



CASE STUDY · LEH, LADAKH

Non-Urban E-Bus Pilot Operations, Data Analysis & Inference

Exploring the Role of the Private Sector as a Catalyst for Accelerating the Transition to E-Buses in India

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SUPPORTED BY

Shakti Sustainable Energy Foundation

KNOWLEDGE PARTNERS

Council on Energy, Environment and Water (CEEW)
Institute for Transportation and Development Policy
(ITDP) India

TECHNICAL PARTNERS

RITES Ltd.
Indian Institute of Technology Delhi

INDUSTRY PARTNER

PMI Electro Mobility Solutions (PMI Foton)

SUGGESTED CITATION

Nezamuddin, N., Gandhi, S., Ganguly, S., Singh, S., & Gola, K. (2026). *Non-urban e-bus pilot operations, data analysis & inference: Case study – Leh, Ladakh*. SGArchitects, New Delhi.

About this publication. This document is produced by SGArchitects, New Delhi, and is to be read in conjunction with the interim report of the study (September 2022). Pilot operations and data collection were conducted in October 2022; the analysis was completed in December 2022. The authors have taken all reasonable care to ensure that the contents do not violate any existing copyright or other intellectual property rights of any person. If any source has been inadvertently missed or any copyright infringed, please notify us in writing for corrective action. You may also contact us for technical clarifications.

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Contents

Executive Summary	8
1 Background	9
1.1 The study	9
1.2 Study area: Leh, Ladakh	10
1.3 The e-bus fleet in Leh	10
1.4 Pilot routes and scope	11
2 Pilot Route Finalisation	14
3 E-Bus Pilot Operations and Data Collection	15
3.1 Instrumentation and data recording	15
3.2 Pilot observations and data	18
4 Data Analysis	21
4.1 Route profiles	22
4.2 Operational data analysis	25
4.3 Regression models for operational data	27
4.4 Charging analysis	28
5 Key Findings and Way Forward	30
5.1 Key findings	30
5.2 Limitations and future scope	30
Bibliography	31
Annexure A: Pilot Vehicle and Charger Specifications	32

List of Figures

Figure 1	The PMI Foton 8.5 m e-bus and DC fast charger used for the pilot in Leh	11
Figure 2	Regional bus route network around Leh, on which the pilot routes lie	12
Figure 3	Pilot routes mapped on Google Earth: Leh – Alchi and Leh – Spituk	13
Figure 4	Pilot operations in Ladakh: altimeter-derived elevation trace and the field team	17
Figure 5	Instruments used for data recording	16
Figure 6	Installing instruments in the pilot e-bus	18
Figure 7	Charging data collection at the Leh charging station	20
Figure 8	Route profile, Leh – Alchi	22
Figure 9	Route profile, Leh – Upshi	23
Figure 10	Route profiles, Leh – Stakna and Chuchot – Leh	23
Figure 11	Route profile, Leh – Spituk	24
Figure 12	Route profile, Leh – Phyang	24
Figure 13	Route profile, Leh – Pathar Sahib	25
Figure 14	Change in SoC (%) per km against gradient, downhill segments	25
Figure 15	Change in SoC (%) per km against gradient, uphill segments	26
Figure 16	Change in SoC (%) per km against gradient, all segments	26
Figure 17	Charge rate against battery SoC for three charging sessions	28

List of Tables

Table 1	Criteria used to shortlist routes for pilot operations	14
Table 2	Pilot operation routes in the UT of Ladakh (October 2022)	15
Table 3	Instruments used for data collection	16
Table 4	Data collection tasks for pilot operations	18
Table 5	Pilot output summary: start and end readings for each trip leg	19
Table 6	Charging data summary	19
Table 7	Summary of route data	21
Table 8	Estimated time to charge across SoC ranges	29
Table 9	E-bus specifications (PMI Foton, Leh fleet)	32
Table 10	Charger specifications (Leh depot)	32

Acknowledgements

The authors are grateful to **Shakti Sustainable Energy Foundation** for supporting this study.

We thank the institutional, technical and knowledge partners and the many individuals who helped make this document possible. We are grateful to the **Administration of the Union Territory of Ladakh** and to **RITES Ltd.** for the opportunity to conduct this study of electric bus operations in hilly terrain, and for technical inputs and guidance in its development. We especially thank Mr. Swagat Biswas, IAS, Transport Secretary, UT of Ladakh, and the **Jammu & Kashmir State Road Transport Corporation (JKSRTC)** for their valuable support in conducting the pilot operations.

We thank our industry partner **PMI Electro Mobility Solutions (PMI Foton)** for providing the buses on which data was collected, without which this study would not have been possible, and for information, data, technical support and guidance. We also thank the **Ladakh Bus Operators Co-operative Ltd. (LBOC)**, Leh, for their inputs.

We especially acknowledge Ms. Priyanka Kataria and Mr. Konchok Tashi of RITES Ltd., and Mr. Sumit Singh and Mr. Ashish of PMI Foton, for their support in conducting the pilot operations and data collection despite challenging weather conditions.

Abbreviations

BMS	Battery management system
CC	Constant current (charging phase)
CEEW	Council on Energy, Environment and Water
CV	Constant voltage (charging phase)
DoD	Depth of discharge
e-bus	Battery-electric bus
GPS	Global Positioning System
HVAC	Heating, ventilation and air-conditioning
IIT Delhi	Indian Institute of Technology Delhi
ITDP	Institute for Transportation and Development Policy
JKSRTC	Jammu & Kashmir State Road Transport Corporation
LBOC	Ladakh Bus Operators Co-operative Ltd.
OEM	Original equipment manufacturer
RPM	Revolutions per minute
SGA	SGArchitects
SIDCO	Sindhu Infrastructure Development Corporation
SoC	State of charge
STA	State Transport Authority
STU	State Transport Undertaking
UT	Union Territory

Executive Summary

Leh, at about 3,500 m above sea level, combines steep and undulating terrain with one of the harshest climates of any Indian town. This publication reports a pilot of battery-electric buses (e-buses) operated on non-urban routes radiating from Leh in October 2022, and the analysis of the data collected, to understand how terrain, passenger load and temperature affect the energy use and charging of e-buses in such conditions.

The pilot forms part of the study “Exploring the role of the private sector as a catalyst for accelerating transition to e-buses in India”, undertaken by SGArchitects (SGA) with knowledge partners CEEW and ITDP India and supported by Shakti Sustainable Energy Foundation. Field operations used the 8.5 m PMI Foton e-buses procured by the Ladakh Administration, with drivers from JKSRRTC and support from RITES Ltd. and PMI. Data was recorded by the SGA team using on-board and add-on instruments, and analysed by the Civil Engineering Department, IIT Delhi.

