

ELECTRIC RICKSHAWS IN DELHI: OPERATIONS, CHARGING INFRASTRUCTURE, AND ECONOMY

SOURAV DAS



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

OCTOBER 2024

© Indian Institute of Technology Delhi (IITD), New Delhi, 2024

ELECTRIC RICKSHAWS IN DELHI: OPERATIONS, CHARGING INFRASTRUCTURE, AND ECONOMY

by

SOURAV DAS

Department of Civil Engineering

Submitted

in partial fulfilment of requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2024

To

My parents, loved ones, and beloved teachers

CERTIFICATE

This is to certify that the dissertation entitled “*Electric Rickshaws in Delhi: Operations, Charging Infrastructure, and Economy*” is being submitted by **Mr. Sourav Das** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**. This is a record of the original research work carried out by him under my supervision and guidance. Neither this dissertation nor any part of this has been submitted for any degree or academic award elsewhere.

Prof. Nezamuddin

Prof. Dinesh Mohan Chair for Transportation Planning

Associate Professor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi – 110016

India

ACKNOWLEDGEMENTS

This journey would not have been possible without the blessings of the Almighty, their silent conspirations never let me give up and finally made my dream come true.

First, I would like to express my gratitude to Prof. Nezamuddin for his guidance and support throughout my doctoral studies at IIT Delhi. It was an honor to work with him and I am deeply indebted for his patience and valuable advice that were indispensable for completing my research.

I would specially like to thank all faculty members of Transportation Engineering and my SRC members: Prof. K.N. Jha, Prof. Geetam Tiwari, Prof. Pramesh Kumar, and Prof. Varun Ramamohan for their suggestions that immensely helped in improving the quality of my work. A heartfelt thanks to Prof. Manoj M. for his interesting and impactful lectures on Public Transportation Systems. I gratefully acknowledge the contribution of the Transportation Research and Injury Prevention Centre (TRIP-C) and Arun Duggal Centre of Excellence for Research in Climate Change and Air Pollution (CERCA) in funding my research.

I would like to express my sincere gratitude to all the staff members of Civil Engineering Department and TRIP-C of IIT Delhi, especially Mr. Mahesh Gaur and Mr. Kaushik Pahari for providing me all necessary administrative and laboratory support. I also want to appreciate Mr. Harvesh Singh Thakur for extensively helping me with the primary data collection.

I cannot be thankful enough to all my friends and colleagues from IIT Delhi who became my family away from home. Special mention to Pranav, Ashish, Anamika, Deotima, Shayesta, Aman, Abu, Krishnan, Mustansir, Poonam, Vamsi, Dr. Mohit Kumar Singh, Dr. Abhary Eleyedath, Dr. Chetan Doddamani, Dr. Punyabeet Sarangi, and Dr. Laxman Singh Bisht for their support, inspiration and daily doses of laughter that kept me going throughout this journey.

I would also like to thank Subhodip and Biswajit, who were my roommates from the day one. I would forever cherish the moments spent together. Lastly, I express my gratitude to all those whose names may not appear here but whose contributions, whether big or small, have played a part in the completion of this dissertation. Your support has been deeply appreciated.

Most importantly, I owe everything to my parents and the loved ones. Their love, unwavering faith and relentless encouragement against all odds made it possible for me to survive the ups and downs of my doctoral program.

This dissertation marks the completion of a journey that started six years ago. It has been a wonderful experience and was made so by countless fellow friends, teachers, and mentors. Before I start my next journey, I would like to take a moment to thank all of them for the countless ways in which they enriched my experience.

Sourav Das

October 2024

ABSTRACT

Electric Rickshaws (e-rickshaws) are a battery-driven, three-wheeled, and demand responsive informal public transport mode operational in various developing countries worldwide, used mainly for last-mile and short trips. In semi-urban and rural areas in India, e-rickshaws serve as one of the major transport modes catering to the demand gap due to insufficient and/or absent public transit modes. But in urban areas like Delhi, public transit system (e.g., buses, metros etc.) is well established, hence e-rickshaws mainly operate as feeder to these.

