in which two different or similar scaling ratio criteria were employed for scaling ABL and model vehicle(s)/ street canyon	265
APPENDIX -IV	: Training file for leeward wall	270
APPENDIX - V	: Training file for windward wall	271
APPENDIX - VI	: Validation file for leeward wall	272
APPENDIX - VII	: Validation file for windward wall	273
APPENDIX - VIII	: Result file for windward wall	274
APPENDIX - IX	: Result file for leeward wall	276
APPENDIX - X	: Network file for Leeward wall	278

APPENDIX - XI : Network file for windward wall

281

Brief Bio- data of the Author

285-287