7 routes 12 trip legs and close to 400 km of e-bus operation recorded	0.33 % SoC/km Battery discharge on flat terrain with no passenger load (driver only)	+0.165 % SoC/km Additional discharge for every 1% of uphill gradient
≈ -2.5 % grade Downhill gradient at which regeneration offsets consumption	81–86 % SoC Point at which charging switches from constant current to constant voltage	1.64–1.77 %/min Charge rate in the constant-current phase, falling to ~0.2 %/min above 90% SoC

Key findings

- **Terrain is the dominant factor.** Gradient explains most of the variation in energy consumption. Average route gradients hide this effect: on undulating routes such as Leh-Alchi, consumption must be estimated segment by segment rather than from the average slope.
- **Regeneration is substantial in the mountains.** On steep downhill sections (around -2.4% to -3% gradient) energy recovered through regenerative braking equals or exceeds consumption, and the state of charge (SoC) can rise.
- **Passenger load matters, but less.** Each passenger of average weight adds about 0.02% SoC/km; within the observed load range (260–760 kg) this does not materially change estimates of consumption.
- **Plan charging around the CC-CV switch.** Charging slows sharply above 81–86% SoC. A practical ceiling of 90% SoC for opportunity charging, and 80% where layover time must be minimised, keeps charging efficient and protects battery health.
- **Winter data is needed.** The pilot captured autumn temperatures only (about 3–22 °C). A winter pilot, and more data across passenger loads, would sharpen predictions and policy recommendations.

01

Background

1.1 The study

A study titled *“Exploring the role of the private sector as catalyst for accelerating transitions of electric buses (e-buses) in India”* has been undertaken as a joint effort by SGArchitects (SGA) and the knowledge partners of the study, the Council on Energy, Environment and Water (CEEW) and the Institute for Transportation and Development Policy (ITDP) India. The study aims to help iron out bottlenecks in accelerating the electrification of buses operating under State Transport Undertakings (STUs) and State Transport Authority (STA) permits on non-urban routes, and to remove doubts on the viability of such vehicles, for a win-win outcome for both industry and government. The study covered five states and union territories: Kerala, the Union Territory (UT) of Ladakh, Madhya Pradesh, Tamil Nadu and Uttar Pradesh.

The study was undertaken in three stages:

Stage 1 - Gaps and bottlenecks. Interactions with operators to identify gaps and bottlenecks in the electrification of stage-carriage buses on non-urban routes, especially by private operators.

Stage 2 - Viability. A deep dive into the viability gap of operating e-buses on such routes, including data collection on specific routes, business models for different e-bus models and pilots on select routes to derive findings on bus performance.

Stage 3 - Policy. Consolidating these findings to identify policy gaps and develop recommendations that help achieve the aim of the study.

This publication presents work undertaken in the second stage, focusing on pilot e-bus operations, data collection and analysis in Leh. It should be read together with the study’s interim report (SGArchitects, 2022b).

1.2 Study area: Leh, Ladakh

Leh, the capital of the UT of Ladakh, is located at an altitude of about 3,500 m (11,483 ft) along a northern tributary of the Indus River in the Leh district of Ladakh (Dame et al., 2019). It is characterised by highly undulating terrain with frequent folds and troughs across the region, and a severe climate in which temperatures range from about 35 °C in summer to –28 °C in winter (Chevuturi et al., 2018).

Buses are an important mode of mobility in Ladakh for both residents and the large number of tourists the region attracts. Services have historically been provided by the Jammu & Kashmir State Road Transport Corporation (JKSRTC) and by private operators organised under a cooperative, and operations are in the process of being transferred to the Ladakh Administration's Sindhu Infrastructure Development Corporation (SIDCO) (SGArchitects, 2022a).

Operating e-buses under such geographic and climatic conditions is a significant challenge. Charging rates and energy consumption become difficult to predict, with direct consequences for operational planning. A detailed study is therefore required to understand the impact of terrain and weather on daily e-bus operation. This study examined e-bus operation on select routes around Leh to understand the factors that influence the state of charge (SoC) of an e-bus and whether e-buses can be operated reliably in these conditions.

1.3 The e-bus fleet in Leh

The Ladakh Administration has procured ten 8.5 m air-conditioned e-buses from PMI Electro Mobility Solutions (PMI Foton), together with DC fast chargers installed in Leh (**Figure 1**). Each bus carries 30 seated and 14 standing passengers and is fitted with a 150 kWh battery. The manufacturer recommends operating within a 20–100% SoC window. Key specifications as reported by the manufacturer and operators are summarised in Annexure A. These buses were used for all pilot runs, with drivers provided by JKSRTC.



(a) PMI Foton 8.5 m e-bus



(b) DC fast charger

Figure 1 The PMI Foton 8.5 m e-bus and DC fast charger used for the pilot in Leh

Source: SGArchitects (2022a); PMI Electro Mobility Solutions

1.4 Pilot routes and scope

The pilot was conducted on seven routes originating from Leh. These lie on the regional bus corridors radiating from Leh shown in **Figure 2**: Alchi, Phyang and Pathar Sahib on the Leh-Kargil/Alchi corridor to the west, Spituk on the urban route to the south-west, and Upshi, Stakna and Chuchot on the Leh-Nyoma corridor to the south-east. Two of the pilot routes, Leh-Alchi and Leh-Spituk, are mapped in detail in **Figure 3**. Five were round-trip routes (Leh to Alchi, Upshi, Spituk, Phyang and Pathar Sahib, and back), totalling ten trips; the remaining two were one-way circular routes (Leh-Stakna-Leh and Leh-Chuchot-Leh). The scope of analysis covered:

- the impact of terrain and loading on SoC and rate of discharge;
- the impact of ambient temperature on SoC and rate of discharge; and
- the impact of ambient temperature on charger efficiency.