Being a demand responsive mode without any fixed schedule, e-rickshaw operations are often chaotic and disorganized. As the e-rickshaws do not follow any schedule, drivers often wait for their vehicles to fill up before starting the journey, and they may even wait at intermediate stops for an indefinite time. Such practices increase passengers' pre-journey waiting and dwell time, affecting the overall trip experience and ability to connect to buses/metros. Unregulated e-rickshaw operations also cause congestion on roadways leading to increased trip durations. Another major issue affecting the efficiency of e-rickshaw operations is lack of charging infrastructure, leading to reduced working hours and fewer daily trips for the e-rickshaws. This encourages malpractices of opening private charging places for e-rickshaws. Often e-rickshaw drivers charge and park their vehicles at these privately owned unregulated facilities by paying high tariff.

This dissertation focuses on three major areas: analyzing the service and operational characteristics of e-rickshaws, designing charging infrastructure for e-rickshaws, and assessing the economy of owning and operating an e-rickshaw. Primary surveys were conducted in Delhi, India to conduct the research work for this dissertation.

At first, e-rickshaw route network, trip, and operational characteristics were analyzed. Further the e-rickshaw trip duration reliability was assessed using various reliability indices, and trip duration reliability-based level-of-service thresholds were identified for the e-

rickshaws using clustering algorithm. Various machine learning based regression models were used to model e-rickshaw pre-journey waiting time, dwell time, and trip durations and identify the factors significantly impacting them.

Next, charging infrastructure for e-rickshaws were designed using a stochastic bi-objective maximal covering type model developed as a part of this dissertation. Optimal locations were identified to set up charging stations and the optimal number of chargers installed at the charging stations were also determined. The concept of dynamic tariff was introduced in the model to achieve a demand-supply equilibrium of e-rickshaw charging workload at the charging stations. E-rickshaw drivers' charging preferences were incorporated in the formulation as parameters and constraints while designing the charging infrastructures. The optimally designed charging stations showed significant performance improvement over the existing charging stations.

Further, the dissertation focused on assessing e-rickshaws as an investment/business opportunity. The e-rickshaw lifecycle cost and profits earned by owning and operating an e-rickshaw were estimated. Next, the impact of discount rates, lifecycle, battery replacement cycle, and daily distance travelled on the e-rickshaw lifecycle costs and profits were analyzed. Finally, linear regression was used to model e-rickshaw lifecycle cost.

Overall, this dissertation highlighted the existing condition of e-rickshaw operations in Delhi and focused on identifying factors impacting the e-rickshaw operations, designing charging infrastructure for e-rickshaws, and analyzing the economy of owning and operating an e-rickshaw. This dissertation can be referred to by stakeholders and policymakers for planning of improved and efficient e-rickshaw services by understanding their operations and providing them with optimally designed infrastructure, which will in turn foster the growth of electric mobility in India.

सार

इलेक्ट्रिक रिक्शा (ई-रिक्शा) एक बैटरी चालित, तीन पहियों वाला और दुनिया भर के विभिन्न विकासशील देशों में चलने वाला अनौपचारिक सार्वजनिक परिवहन साधन है, जिसका उपयोग मुख्य रूप से अंतिम मील और छोटी यात्राओं के लिए किया जाता है। भारत में अर्ध-शहरी और ग्रामीण क्षेत्रों में, ई-रिक्शा अपर्याप्त और/या अनुपस्थित सार्वजनिक परिवहन साधनों के कारण मांग के अंतर को पूरा करने वाले प्रमुख परिवहन साधनों में से एक के रूप में कार्य करता है। लेकिन दिल्ली जैसे शहरी क्षेत्रों में, सार्वजनिक परिवहन प्रणाली (जैसे, बसें, मेट्रो आदि) अच्छी तरह से स्थापित है, इसलिए ई-रिक्शा मुख्य रूप से इनके लिए फीडर के रूप में काम करते हैं। बिना किसी निश्चित समय-सारणी के मांग के प्रति संवेदनशील मोड होने के कारण, ई-रिक्शा संचालन अक्सर अव्यवस्थित और अव्यवस्थित होता है। चूंकि ई-रिक्शा किसी शेड्यूल का पालन नहीं करते हैं, इसलिए चालक अक्सर यात्रा शुरू करने से पहले अपने वाहनों में सामान भरने का इंतजार करते हैं, और वे अनिश्चित समय के लिए मध्यवर्ती स्टॉप पर भी इंतजार कर सकते हैं। इस तरह की प्रथाओं से यात्रियों की यात्रा-पूर्व प्रतीक्षा और रुकने का समय बढ़ जाता है, जिससे समग्र यात्रा अनुभव और बसों/महानगरों से जुड़ने की क्षमता प्रभावित होती है। अनियमित ई-रिक्शा संचालन से भी सड़कों पर भीड़भाड़ होती है जिससे यात्रा की अवधि बढ़ जाती है। ई-रिक्शा संचालन की दक्षता को प्रभावित करने वाला एक अन्य प्रमुख मुद्दा चार्जिंग बुनियादी ढांचे की कमी है, जिसके कारण काम के घंटे कम हो गए हैं और ई-रिक्शा के लिए दैनिक यात्राएं कम हो गई हैं। इससे ई-रिक्शा के लिए निजी चार्जिंग स्थान खोलने की कदाचार को बढ़ावा मिलता है। अक्सर ई-रिक्शा चालक उच्च टैरिफ का भुगतान करके इन निजी स्वामित्व वाली अनियमित सुविधाओं पर अपने वाहनों को पार्क करते हैं।

