

**AN ASSESSMENT OF THE TRAVEL BEHAVIOUR OF
ELECTRIC CAR USERS AND MARKET DEMAND
ANALYSIS FOR THE ALTERNATIVE FUEL CARS**

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by

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Submitted

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

to the



Indian Institute of Technology Delhi

April 2026

*This thesis is dedicated
To
Mummy and Pappa*

CERTIFICATE

This is to certify that the thesis entitled ‘**AN ASSESSMENT OF THE TRAVEL BEHAVIOUR OF ELECTRIC CAR USERS AND MARKET DEMAND ANALYSIS FOR THE ALTERNATIVE FUEL CARS**’ is being submitted by **Ms. Adsule Poonam Rajaram** to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy. This is a record of the research work and is entirely carried out under my supervision and guidance. The research report presented in this thesis has not been submitted for the award of any other degree or diploma.

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SUMMARY

Over the past few decades, electric vehicles (EVs) have steadily gained significant market share in cities worldwide. This growing interest is primarily driven by increasing concerns over climate change, environmental degradation, and the rapid depletion of natural resources. EVs are known to reduce emissions from road transportation, contribute to long-term cost savings, and make them a sustainable transportation option. Therefore, the market demand for alternative fuel vehicles has been a topic of scientific discourse. Despite their benefits, the worldwide acceptance and use of EVs are limited due to insufficient charging infrastructure, electric vehicle-related constraints, and human ‘barriers’ such as range anxiety. These limitations may influence consumer preferences for alternative fuel vehicles and may alter travel behaviour when using electric vehicles. Therefore, the travel behaviour of EV users and demand modelling analysis for alternative fuel vehicles have become important subjects of research and discussion. Therefore, this thesis focuses on the market demand analysis of alternative fuel cars, followed by an examination of the travel behaviour of E-car users.

In recent years, consumers have had various options for selecting an alternative fuel car. However, each alternative has pros and cons from the consumer’s point of view, which ultimately impact their choices. Past studies on consumer preferences for alternative fuel vehicles have primarily focused on selecting the best option, often overlooking the remaining alternatives. Also, studies on consumer preferences for electric cars (E-cars) have overlooked the heterogeneity that exists in the population, despite consumers having different preferences under the same conditions. Building on the research gaps identified in past studies on consumer preferences for alternative fuel vehicles, this thesis aims to explore consumers’ preferences for alternative fuel cars, considering both their best and worst choices. It also examines the heterogeneity in consumers’ preferences for E-cars. Further, despite the growing interest in the travel behaviour of electric vehicle users, the route choice behaviour considering the charging decision of E-car users has not been explored in detail. While travel behaviour impacts on charging decisions have been explored in earlier studies, those studies have excluded the possibility of shifting to conventional fuel vehicles by E-car users. In addition, the variation in E-car preferences for trip chain types and trip purposes is also unexplored in the travel behaviour literature. Hence, to understand the travel behaviour of E-car users, the thesis examines route choice behaviour for long-distance trips, considering routes connecting Delhi and Agra, India. The thesis also examines the travel and charging preferences of E-car users

who own a conventional-fuel vehicle. Further, it examines how E-car preferences differ between simple and complex trip chains, as well as between work and non-work trips.

To achieve the study objectives, an intercept survey was conducted in Delhi, which included stated preference choices, attitudinal statements, and users' socio-demographic characteristics. The data were collected from New Delhi, South East Delhi and South Delhi, where the density of public charging stations and the frequency of charging incidents are high. The survey was conducted at 20 randomly selected charging stations in the area. The target population includes current E-car owners who have had a minimum of 5 months of experience driving and using electric vehicles and owned at least one conventional-fuel-powered personal vehicle (car or motorcycle), as well as conventional fuel car owners. The survey was carried out in 2023 and implemented in two phases. Phase one addressed the study objectives concerning the market demand analysis of alternative fuel vehicles, while phase two focused on examining the travel behaviour of E-car users. In total, Phase 1 collected responses from 702 individuals, whereas Phase 2 collected data from 526 individuals. The collected responses were analysed using advanced discrete choice models, such as the Nested Logit Integrated Choice and Latent Variable (NL-ICLV) model, the Latent Class Multinomial Logit (LC-MNL) model, and the Best Worst Discrete Choice (BWDC) model, among others.