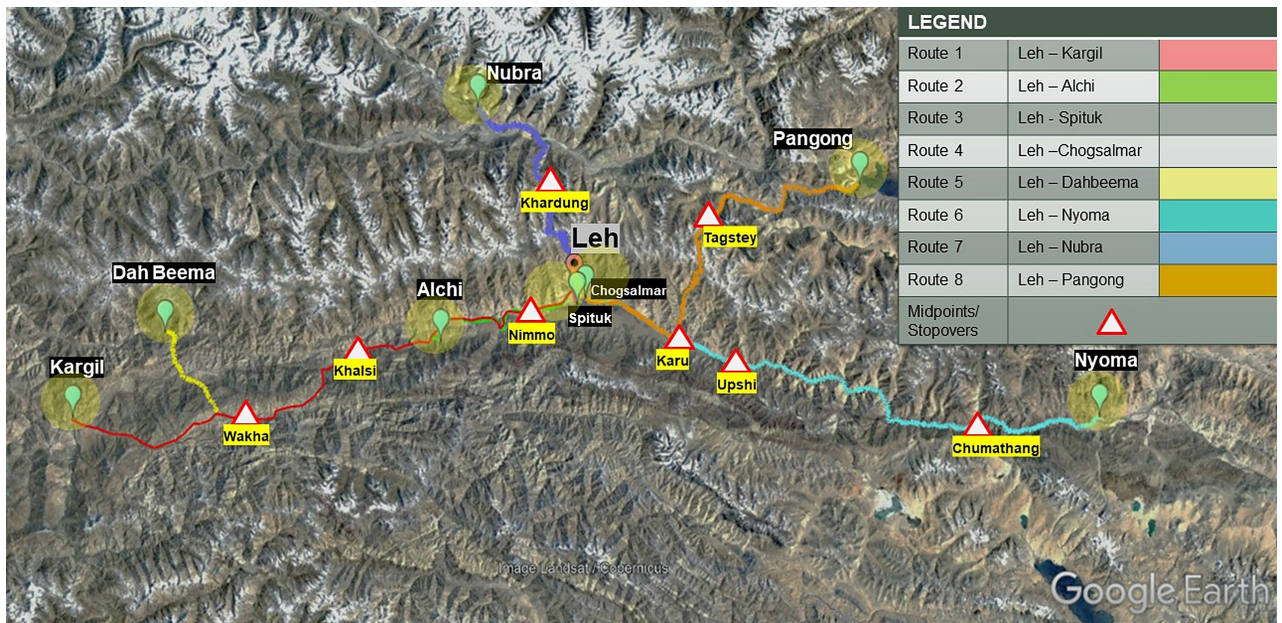
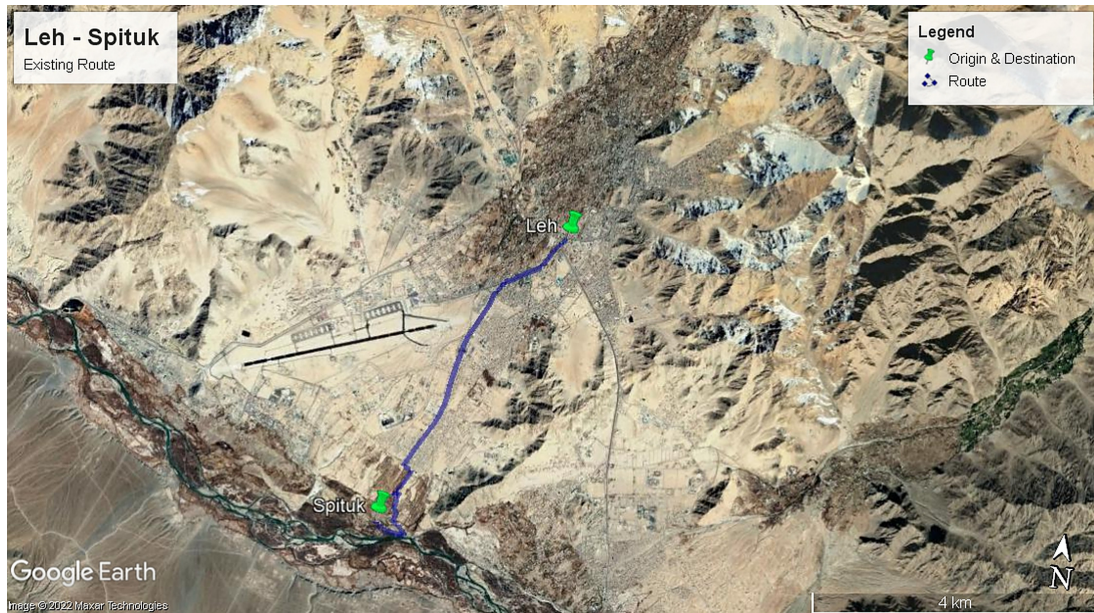


Figure 2 Regional bus route network around Leh, on which the pilot routes lie

Source: SGArchitects (2022a); base imagery © Google Earth, Landsat / Copernicus



(a) Leh – Alchi, with stop-over at Nimmo (scale bar: 20 km)



(b) Leh – Spitik (scale bar: 4 km)

Figure 3 Pilot routes mapped on Google Earth: Leh – Alchi and Leh – Spitik

Source: SGArchitects (2022a); base imagery © Google Earth, Maxar Technologies, CNES / Airbus

02

Pilot Route Finalisation

The objective of the pilot was to validate the claims and data provided by the original equipment manufacturer (OEM) and to refine the operational plan for the selected routes based on the findings. Route-selection criteria were developed, with inputs from stakeholders, to identify the routes best suited for pilot implementation (**Table 1**).

Table 1 Criteria used to shortlist routes for pilot operations

Criterion	What it indicates	Scoring
Total passenger trips catered in a day, or earning per kilometre	Earning potential of the route; the two indicators were weighted together	Ordinal scale from 5 (very high) to 1 (very low)
Total vehicle-km operated in a day	Scale of operations	Ordinal scale from 5 (very high) to 1 (very low)
Total number of buses deployed on the route (up and down)	Fleet requirement	Ordinal scale from 5 (very high) to 1 (very low)
Overlapping routes	Possibility of sharing en-route charging infrastructure	5 if one or more charging stations are shared; 1 if none (excluding the origin)
Length of the route	Need for charging infrastructure en route or at destination	5 if none needed beyond the origin; 3 if one needed; 1 if two or more needed (including destination)

On this basis, routes were shortlisted and business and operational plans were developed. Online and in-person meetings were then held in all five geographies to vet and finalise these plans and initiate pilot demonstrations. Following up with the concerned authorities for permissions, the project team received approval to conduct pilot operations in the UT of Ladakh; discussions for pilots in the other geographies were ongoing at the time of reporting. The Ladakh pilot is described in the following chapters.

03

E-Bus Pilot Operations and Data Collection

The project team conducted e-bus pilot operations on seven routes in the UT of Ladakh in two phases, collecting data for close to 400 km of operation. The pilots were conducted with the support of RITES Ltd., which was engaged by the Ladakh Administration to prepare a Transport Master Plan for the UT. Active assistance was provided by PMI Foton, JKSRTC and the Ladakh Motor Garage (responsible for maintenance and charging of the buses). Data was collected by the project team through on-board instruments and analysed by the Civil Engineering Department, IIT Delhi.

Because e-bus charging infrastructure was available only in Leh, each pilot run had to be completed on a single charge, which governed the choice of routes. The routes operated are listed in [Table 2](#).

Table 2 Pilot operation routes in the UT of Ladakh (October 2022)

No.	Route	Distance (km)	Date	Timing	Type
1	Leh – Alchi	69.38	7 Oct 2022	11:03 am – 3:02 pm	Two-way
2	Leh – Upshi	48.62	10 Oct 2022	2:26 pm – 5:28 pm	Two-way
3	Leh – Stakna	27.00	18 Oct 2022	11:00 am – 11:38 am	One-way
4	Chuchot – Leh	21.00	18 Oct 2022	11:55 am – 12:30 pm	One-way
5	Leh – Spituk	11.00	18 Oct 2022	4:20 pm – 5:35 pm	Two-way
6	Leh – Phyang	19.00	19 Oct 2022	2:12 pm – 5:12 pm	Two-way
7	Leh – Pathar Sahib	25.00	20 Oct 2022	10:40 am – 12:05 pm	Two-way

Source: SGArchitects pilot field observations, October 2022

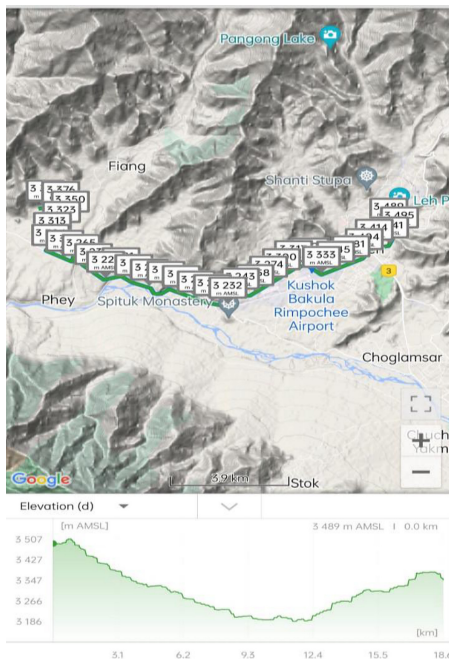
3.1 Instrumentation and data recording

A wide range of parameters is recorded by the bus's on-board battery management system (BMS); however, this data was not available to the project team in a usable format. The team therefore adopted observation-based data collection from the charger display, the existing on-board instrument cluster and additional instruments installed in the bus. Multiple data points ([Table 3](#)) were recorded to measure the effect of altitude, temperature, loading and distance on e-bus performance.