यह शोध प्रबंध तीन प्रमुख क्षेत्रों पर केंद्रित है: ई-रिक्शा की सेवा और परिचालन विशेषताओं का विश्लेषण करना, ई-रिक्शा के लिए चार्जिंग बुनियादी ढांचे को डिजाइन करना, और ई-रिक्शा

के स्वामित्व और संचालन की अर्थव्यवस्था का आकलन करना। इस शोध प्रबंध के लिए शोध कार्य संचालित करने के लिए दिल्ली, भारत में प्राथमिक सर्वेक्षण आयोजित किए गए थे।

सबसे पहले, ई-रिक्शा रूट नेटवर्क, यात्रा और परिचालन विशेषताओं का विश्लेषण किया गया। इसके अलावा ई-रिक्शा यात्रा अवधि की विश्वसनीयता का मूल्यांकन विभिन्न विश्वसनीयता सूचकांकों का उपयोग करके किया गया था, और क्लस्टरिंग एल्गोरिदम का उपयोग करके ई-रिक्शा के लिए यात्रा अवधि विश्वसनीयता-आधारित सेवा सीमा के स्तर की पहचान की गई थी। ई-रिक्शा के यात्रा-पूर्व प्रतीक्षा समय, रुकने के समय और यात्रा की अवधि को मॉडल करने और उन्हें महत्वपूर्ण रूप से प्रभावित करने वाले कारकों की पहचान करने के लिए विभिन्न मशीन लर्निंग आधारित रिग्रेशन मॉडल का उपयोग किया गया था।

इसके बाद, ई-रिक्शा के लिए चार्जिंग इंफ्रास्ट्रक्चर को इस शोध प्रबंध के एक भाग के रूप में विकसित स्टोकेस्टिक द्वि-उद्देश्यीय अधिकतम कवरिंग प्रकार मॉडल का उपयोग करके डिजाइन किया गया था। चार्जिंग स्टेशन स्थापित करने के लिए इष्टतम स्थानों की पहचान की गई और चार्जिंग स्टेशनों पर स्थापित चार्जर्स की इष्टतम संख्या भी निर्धारित की गई। चार्जिंग स्टेशनों पर ई-रिक्शा चार्जिंग वर्कलोड की मांग-आपूर्ति संतुलन प्राप्त करने के लिए मॉडल में गतिशील टैरिफ की अवधारणा पेश की गई थी। चार्जिंग बुनियादी ढांचे को डिजाइन करते समय ई-रिक्शा चालकों की चार्जिंग प्राथमिकताओं को मापदंडों और बाधाओं के रूप में शामिल किया गया था। सर्वोत्तम रूप से डिजाइन किए गए चार्जिंग स्टेशनों ने मौजूदा चार्जिंग स्टेशनों की तुलना में महत्वपूर्ण प्रदर्शन में सुधार दिखाया है।

इसके अलावा, शोध प्रबंध एक निवेश/व्यावसायिक अवसर के रूप में ई-रिक्शा का मूल्यांकन करने पर केंद्रित था। ई-रिक्शा की जीवनचक्र लागत और ई-रिक्शा के स्वामित्व और संचालन से अर्जित लाभ का अनुमान लगाया गया। इसके बाद, ई-रिक्शा जीवनचक्र लागत और मुनाफे पर छूट दरों, जीवनचक्र, बैटरी प्रतिस्थापन चक्र और यात्रा की गई दैनिक दूरी के प्रभाव का