The consumer preference for alternative fuel cars was analysed using the BWDC model, calculating different parameters for the best and worst choices. Additionally, the correlation between the unobserved attributes for the best and worst choices was examined using a nested structure. Whereas the consumer responses for E-car were used to estimate an LC-MNL model, with class allocation identified based on individuals' income, motorised two-wheeler ownership, the number of cars owned in the past, and attitudinal factors. Additionally, the willingness to pay for the attributes of an Electric Car was calculated. The route choice behaviour of E-car users was analysed using the NL-ICLV model. The sensitivity analysis was conducted for the route attributes. To assess individuals' choices among 'travel according to the tour plan without charging the EV,' 'travel according to the tour plan with charging the EV,' and 'complete the tour by shifting to conventional-fuel vehicles,' an NL-ICLV model was estimated. The variation between simple and complex trip chains, as well as between work and non-work tours, was examined using a segmentation analysis.

From the market demand analysis of alternative fuel cars, the analysis does not find that purchase cost affects decisions regarding battery electric car choices; however, individuals are more likely to select plug-in hybrid electric cars and battery electric cars as the worst options

when the running costs are high. Safety features, such as Advanced Driver-Assistance Systems (ADAS), do not make a battery electric car an attractive choice, perhaps due to the confounding factor of upfront cost, while improvements in vehicular noise make all cars a more attractive option. In the investigation of consumer preferences for E-cars, the latent class multinomial logit model identified two distinct classes of consumers: *Rational consumers* and *Impulsive consumers*, who differ in terms of household income, vehicle ownership, and attitude towards battery information. *Rational consumers* are found to be more sensitive to purchase price than *Impulsive consumers*. In understanding the travel behaviour of E-car users, the study observed that E-car users primarily select a route and then decide to charge at the first charging station within that route. The route choice behaviour considering charging decision is mainly influenced by route characteristics, users' socio-demographic characteristics, and their attitude. Users' range anxious and trip planning attitude impact their route choices. E-car users are more likely to prefer (National Highway 44) NH 44, regardless of the charging decision, compared to the Yamuna Expressway. An increase in the total cost decreases the demand for both routes; however, a charging decision affects the route demand. When higher-income E-car users want to charge their car at the first charging station, they showed a preference for the Yamuna Expressway. Furthermore, the study assesses the travel and charging behaviour of E-car users. The study finds that increased tour distance leads to a preference for a conventional fuel vehicle over an E-car. Besides, participation in a work tour and trip chain complexity positively affect the choice of conventional fuel vehicles. A higher initial State of Charge (SoC) leads to decreased preferences for completing a tour in an E-car with charging and shifting to conventional fuel vehicles. Overall, the study finds that travel behaviour influences charging choices and travel decisions. E-car users still value conventional-fuel vehicles in accomplishing their travel needs if E-car attributes are unfavourable. The study also reveals that the effects of E-car attributes and travel features of E-car decisions vary by the complexity of trip chains and the purpose of tours. The effect of the remaining SoC on the choice of E-cars for a simple trip chain is almost equal for the two SoC levels; however, the coefficient is three times the value at the 40 percent level for the complex trip chain. The utility of an E-car for completing a non-work tour increases with the remaining SoC levels. Older individuals are found to choose E-cars for simple trip chains and for non-work tours. The study concludes that the effects of E-car attributes, travel contexts, and individuals' characteristics vary by the complexity and purposes of trip chains. Overall, the thesis highlights implications for market and travel demand analysis. Findings reveal deeper insights into consumer preferences by considering population

heterogeneity, which aids policymakers and stakeholders in building sustainable transportation systems. Understanding E-car users' travel behaviour supports governments and researchers in developing effective charging infrastructure.