Data was collected in two parts: during pilot operations while the battery was discharging, and at the charger while buses were being charged. Charging observations included elapsed time, SoC, charging voltage and current, and battery temperature. The on-board instrument cluster displays SoC, voltage, battery temperature and other parameters. External instruments comprised a video camera recording the dashboard continuously, a mobile phone camera, an ambient temperature sensor and an altimeter.

Table 3 Instruments used for data collection

Instrument and function	Type	Data collected
Driver dashboard and instrument cluster – displays BMS and vehicle information such as speed and RPM	Pre-existing, fixed in the bus	Date and time, odometer reading, motor-controller and motor temperature (°C), low-voltage system voltage (V) and current (A), battery total voltage (V) and current (A), maximum and minimum cell voltage (V), maximum and minimum battery temperature (°C), RPM, speed (km/h) and SoC (%)
Charger display	Pre-existing, fixed in the charger	SoC, charging voltage, current and battery temperature
Mobile phone camera – geo-tagged images of the dashboard and external instruments every 5 minutes	External, manually operated	Geo-tagged images of the dashboard; latitude, longitude and altitude; date and time
Thermo-hygrometer with extendable sensor – ambient readings in the bus (every 5 min) and at the charger (every minute), captured through geo-tagged photographs	External	Ambient temperature and relative humidity in the bus and at the charger
Altimeter mounted on top of the dashboard	External	Altitude
Video camera mounted in front of the dashboard (attached to the steering column)	External	Continuous video of the dashboard and altimeter
Weighing scale for all occupants of the bus	External	Occupant weight, recorded on a form
Mobile phone camera at the charger, every minute	External	Geo-tagged images of the charger display



(a) Geo-tagged elevation trace, Leh – Phyang

(b) Field team with the pilot e-bus at Leh

Figure 4 Pilot operations in Ladakh: altimeter-derived elevation trace and the field team

Source: SGArchitects; elevation trace extracted using a freely available altimeter app

A sequential, step-by-step process was defined for data collection and recording (**Table 4**). The camera was positioned and secured with mounts so that it remained focused on the dashboard and captured clear readings throughout the trip. The altimeter was fixed close to the dashboard so that the camera could capture both displays in the same frame. The placement of instruments is shown in **Figure 5** and **Figure 6**.



(a) Digital thermo-hygrometer



(b) Dashboard with altimeter and video camera

Figure 5 Instruments used for data recording

Source: SGArchitects pilot field observations, October 2022

Table 4 Data collection tasks for pilot operations

No.	Task
1	Collect secondary data on bus and charger details and performance specifications (battery size, SoC, mileage, etc.) from OEMs and operators.
2	Seek prior permissions and approvals from operators and the concerned government authorities for conducting pilot runs.
3	Collect secondary information on routes (length, terrain, demand, etc.) and finalise trial routes based on route-evaluation analysis and discussions with operators and OEMs.
4	Identify equipment requirements and ensure the team is trained to use the instruments.
5	Develop a data collection checklist and design forms for any specific data to be collected.
6	Prepare a workforce allocation plan with assigned tasks.
7	Fix gadgets and instruments in the bus to collect the required data during the pilot.
8	Capture images of the instrument cluster or record observations at periodic intervals during bus operation.
9	Capture images of the charger display or record observations at periodic intervals during charging.
10	Record, store and safely keep all data, including downloading camera/video files and transcribing observations from photographs, video and survey forms (passenger weight) into spreadsheets.



(a) Fixing the camera and altimeter



(b) Fixing the external temperature probe



(c) Driver cabin with instruments in place

Figure 6 Installing instruments in the pilot e-bus

Source: SGArchitects pilot field observations, October 2022

3.2 Pilot observations and data

Observations captured during data collection were manually digitised and recorded in spreadsheets. Data from bus operations comprised SoC readings throughout each route, temperature, altitude, GPS position (latitude and longitude), distance travelled, trip time, occupancy and the weight of occupants. A summary of all twelve trip legs is presented in **Table 5**.

Table 5 Pilot output summary: start and end readings for each trip leg

No.	Trip leg	Start End	Passenger weight (kg) start / end	SoC (%) start → end	SoC used (%)	Altitude (m) start / end	Ambient temp. (°C) start / end
1	Leh → Alchi	11:03 am 12:53 pm	415 / 415	99 → 76	23	3,407 / 3,087	16.9 / 16.9
2	Alchi → Leh	1:19 pm 3:02 pm	415 / 415	76 → 46	30	3,088 / 3,443	13.7 / 13.7
3	Leh → Upshi	2:26 pm 3:34 pm	760 / 334	70 → 51	19	3,447 / 3,398	21.9 / 14.6
4	Upshi → Leh	4:09 pm 5:28 pm	334 / 334	51 → 23	28	3,398 / 3,433	14.4 / 11.4
5	Leh → Stakna	11:00 am 11:38 am	264 / 264	97 → 86	11	3,382 / 3,208	9.3 / 7.4
6	Chuchot → Leh	11:55 am 12:30 pm	264 / 264	86 → 76	10	3,208 / 3,380	7.7 / 9.7
7	Leh → Spituk	4:20 pm 5:01 pm	1,200 / 240	75 → 74	1	3,381 / 3,132	4.9 / 5.1
8	Spituk → Leh	5:10 pm 5:35 pm	480 / 480	74 → 65	9	3,132 / 3,381	5.1 / 3.1
9	Leh → Phyang	2:12 pm 2:45 pm	1,277 / 1,277	60 → 54	6	3,403 / 3,303	11.9 / 15.5
10	Phyang → Leh	4:40 pm 5:12 pm	1,277 / 1,277	54 → 42	12	3,303 / 3,435	14.5 / 6.4
11	Leh → Pathar Sahib	10:40 am 11:15 am	293 / 293	56 → 45	11	3,419 / 3,460	15.6 / 10.0
12	Pathar Sahib → Leh	11:30 am 12:05 pm	293 / 293	45 → 36	9	3,461 / 3,402	10.9 / 11.8

Source: SGArchitects pilot field observations, October 2022. "SoC used" is calculated as start SoC minus end SoC.

To capture charging data, one designated team member recorded readings from the charger display every minute (**Figure 7**). Three charging sessions were recorded (**Table 6**).