विश्लेषण किया गया। अंत में, ई-रिक्शा जीवनचक्र लागत को मॉडल करने के लिए रैखिक प्रतिगमन का उपयोग किया गया।

कुल मिलाकर, इस शोध प्रबंध ने दिल्ली में ई-रिक्शा संचालन की मौजूदा स्थिति पर प्रकाश डाला और ई-रिक्शा संचालन को प्रभावित करने वाले कारकों की पहचान करने, ई-रिक्शा के लिए चार्जिंग बुनियादी ढांचे को डिजाइन करने और ई-रिक्शा के स्वामित्व और संचालन की अर्थव्यवस्था का विश्लेषण करने पर ध्यान केंद्रित किया। इस शोध प्रबंध को हितधारकों और नीति निर्माताओं द्वारा उनके संचालन को समझकर बेहतर और कुशल ई-रिक्शा सेवाओं की योजना बनाने और उन्हें सर्वोत्तम रूप से डिजाइन किए गए बुनियादी ढांचे प्रदान करने के लिए संदर्भित किया जा सकता है, जो बदले में भारत में इलेक्ट्रिक गतिशीलता के विकास को बढ़ावा देगा।

Table of Contents

CERTIFICATE.....	i
ACKNOWLEDGEMENTS	iii
ABSTRACT.....	v
List of Figures	xv
List of Tables.....	xix
List of Acronyms.....	xxi
CHAPTER 1: INTRODUCTION	1
1.1 Motivation.....	3
1.2 Dissertation Contributions	4
1.3 Dissertation Structure.....	6
CHAPTER 2: LITERATURE REVIEW	7
2.1 Paratransit in Developing Countries	7
2.2 E-rickshaw	9
2.3 Analyzing Supply and Demand Characteristics of E-rickshaw Route Networks	11
2.3.1 Public Transport Waiting and Dwell Time.....	11
2.3.2 Public Transport Travel Time Reliability.....	11
2.4 Modeling E-rickshaw Operations	12
2.4.1 Public Transport Dwell Time Modeling.....	13
2.4.2 Public Transport Travel Time Modeling.....	14
2.5 Designing E-rickshaw Charging Infrastructure	15
2.5.1 Coverage Type Facility Location Models with Immobile Servers	15
2.5.2 Facility Workload Balancing	16
2.5.3 Gradual Covering Decay and Cooperative Coverage.....	17
2.5.4 Dynamic Maximal Covering Location Problem	17
2.5.5 Optimal Location for Electric Vehicle Charging Stations	18
2.5.6 Need for a Separate E-rickshaw Charging Infrastructure Design Model	19
2.6 Assessing E-rickshaw Lifecycle Cost and Profit	21
2.6.1 Estimation of Lifecycle Cost for Electric and Fossil-fuel Driven Vehicles.....	21
CHAPTER 3: ANALYZING SUPPLY AND DEMAND CHARACTERISTICS OF E-RICKSHAW ROUTE NETWORKS	23
3.1 Study Area Selection.....	23
3.2 Data Collection Process	25