Keywords: Electric cars, Consumer preferences, Travel behaviour, Stated preferences, India

सार

पिछले कुछ दशकों में, इलेक्ट्रिक वाहनों (ईवी) ने दुनिया भर के शहरों में लगातार महत्वपूर्ण बाजार हिस्सेदारी हासिल की है। यह बढ़ती रुचि मुख्य रूप से जलवायु परिवर्तन, पर्यावरणीय क्षरण और प्राकृतिक संसाधनों के तेजी से घटते स्तर को लेकर बढ़ती चिंताओं से प्रेरित है। ईवी सड़क परिवहन से होने वाले उत्सर्जन को कम करने, दीर्घकालिक लागत बचत में योगदान देने और उन्हें एक स्थायी परिवहन विकल्प बनाने के लिए जाने जाते हैं। इसलिए, वैकल्पिक ईंधन वाहनों की बाजार मांग वैज्ञानिक चर्चा का विषय रही है। अपने लाभों के बावजूद, अपर्याप्त चार्जिंग बुनियादी ढांचे, इलेक्ट्रिक वाहनों से संबंधित बाधाओं और रेंज चिंता जैसी मानवीय 'बाधाओं' के कारण ईवी की दुनिया भर में स्वीकृति और उपयोग सीमित है। ये सीमाएँ वैकल्पिक ईंधन वाहनों के लिए उपभोक्ता वरीयताओं को प्रभावित कर सकती हैं और इलेक्ट्रिक वाहनों का उपयोग करते समय यात्रा व्यवहार को बदल सकती हैं। इसलिए, ईवी उपयोगकर्ताओं का यात्रा व्यवहार और वैकल्पिक ईंधन वाहनों के लिए मांग मॉडलिंग विश्लेषण अनुसंधान और चर्चा के महत्वपूर्ण विषय बन गए हैं। इसलिए, यह शोध प्रबंध वैकल्पिक ईंधन कारों की बाजार मांग के विश्लेषण पर केंद्रित है, जिसके बाद ई-कार उपयोगकर्ताओं के यात्रा व्यवहार का परीक्षण किया गया है।

हाल के वर्षों में, उपभोक्ताओं के पास वैकल्पिक ईंधन कार चुनने के कई विकल्प रहे हैं। हालाँकि, उपभोक्ता के दृष्टिकोण से प्रत्येक विकल्प के अपने फायदे और नुकसान हैं, जो अंततः उनकी पसंद को प्रभावित करते हैं। वैकल्पिक ईंधन वाहनों के लिए उपभोक्ता वरीयताओं पर पिछले अध्ययनों ने मुख्य रूप से सर्वोत्तम विकल्प चुनने पर ध्यान केंद्रित किया है, और अक्सर शेष विकल्पों को नज़रअंदाज़ कर दिया है। इसके अलावा, इलेक्ट्रिक कारों (ई-कारों) के लिए उपभोक्ता वरीयताओं पर किए गए अध्ययनों ने जनसंख्या में मौजूद विविधता को नज़रअंदाज़ कर दिया है, जबकि समान परिस्थितियों में उपभोक्ताओं की प्राथमिकताएँ अलग-अलग होती हैं। वैकल्पिक ईंधन वाहनों के लिए उपभोक्ता वरीयताओं पर पिछले अध्ययनों में पहचाने गए शोध अंतरालों के आधार पर, इस शोध प्रबंध का उद्देश्य वैकल्पिक ईंधन कारों के लिए उपभोक्ताओं की प्राथमिकताओं का पता लगाना है, जिसमें उनके सर्वोत्तम और सबसे खराब, दोनों विकल्पों पर विचार किया गया है। यह ई-कारों के लिए उपभोक्ताओं की प्राथमिकताओं में विविधता की भी जाँच करता है। इसके अलावा, इलेक्ट्रिक वाहन उपयोगकर्ताओं के यात्रा व्यवहार में बढ़ती रुचि के बावजूद, ई-कार उपयोगकर्ताओं के चार्जिंग निर्णय को ध्यान में रखते हुए मार्ग चयन व्यवहार का विस्तार से अध्ययन नहीं किया गया है। हालाँकि पहले के अध्ययनों में चार्जिंग निर्णयों पर यात्रा व्यवहार के प्रभावों का पता लगाया गया है, लेकिन उन अध्ययनों ने ई-कार उपयोगकर्ताओं द्वारा पारंपरिक ईंधन