Table 6 Charging data summary

Date	Starting SoC (%)	End SoC (%)	Duration (min)
12 Oct 2022	30	85	34.7
12 Oct 2022	76	99	21.0
21 Oct 2022	43	99	47.6

Source: SGArchitects pilot field observations, October 2022



(a) Recording charger readings



(b) Charger display panel

Figure 7 Charging data collection at the Leh charging station

Source: SGArchitects pilot field observations, October 2022

04

Data Analysis

This chapter presents the analysis, undertaken by the Civil Engineering Department, IIT Delhi, of the data collected during the pilots. It examines the effect of topography, loading and ambient temperature on the SoC / depth of discharge (DoD) and rate of discharge of the battery, and the effect of ambient temperature on charging. The analysis covers all seven routes and the three recorded charging sessions.

Terrain, temperature, loading (passengers and luggage), driving conditions and auxiliary loads such as heating, ventilation and air-conditioning (HVAC) are key factors in estimating the energy consumption of an e-bus. In non-urban operation, driving conditions (stop-start traffic) are not likely to be a significant factor. However, energy can be regenerated if the driver decelerates slowly and steadily from a higher speed. The length and altitude details of the trips analysed are presented in **Table 7**.

Table 7 Summary of route data

No.	Trip leg	Length (km)	Travel time (min)	Altitude difference (m)
1	Leh → Alchi	67	110	-320
2	Alchi → Leh	67	103	+354
3	Leh → Upshi	48.6	68	-49
4	Upshi → Leh	48.6	78	+49
5	Leh → Stakna	27	38	-174
6	Chuchot → Leh	21	38	+171
7	Leh → Spituk	11	41	-249
8	Spituk → Leh	11	25	+249
9	Leh → Phyang	19	33	-100
10	Phyang → Leh	18	32	+111
11	Leh → Pathar Sahib	25	35	+49
12	Pathar Sahib → Leh	25	35	-59

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

4.1 Route profiles

Route profiles were developed from altimeter and trip-distance readings captured in dashboard images and on-board instruments. Gradients marked on each profile are the average gradients of the corresponding segments; positive values indicate uphill and negative values downhill travel.

Leh - Alchi. The distance between Leh and Alchi is about 67 km and the terrain is highly undulating (**Figure 8**). Although the average gradient of the route is about 2.8% downhill, this does not show the full picture: the route comprises several uphill and downhill segments with gradients ranging from 1.7% to 3.6%. Estimating energy consumption is therefore not straightforward, as consumption falls on downhill sections due to regeneration, and on steep descents the SoC may even increase. The net energy consumption of such routes cannot be estimated from the average slope of the entire route.

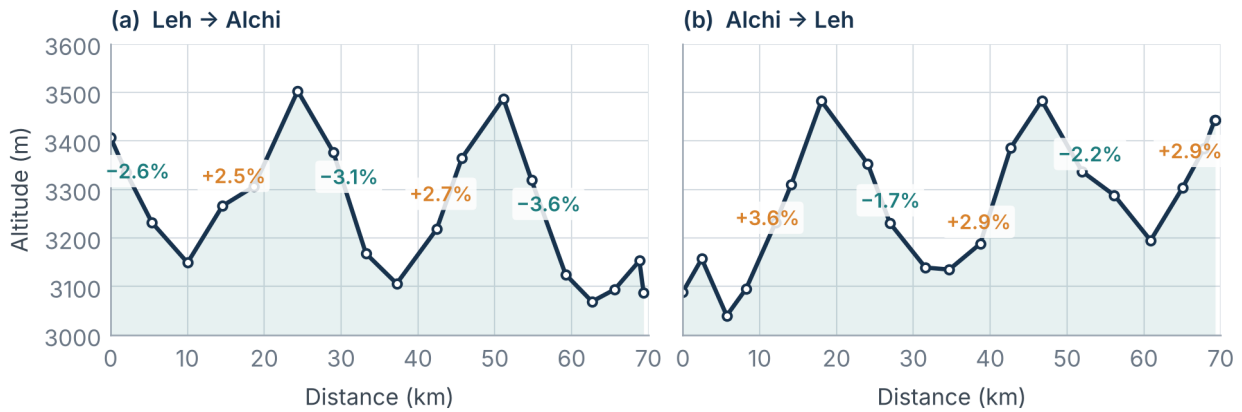


Figure 8 Route profile, Leh - Alchi

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Leh - Upshi. The distance between Leh and Upshi is about 49 km. In contrast to Leh-Alchi, the route is nearly flat except for a segment of about 5 km close to Leh, where the gradient is around 3.9% (**Figure 9**).

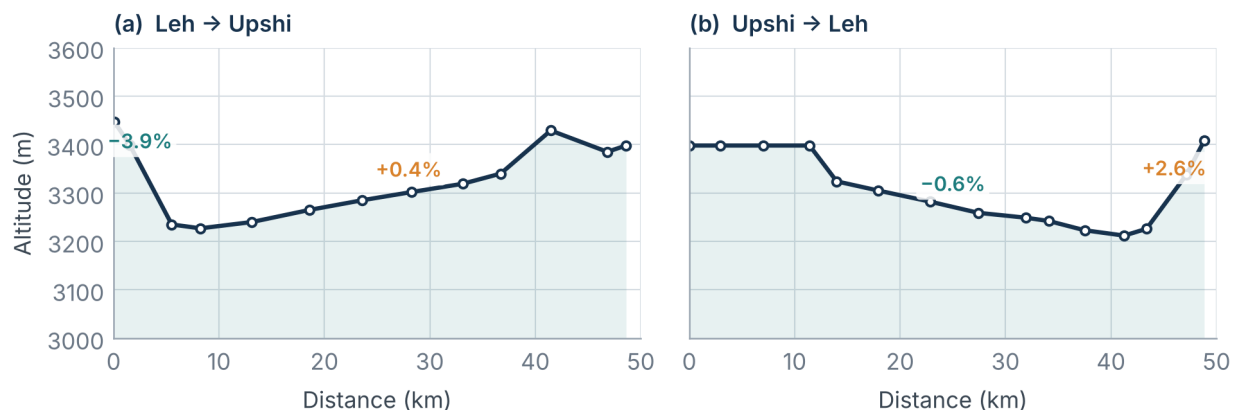


Figure 9 Route profile, Leh – Upshi

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Leh - Stakna and Chuchot - Leh. The Leh-Stakna route (about 27 km) starts flat, followed by a sharp downhill section of around 3.2%; the rest of the route is relatively flat with an average uphill gradient of 0.25%. The Chuchot-Leh route (about 21 km) is almost flat for about 75% of its length, with an average gradient of about -0.31% , followed by a significant climb of about 3.4% (**Figure 10**).