3.3 Descriptive Statistics.....	27
3.4 Distribution Fitting	29
3.5 E-rickshaw Passenger Occupancy	31
3.6 E-rickshaw Trip Duration Reliability.....	32
3.7 E-rickshaw Operational LOS Determination.....	33
3.8 Summary	36
CHAPTER 4: MODELING E-RICKSHAW OPERATIONS.....	37
4.1 Modeling Workflow	37
4.2 Nonlinear Regression Models.....	39
4.2.1 Machine Learning Models	39
4.2.2 Generalized Additive Model (GAM)	41
4.3 Hyperparameter Tuning	42
4.4 E-rickshaw Pre-journey Waiting Time (EPWT) Modeling.....	43
4.5 E-rickshaw Dwell Time (EDT) Modeling	46
4.6 E-rickshaw Trip Duration (ETD) Modeling	50
4.7 Summary	53
CHAPTER 5: DESIGNING E-RICKSHAW CHARGING INFRASTRUCTURE	55
5.1 Fundamental Model Properties	55
5.2 Drivers' Charging Preferences	58
5.3 Charging Time Calculation	63
5.4 Model Formulation	64
5.4.1 Design Level-of-Service (LOS)	66
5.4.2 Stochastic Formulation for Modeling Charging Demand Variation	71
5.5. Results for Charging Infrastructure Design in Uttam Nagar	74
5.5.1 Effect of Total Pairwise Absolute Workload Balancing on Energy Consumption ..	79
5.5.2 Effect of Dynamic Tariffs on the Charging Station Revenue	80
5.5.3 Effect of Dynamic Tariff on the Average Time Spent at Charging Stations	81
5.5.4 Comparison Between the Performance of Existing and Optimal Charging Stations	82
5.6 Sensitivity Analysis for Uttam Nagar	83
5.6.1 Objective Weights vs. Demand Coverage & Highest Pairwise Absolute Workload Difference.....	83
5.6.2 Elasticity vs. the Temporal Distribution of the E-Rickshaw Charging Workload...85	
5.6.3 Objective Weights vs. Number of Chargers at the Charging Stations	86

5.7 Results for Charging Infrastructure Design in Karol Bagh	87
5.7.1 <i>Effect of Total Pairwise Absolute Workload Balancing on Energy Consumption</i> ..	92
5.7.2 <i>Effect of Dynamic Tariffs on the Charging Station Revenue</i>	93
5.7.3 <i>Effect of Dynamic Tariff on the Average Time Spent at Charging Stations</i>	94
5.7.4 <i>Comparison Between the Performance of Existing and Optimal Charging Stations</i>	95
5.8 Sensitivity Analysis for Karol Bagh	95
5.8.1 <i>Objective Weights vs. Demand Coverage & Highest Pairwise Absolute Workload Difference</i>	96
5.8.2 <i>Elasticity vs. the Temporal Distribution of the E-Rickshaw Charging Workload</i> ...	98
5.8.3 <i>Objective Weights vs. Number of Chargers at the Charging Stations</i>	98
5.9 Summary	99
CHAPTER 6: ASSESSING E-RICKSHAW LIFECYCLE COST AND PROFIT	103
6.1 Methodology and Descriptive Statistics	103
6.1.1 <i>Descriptive Statistics</i>	104
6.1.2 <i>Equations for E-rickshaw Lifecycle Cost Estimation</i>	104
6.2 E-rickshaw LCC and Profit Estimation Results.....	107
6.3 Sensitivity Analyses	111
6.3.1 <i>Discount Rate vs. PV of E-rickshaw LCC and Profit Over Lifecycle</i>	111
6.3.2 <i>E-rickshaw Lifecycle vs. PV of E-rickshaw LCC and Profit Over Lifecycle</i>	113
6.3.3 <i>Battery Replacement Cycle vs. PV of E-rickshaw LCC and Profit Over Lifecycle</i>	114
6.3.4 <i>Daily Distance Travelled vs. PV of E-rickshaw LCC and Profit Over Lifecycle</i> ..	115
6.4 E-rickshaw Lifecycle Cost (LCC) Modeling.....	116
6.5 Policy Implications	118
6.6 Summary	119
CHAPTER 7: CONCLUSION AND FUTURE EXTENSION	121
7.1 Research Contributions	121
7.1.1 <i>Analyzing Supply and Demand Characteristics of E-rickshaw Route Networks</i> ..	121
7.1.2 <i>Modeling E-rickshaw Operations</i>	122
7.1.3 <i>Designing E-rickshaw Charging Infrastructure</i>	123
7.1.4 <i>Assessing E-rickshaw Lifecycle Cost and Profit</i>	124
7.2 Future Extensions.....	127
References.....	129