वाहनों पर स्विच करने की संभावना को खारिज कर दिया है। इसके अलावा, यात्रा श्रृंखला के प्रकारों और यात्रा के उद्देश्यों के लिए ई-कार की प्राथमिकताओं में भिन्नता भी यात्रा व्यवहार साहित्य में अभी तक खोजी नहीं गई है। इसलिए, ई-कार उपयोगकर्ताओं के यात्रा व्यवहार को समझने के लिए, यह शोध-प्रबंध दिल्ली और आगरा, भारत को जोड़ने वाले मार्गों पर विचार करते हुए, लंबी दूरी की यात्राओं के लिए मार्ग चयन व्यवहार का परीक्षण करता है। यह शोध-प्रबंध पारंपरिक ईंधन वाले वाहन रखने वाले ई-कार उपयोगकर्ताओं की यात्रा और चार्जिंग प्राथमिकताओं का भी परीक्षण करता है। इसके अलावा, यह इस बात की भी जाँच करता है कि सरल और जटिल यात्रा श्रृंखलाओं के साथ-साथ कार्य और गैर-कार्य यात्राओं के बीच ई-कार की प्राथमिकताएँ कैसे भिन्न होती हैं।

अध्ययन के उद्देश्यों को प्राप्त करने के लिए, दिल्ली में एक इंटरसेप्ट सर्वेक्षण किया गया था, जिसमें बताई गई प्राथमिकताएँ, मनोवृत्ति संबंधी बयान और उपयोगकर्ताओं की सामाजिक-जनसांख्यिकीय विशेषताएँ शामिल थीं। डेटा नई दिल्ली, दक्षिण पूर्व दिल्ली और दक्षिणी दिल्ली से एकत्र किया गया था, जहाँ सार्वजनिक चार्जिंग स्टेशनों का घनत्व और चार्जिंग की घटनाओं की आवृत्ति अधिक है। सर्वेक्षण क्षेत्र में बेतरतीब ढंग से चुने गए 20 चार्जिंग स्टेशनों पर किया गया था। लक्षित आबादी में वर्तमान ई-कार मालिक शामिल हैं, जिनके पास इलेक्ट्रिक वाहन चलाने और उपयोग करने का कम से कम 5 महीने का अनुभव है और उनके पास कम से कम एक पारंपरिक ईंधन से चलने वाला निजी वाहन (कार या मोटरसाइकिल) है, साथ ही पारंपरिक ईंधन कार के मालिक भी हैं। सर्वेक्षण 2023 में किया गया और दो चरणों में लागू किया गया। चरण एक ने वैकल्पिक ईंधन वाहनों की बाजार मांग के विश्लेषण से संबंधित अध्ययन उद्देश्यों को संबोधित किया एकत्रित प्रतिक्रियाओं का विश्लेषण उन्नत असतत विकल्प मॉडल, जैसे नेस्टेड लॉगिट इंटीग्रेटेड चॉइस एंड लेटेंट वेरिएबल (एनएल-आईसीएलवी) मॉडल, लेटेंट क्लास मल्टीनोमियल लॉगिट (एलसी-एमएनएल) मॉडल, और बेस्ट वर्स्ट डिस्क्रीट चॉइस (बीडब्ल्यूडीसी) मॉडल, आदि का उपयोग करके किया गया।

वैकल्पिक ईंधन कारों के लिए उपभोक्ता वरीयता का विश्लेषण बीडब्ल्यूडीसी मॉडल का उपयोग करके किया गया, जिसमें सर्वोत्तम और सबसे खराब विकल्पों के लिए विभिन्न मापदंडों की गणना की गई। इसके अतिरिक्त, सर्वोत्तम और सबसे खराब विकल्पों के लिए अप्रत्याशित विशेषताओं के बीच सहसंबंध को नेस्टेड संरचना का उपयोग करके जांचा गया। जबकि ई-कार के लिए उपभोक्ता प्रतिक्रियाओं का उपयोग एलसी-एमएनएल मॉडल का अनुमान लगाने के लिए किया गया था, जिसमें व्यक्तियों की आय, मोटर चालित दोपहिया वाहन स्वामित्व, अतीत में स्वामित्व वाली कारों की संख्या और मनोवृत्ति कारकों के आधार पर वर्ग आवंटन की पहचान की गई थी 'ईवी को चार्ज किए बिना टूर प्लान के अनुसार यात्रा करना', 'ईवी को चार्ज करके टूर प्लान के अनुसार यात्रा करना', और 'पारंपरिक ईंधन वाले वाहनों में