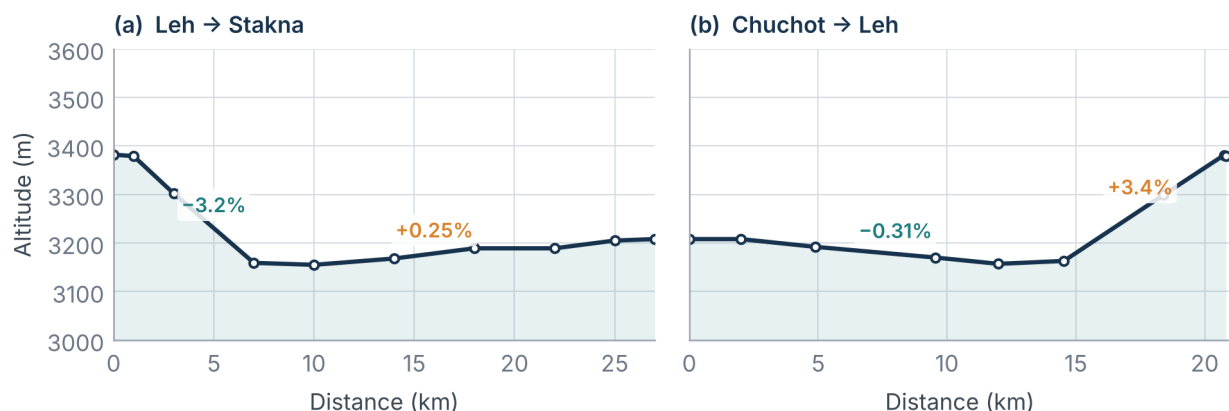


Figure 10 Route profiles, Leh – Stakna and Chuchot – Leh

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Leh - Spituk. The distance between Leh and Spituk is roughly 11–13 km. The route follows an almost constant gradient of about 2.5–2.8% (**Figure 11**). As the return journey used a different alignment, the distances recorded in the two directions differ.

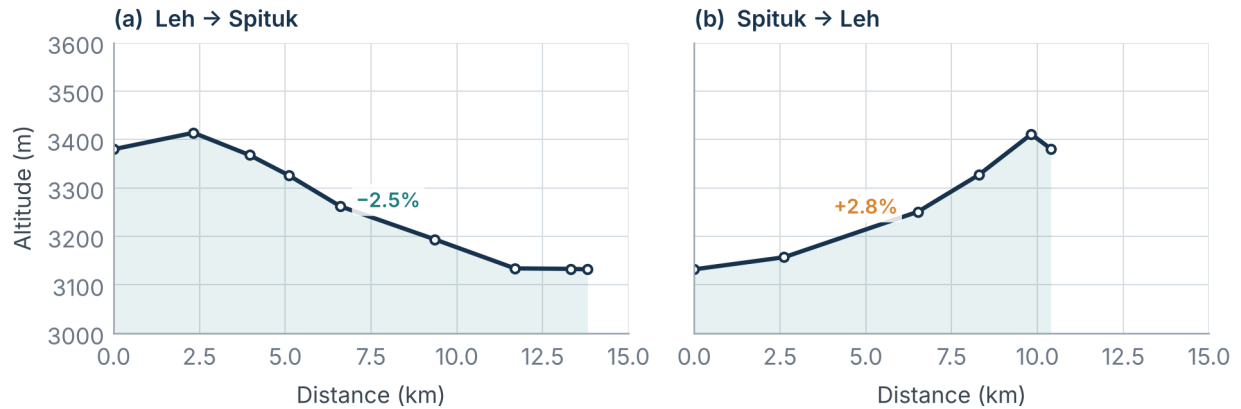


Figure 11 Route profile, Leh – Spituk

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Leh - Phyang. The distance between Leh and Phyang is about 18 km. From Leh the route descends for about 10 km and then climbs with an average gradient of 2.3% to the end (**Figure 12**).

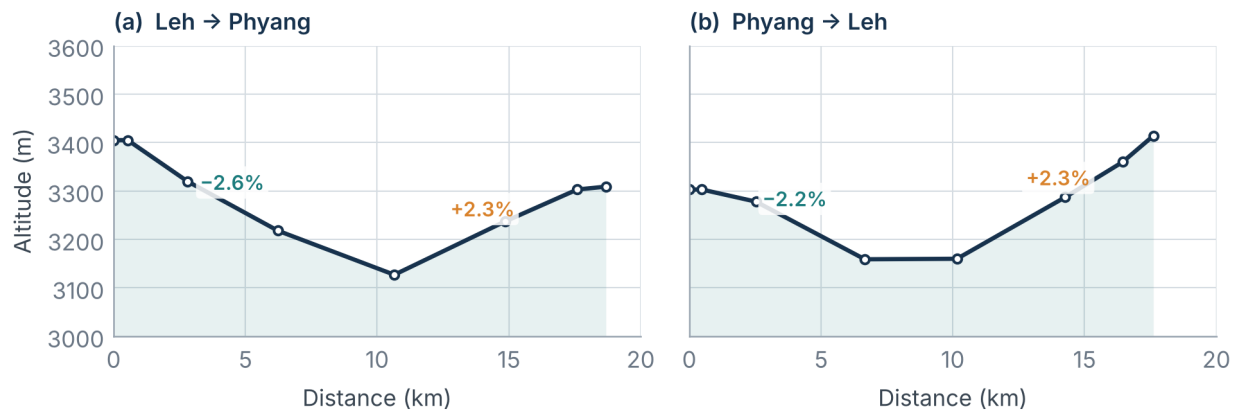


Figure 12 Route profile, Leh – Phyang

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Leh - Pathar Sahib. The distance between Leh and Pathar Sahib is about 25 km. The profile follows a trend broadly similar to Leh-Phyang (**Figure 13**).

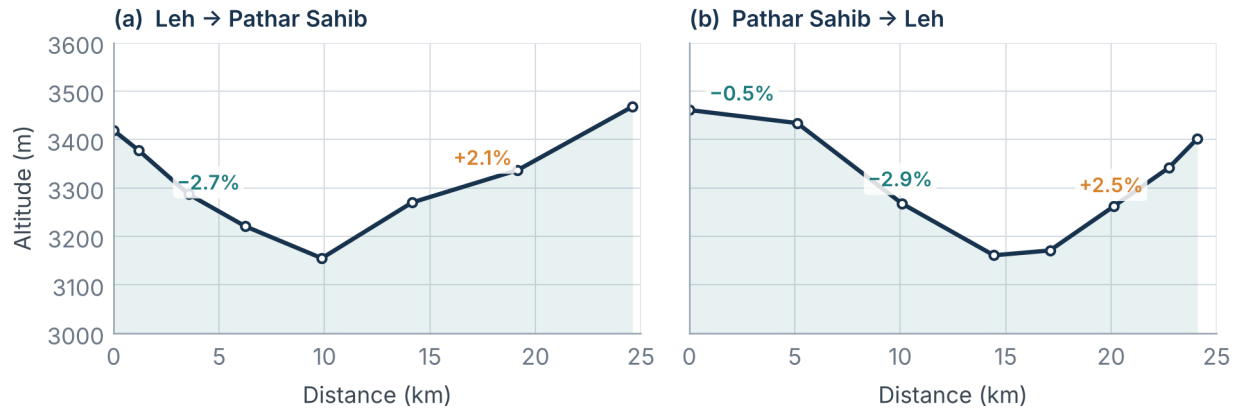


Figure 13 Route profile, Leh – Pathar Sahib

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

4.2 Operational data analysis

Data from the seven routes was used to study the effect of factors such as trip length, altitude, gradient and temperature on the rate of SoC consumption during operation. As the study area is hilly, linear regression analysis was carried out using the average gradient of the route segments between consecutive data readings. The analysis was carried out for the overall dataset and separately for negative (downhill) and positive (uphill) gradients (**Figure 14**, **Figure 15** and **Figure 16**).