Appendix A	147
Appendix B	151
PUBLICATIONS	153
VITA	155

List of Figures

Figure 1.1: Methodological framework	5
Figure 3.1: Study areas in Delhi, India	24
Figure 3.2: E-rickshaws outside metro stations at survey areas	24
Figure 3.3: E-rickshaw operational routes and network topology in Uttam Nagar	26
Figure 3.4: E-rickshaw operational routes and network topology in Karol Bagh	26
Figure 3.5: E-rickshaw route length distributions in study areas.....	28
Figure 3.6: Best fitting distributions for e-rickshaw pre-journey waiting, dwell time, and trip duration	30
Figure 3.7: E-rickshaw passenger occupancy vs. number of intermediate stops.....	31
Figure 3.8: Temporal variation of buffer time index (BTI) and misery index (MI)	33
Figure 3.9: Silhouette analysis for identifying optimal number of clusters.....	34
Figure 3.10: Clustering analysis for LOS threshold determination	35
Figure 4.1: E-rickshaw operation modeling workflow	38
Figure 4.2: Hybrid ensemble model development process (Breiman, 1996)	40
Figure 4.3: Correlation matrix for EPWT modeling.....	44
Figure 4.4: Variable importance scores for EPWT modeling	46
Figure 4.5: Correlation matrix for EDT modeling.....	47
Figure 4.6: Variable importance scores for EDT modeling	49
Figure 4.7: Correlation matrix for ETD/km modeling.....	50
Figure 4.8: Variable importance scores for ETD/km modeling.....	52
Figure 5.1: Toy network for workload imbalancing illustration (Daskin, 2013).....	57
Figure 5.2: Distribution of acceptable detour distance from the trip route for charging in Uttam Nagar.....	59
Figure 5.3: Distribution of acceptable detour distance from the trip route for charging in Karol Bagh.....	60
Figure 5.4: Preferred charging time for e-rickshaws during operational hours in Uttam Nagar	61
Figure 5.5: Preferred charging time for e-rickshaws during operational hours in Karol Bagh.....	61
Figure 5.6: Optimal charging station locations proposed by the stochastic model (Uttam Nagar)	77

Figure 5.7: Comparison between e-rickshaw charging workload distributions with and without dynamic tariff (Uttam Nagar)	78
Figure 5.8: Comparative analysis for the proposed model variants (Uttam Nagar)	78
Figure 5.9: Base Tariff vs. Dynamic Tariff (Uttam Nagar).....	79
Figure 5.10: Comparison between the stochastic model results with and without workload balancing objective (Uttam Nagar).....	80
Figure 5.11: Comparison between average time spent at the charging stations with and without the dynamic tariff (Uttam Nagar)	81
Figure 5.12: Existing and optimal charging station locations in Uttam Nagar.....	82
Figure 5.13: Objective function weights vs. demand coverage and workload balancing (Uttam Nagar)	84
Figure 5.14: Impact of elasticity on the temporal distribution of e-rickshaw charging workload (Uttam Nagar).....	85
Figure 5.15: Demand coverage objective weights vs. total number of AC - 001 charger (Uttam Nagar).....	87
Figure 5.16: Optimal charging station locations proposed by the stochastic model (Karol Bagh).....	90
Figure 5.17: E-rickshaw charging pattern proposed by the stochastic model (Karol Bagh).....	91
Figure 5.18: Comparative analysis for the proposed model variants (Karol Bagh)	91
Figure 5.19: Base Tariff vs. Dynamic Tariff (Karol Bagh).....	92
Figure 5.20: Comparison between the stochastic model results with and without workload balancing objective (Karol Bagh)	93
Figure 5.21: Comparison between average time spent at the charging stations with and without the dynamic tariff (Karol Bagh)	94
Figure 5.22: Existing and optimal charging station locations in Karol Bagh.....	95
Figure 5.23: Objective function weights vs. demand coverage and workload balancing (Karol Bagh).....	96
Figure 5.24: Impact of elasticity on the temporal distribution of e-rickshaw charging workload (Karol Bagh)	98
Figure 5.25: Demand coverage objective weights vs. total number of AC - 001 charger (Karol Bagh).....	99
Figure 6.1: Present value of e-rickshaw lifecycle costs (LCC) and profits over the lifecycle	109

Figure 6.2: Benefit-cost ratios.....	110
Figure 6.3: LCC component contributions for home and outside charging and parking	110
Figure 6.4: Discount Rate vs. PV of LCC and profit over lifecycle.....	112
Figure 6.5: Lifecycle vs. PV of LCC/km and profit/km over lifecycle	113
Figure 6.6: Battery replacement cycle vs. PV of LCC and profit over lifecycle.....	114
Figure 6.7: Tire replacement cycle vs. e-rickshaw daily distance travelled	115
Figure 6.8: E-rickshaw daily distance travelled vs. PV of LCC and profit over lifecycle ...	116
Figure 6.9: Correlation matrix for e-rickshaw lifecycle cost (LCC) modeling	117