बदलाव करके टूर पूरा करना' के बीच व्यक्तियों के विकल्पों का आकलन करने के लिए, एक एनएल-आईसीएलवी मॉडल का अनुमान लगाया गया। सरल और जटिल यात्रा श्रृंखलाओं के साथ-साथ कार्य और गैर-कार्य यात्राओं के बीच अंतर की जाँच एक विभाजन विश्लेषण का उपयोग करके की गई।

वैकल्पिक ईंधन कारों की बाजार मांग के विश्लेषण से, विश्लेषण यह नहीं पाता है कि खरीद लागत बैटरी इलेक्ट्रिक कार विकल्पों के बारे में निर्णयों को प्रभावित करती है; हालांकि, जब परिचालन लागत अधिक होती है तो लोग प्लग-इन हाइब्रिड इलेक्ट्रिक कारों और बैटरी इलेक्ट्रिक कारों को सबसे खराब विकल्प के रूप में चुनने की अधिक संभावना रखते हैं। उन्नत चालक सहायता प्रणाली (ADAS) जैसी सुरक्षा विशेषताएँ, बैटरी इलेक्ट्रिक कार को एक आकर्षक विकल्प नहीं बनाती हैं, शायद शुरुआती लागत के भ्रामक कारक के कारण, जबकि वाहन के शोर में सुधार सभी कारों को अधिक आकर्षक विकल्प बनाता है। ई-कारों के लिए उपभोक्ता वरीयताओं की जांच में, लेटेंट क्लास मल्टीनोमियल लॉगिट मॉडल ने उपभोक्ताओं के दो अलग-अलग वर्गों की पहचान की: तर्कसंगत उपभोक्ता और आवेगी उपभोक्ता चार्जिंग निर्णय को ध्यान में रखते हुए मार्ग चयन व्यवहार मुख्यतः मार्ग की विशेषताओं, उपयोगकर्ताओं की सामाजिक-जनसांख्यिकीय विशेषताओं और उनके दृष्टिकोण से प्रभावित होता है। उपयोगकर्ताओं की दूरी की चिंता और यात्रा नियोजन का दृष्टिकोण उनके मार्ग विकल्पों को प्रभावित करता है। चार्जिंग निर्णय चाहे जो भी हो, ई-कार उपयोगकर्ता एनएच 44 को पसंद करने की अधिक संभावना रखते हैं। ई-कार उपयोगकर्ताओं की लागत संवेदनशीलता पहले चार्जिंग स्टेशन पर उनके चार्जिंग निर्णय पर निर्भर करती है। जब उच्च आय वाले ई-कार उपयोगकर्ता अपनी कार को पहले चार्जिंग स्टेशन पर चार्ज करना चाहते हैं, तो वे यमुना एक्सप्रेसवे को प्राथमिकता देते हैं। इसके अलावा, अध्ययन ई-कार उपयोगकर्ताओं की यात्रा और चार्जिंग व्यवहार का आकलन करता है। अध्ययन में पाया गया है कि यात्रा की बढ़ी हुई दूरी ई-कार की तुलना में पारंपरिक ईंधन वाले वाहन को प्राथमिकता देती है। इसके अलावा, कार्य यात्रा में भागीदारी और यात्रा श्रृंखला की जटिलता पारंपरिक ईंधन वाले वाहनों के चयन को सकारात्मक रूप से प्रभावित करती है। उच्च प्रारंभिक चार्ज स्थिति (SoC) के कारण चार्जिंग के साथ ई-कार में यात्रा पूरी करने की प्राथमिकता कम हो जाती है और पारंपरिक ईंधन वाले वाहनों पर स्विच करने की प्रवृत्ति बढ़ जाती है। कुल मिलाकर, अध्ययन में पाया गया है कि यात्रा व्यवहार चार्जिंग विकल्पों और यात्रा निर्णयों को प्रभावित करता है। यदि ई-कार विशेषताएँ प्रतिकूल हैं, तो भी ई-कार उपयोगकर्ता अपनी यात्रा पैटर्न को पूरा करने में पारंपरिक ईंधन वाले वाहनों को महत्व देते हैं। अध्ययन यह भी दर्शाता है कि ई-कार के गुणों और ई-कार निर्णयों की यात्रा विशेषताओं का प्रभाव यात्रा श्रृंखलाओं की जटिलता और यात्राओं के उद्देश्य के अनुसार अलग-अलग होता है। एक साधारण यात्रा श्रृंखला के लिए ई-कारों के चयन पर शेष SoC का प्रभाव दोनों SoC स्तरों के लिए लगभग समान होता है; हालाँकि, जटिल यात्रा श्रृंखला के