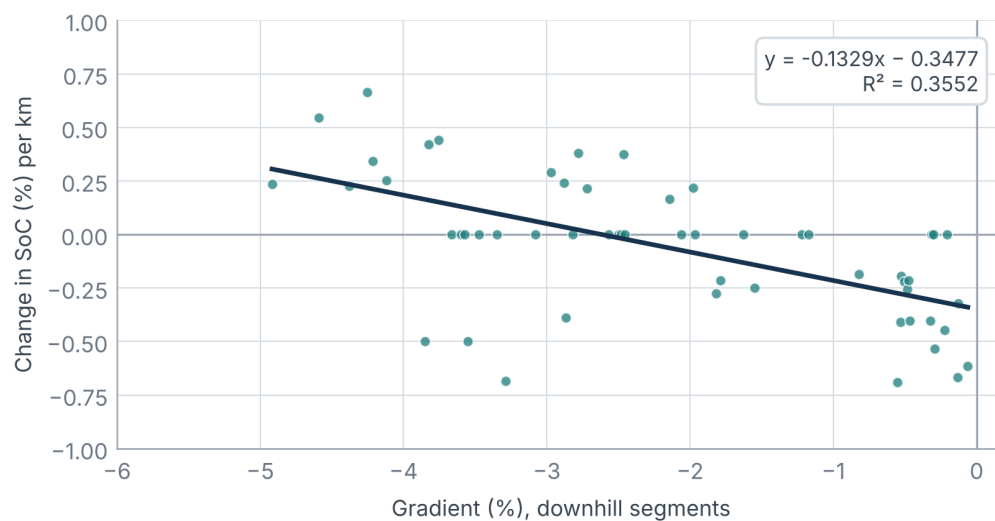


Figure 14 Change in SoC (%) per km against gradient, downhill segments

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022); 55 segment observations

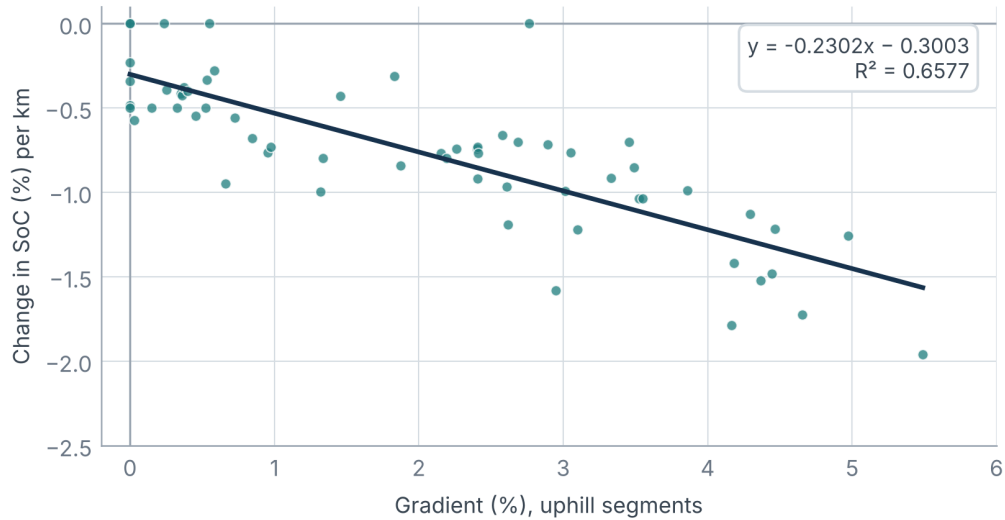


Figure 15 Change in SoC (%) per km against gradient, uphill segments

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022); 62 segment observations

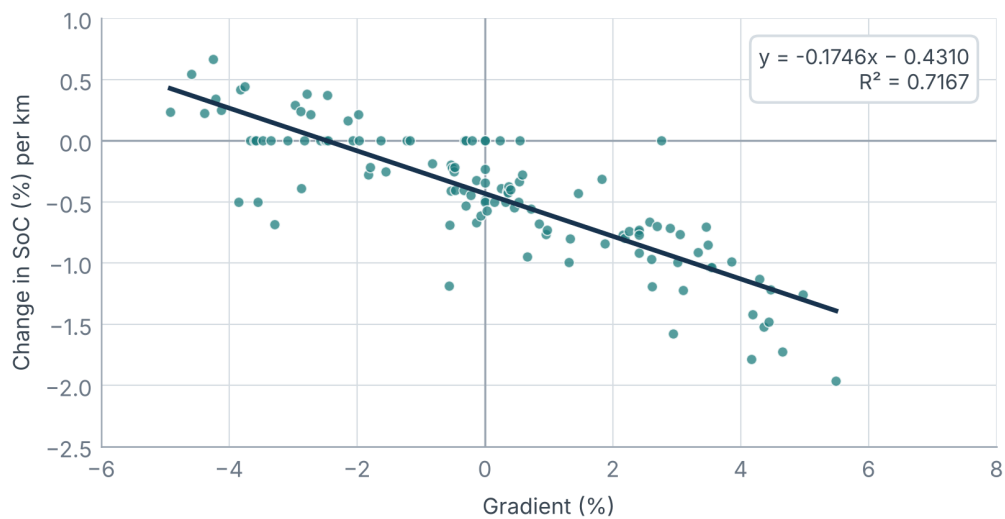


Figure 16 Change in SoC (%) per km against gradient, all segments

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022); 118 segment observations

As the gradient increases in the positive direction, the change in SoC per km becomes increasingly negative: the energy consumption rate of the e-bus rises with the uphill gradient. When travelling downhill, the SoC consumption rate falls because of energy regeneration. On steep downhill segments the regeneration rate equals the consumption rate (at around -2.4% to -2.6% gradient) or exceeds it, leading to a net increase in the battery's SoC.

4.3 Regression models for operational data

The relationship between the change in SoC per km and the significant explanatory variables is given in Equations (1) to (3). Gradient and passenger loading were the most influential factors for variation in energy consumption. Owing to limited data, the equations were derived for a passenger load range of 260–760 kg.

ALL SEGMENTS	$\Delta\text{SoC (\%/km)} = -0.309 - 0.0003 \times \text{Passenger load (kg)} - 0.165 \times \text{Gradient (\%)}$	$R^2 = 0.69$	(1)
UPHILL SEGMENTS	$\Delta\text{SoC (\%/km)} = -0.073 - 0.0005 \times \text{Passenger load (kg)} - 0.233 \times \text{Gradient (\%)}$	$R^2 = 0.68$	(2)
DOWNHILL SEGMENTS	$\Delta\text{SoC (\%/km)} = -0.396 - 0.131 \times \text{Gradient (\%)}$	$R^2 = 0.30$	(3)

The analysis indicates that the battery discharge rate is approximately 0.33% SoC/km on flat terrain with no passenger load (taking the driver's weight as 80 kg). Equation (1) suggests that the consumption rate increases by about 0.02% SoC/km for each additional passenger of average weight. The model based on the overall data (both uphill and downhill sections) shows that energy consumption is significantly influenced by only two factors: gradient and passenger loading. Because more energy is needed to climb, the discharge rate increases by about 0.16% SoC/km for each 1% increase in uphill gradient with only the driver on board (Equation 1).