List of Tables

Table 3.1: E-rickshaw route characteristics	27
Table 3.2: E-rickshaw trip characteristics	27
Table 3.3: E-rickshaw operational characteristics	28
Table 3.4: Distribution fitting for e-rickshaw pre-journey waiting time, dwell time, and trip durations.....	30
Table 3.5: Descriptive statistics of e-rickshaw trip duration/km	32
Table 3.6: E-rickshaw operational LOS thresholds	35
Table 4.1: Regressors for EPWT, EDT, and ETD/km modeling	38
Table 4.2: Gene expression programming (GEP) model parameters	41
Table 4.3: Hyperparameters for machine learning regression models.....	42
Table 4.4: Linear modeling results for EPWT prediction.....	44
Table 4.5: Results for EPWT prediction modeling.....	45
Table 4.6: Linear modeling results for EDT prediction.....	47
Table 4.7: Results for EDT prediction modeling	48
Table 4.8: Linear models for ETD/km prediction.....	51
Table 4.9: Results for ETD/km prediction modeling.....	52
Table 5.1: Charging preferences of e-rickshaw drivers in Uttam Nagar	58
Table 5.2: Charging preferences of e-rickshaw drivers in Karol Bagh.....	59
Table 5.3: Comparison between recommended slow/moderate chargers for e-rickshaws	63
Table 5.4: Notations for model formulation	65
Table 5.5: Key parameter values used in modeling purpose	73
Table 5.6: Summary of the optimal results proposed by the stochastic model (Uttam Nagar)	76
Table 5.7: Comparison between charging station revenues for dynamic and base Tariffs (Uttam Nagar).....	80
Table 5.8: Summary of the optimal results proposed by the stochastic model (Karol Bagh)..	89
Table 5.9: Comparison between charging station revenues for dynamic and base Tariffs (Karol Bagh)	93
Table 6.1: Descriptive statistics of e-rickshaw lifecycle cost (LCC) component values.....	104
Table 6.2: Other key parameter values for e-rickshaw LCC and profit estimation	106
Table 6.3: Present values (PV) of LCC/km and Profit/km over the e-rickshaw lifecycle	111

Table 6.4: Regressors for e-rickshaw LCC modeling..... 117

List of Acronyms

AGS	Average gap between stops
AI	Annual income
AKT	Annual kilometers travelled
ANN	Artificial neural network
BCC	Battery charger cost
BD	Boarding density
BDT	Bus dwell time
BRC	Battery replacement cost
BRCY	Battery replacement cycle
BSJ	Boarding at the start of journey
BTI	Buffer time index
CC	Capital cost
CPC	Charging and parking cost
CV	Coefficient of variation
DDT	Daily distance travelled
DNN	Deep neural network
DOW	Day of week
DT	Decision tree
EDT	E-rickshaw dwell time
EPWT	E-rickshaw pre-journey waiting time
ETD	E-rickshaw trip duration
EV	Electric vehicle
FCLM	Flow capturing location-allocation model
FRLM	Flow refueling location model
FS	Fleet size
GA	Genetic algorithm
GAM	Generalized additive model
GEP	Gene expression programming
GMM	Gaussian mixture model
GRNN	Generalized regression neural network
HCC	Home charging and parking cost

HEM	Hybrid ensemble model
INR	Indian rupees
LCC	Lifecycle cost
LOS	Level-of-service
MAPE	Mean absolute percentage error
MCLP	Maximal covering location problem
MedAE	Median absolute error
MI	Misery index
ML	Machine learning
NRMSE	Normalized root mean squared error
NS	Number of intermediate stops
OMC	Operational and maintenance cost
ORP	On-road price
PV	Present value
RF	Random forest
RL	Route length
RV	Resale value
SoC	State of charge
SS	Subsidy
SVR	Support vector regression
TAI	Total annual income
TBRC	Total battery replacement cost
TCO	Total cost of ownership
TDir	Trip direction
TF	Trip frequency
TKT	Total kilometers travelled
TOD	Time of the day
TRC	Tire replacement cost
TRCY	Tire replacement cycle
TTRC	Total tire replacement cost
XGBoost	Extreme gradient boosting