लिए गुणांक 40 प्रतिशत स्तर के मान का तीन गुना होता है। गैर-कार्य यात्रा को पूरा करने के लिए ई-कार की उपयोगिता शेष SoC स्तरों के साथ बढ़ती है। वृद्ध व्यक्ति साधारण यात्रा श्रृंखलाओं और गैर-कार्य यात्राओं के लिए ई-कार चुनते पाए गए हैं। अध्ययन का निष्कर्ष है कि ई-कार के गुणों, यात्रा संदर्भों और व्यक्तियों की विशेषताओं का प्रभाव यात्रा श्रृंखलाओं की जटिलता और उद्देश्यों के अनुसार अलग-अलग होता है। कुल मिलाकर, यह शोध प्रबंध बाजार और यात्रा मांग विश्लेषण के निहितार्थों पर प्रकाश डालता है। निष्कर्ष जनसंख्या विविधता पर विचार करके उपभोक्ता वरीयताओं के बारे में गहरी अंतर्दृष्टि प्रकट करते हैं, जो नीति निर्माताओं और हितधारकों को स्थायी परिवहन प्रणालियों के निर्माण में सहायता करता है। ई-कार उपयोगकर्ताओं के यात्रा व्यवहार को समझना सरकारों और शोधकर्ताओं को प्रभावी चार्जिंग अवसंरचना विकसित करने में सहायता करता है।

कीवर्ड: इलेक्ट्रिक कारें, उपभोक्ता प्राथमिकताएं, यात्रा व्यवहार, घोषित प्राथमिकताएं, भारत

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ABBREVIATIONS AND NOTATIONS

AC	Air Conditioner
ABS	Automated Braking System
AFV	Alternative Fuel Vehicle
AIC	Akaike Information Criterion
BEC	Battery Electric Car
BEV	Battery Electric Vehicles
BIC	Bayesian Information Criterion
BV	Biofuel Vehicle
BW	Best-Worst
BWDC	Best-Worst Discrete Choice
CFC	Conventional Fuel Car
CFI	Comparative Fit Index
CNG	Compressed Natural Gas
CV	Conventional vehicle
DCM	Discrete Choice Model
DV	Diesel Vehicle
E-car	Electric Car
EV	Electric Vehicle
FCV	Fuel cell vehicle
GV	Gasoline Vehicle
HFCE	Hydrogen Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicles
ICLV	Integrated Choice and Latent Variable
IIA	Independence of Irrelevant Alternatives
IMR	Inverse Mills Ratio
LC	Latent Class
LC-MNL	Latent Class Multinomial Logit
LL	Log-Likelihood
LPG	Liquefied Petroleum Gas
LR	Likelihood Ratio
MDCEV	Multiple Discrete-Continuous Extreme Value

MIMIC	Multiple-Indicator Multiple-Cause
MNL	Multinomial Logit
MNR	Multinomial logit regression
MXL	Mixed logit
NGV	Natural Gas Vehicle
NFI	Normed Fit Index
NH	National Highway
NL	Nested Logit
NL-ICLV	Nested Logit Integrated Choice and Latent Variable
OL	Ordered Logit
PCA	Principal Component Analysis
PEV	Plug-in Electric Vehicles
PHEC	Plug-in Hybrid Electric Car
PHEV	Plug-in Hybrid Electric Vehicles
PV	Petrol Vehicle
RMSEA	Root Mean Square Of Approximation
SC	Stated Choice
SEM	Structural Equation Modeling
SoC	State of Charge
SP	Stated Preference
TRA	Theory of Reasoned Action
TW	Two-Wheeler
VKT	Vehicle Kilometer Traveled
WTP	Willingness to Pay
df	Degree of Freedom
EUR	Euro
INR	Indian Rupee
Kw	Kilowatt
km	Kilometer
LL	Log-likelihood
USD	United States Dollar