In downhill situations, battery recharging through regenerative braking further reduces net energy consumption, and on steeper sections can recharge the battery by more than is consumed. The model shows that as downhill gradients approach about 3%, the energy regenerated balances the energy consumed. Passenger loading was not a significant factor for energy consumption or regeneration while travelling downhill. Equations (2) and (3) show the factors that significantly influence the SoC consumption rate for uphill and downhill conditions respectively.

READING THE MODELS

A negative ΔSoC indicates battery discharge; a positive value indicates net charging through regeneration. Gradient is entered with its sign (uphill positive, downhill negative). The models are empirical and were estimated from autumn data within a 260–760 kg passenger-load range; they should be applied with caution outside these conditions.

4.4 Charging analysis

Lithium-ion batteries are charged in a Constant Current (CC) phase followed by a Constant Voltage (CV) phase. During the CC phase, SoC increases linearly with charging time until the battery's terminal voltage reaches a threshold, typically between 80% and 90% SoC. The CV phase then begins, in which charging slows and SoC has a non-linear (concave) relationship with charging time (Sassone et al., 2014).

Three charging sessions, spanning 32% to 99% SoC, were studied to determine the approximate charge rate in the CC and CV phases and the SoC at which the phase change occurs. **Figure 17** shows the SoC charged per minute against the battery SoC for each session; the dashed line marks the average CC-phase charge rate and the vertical line the SoC at which the phase switch takes place.

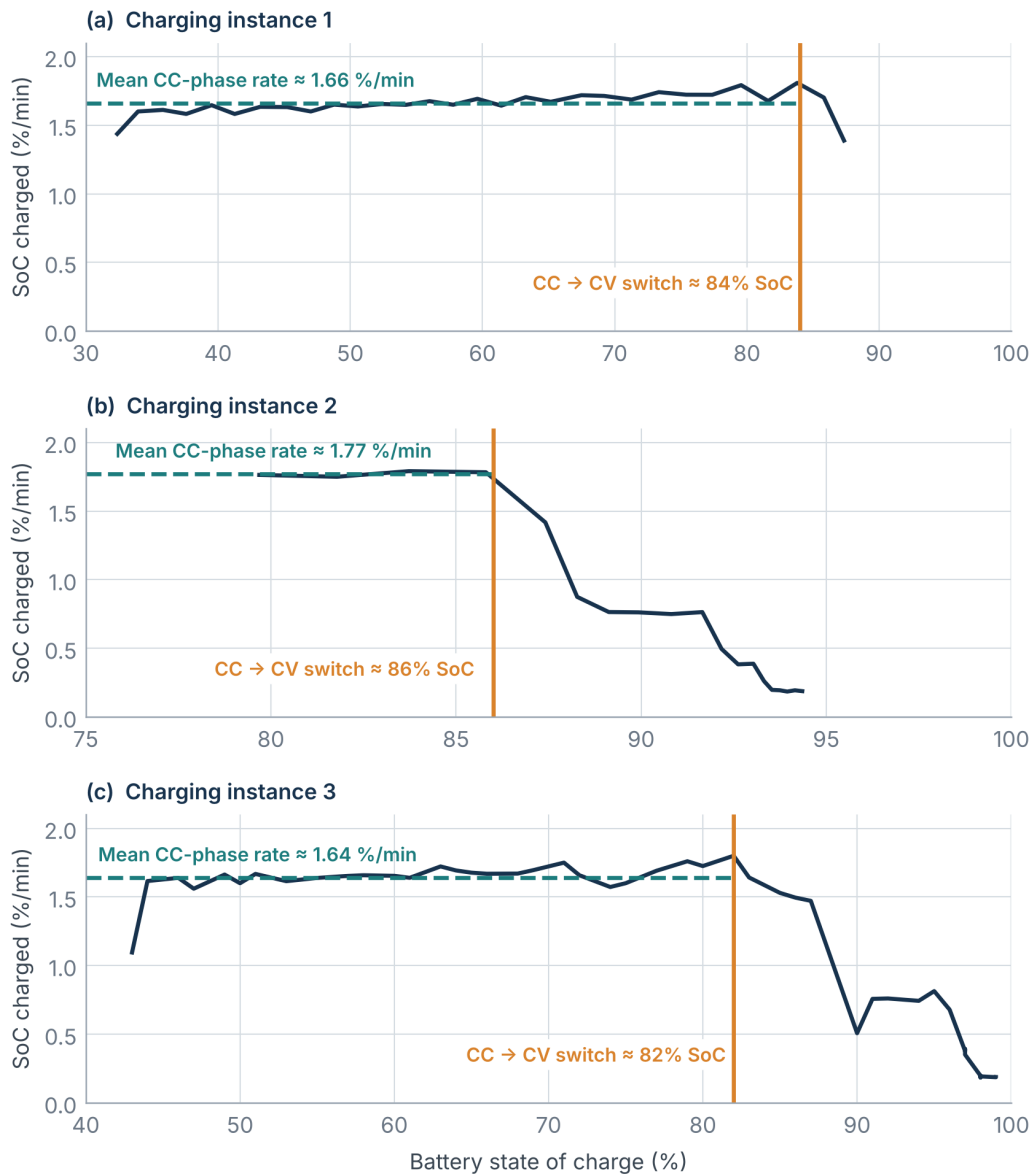


Figure 17 Charge rate against battery SoC for three charging sessions

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

In all three sessions a significant drop in charge rate was observed at the SoC level where charging shifts from the CC to the CV phase, which occurred at 81–86% SoC. The average charge rate in the CC phase was about 1.64–1.77% SoC per minute, falling to as low as 0.2% SoC per minute in the CV phase.

If an operator charges an e-bus above 90% SoC, the time taken for the same amount of charge will therefore be much longer than in the CC phase. Charging in the CV phase may also be detrimental to battery state of health. **Table 8** presents the estimated time to charge across set SoC ranges. These estimates may vary with temperature: at low temperatures the terminal voltage for the CV phase can be reached earlier, leading to a prolonged CV phase (Liu et al., 2020).

Table 8 Estimated time to charge across SoC ranges

SoC range (%)	Estimated time (min)	Charging phase
20 – 80	36.6	Constant current
80 – 85	3.1	Transition
85 – 90	4.2	Constant voltage
90 – 95	10.5	Constant voltage
95 – 100	16.6	Constant voltage

Source: Analysis by Civil Engineering Department, IIT Delhi (Nezamuddin, 2022)

Key Findings and Way Forward

5.1 Key findings

Charging strategy. The data suggests that charging switches from the constant-current (CC) to the constant-voltage (CV) phase between about 80% and 86% SoC. Charging slows considerably in the CV phase and may also lead to deterioration of battery health. The usable battery capacity should therefore be planned within a range that keeps charging time efficient. A maximum SoC of 90% can practically be achieved during opportunity charging, while limiting charging to 80% SoC may be desirable to minimise layover time.

Terrain. In operation, the predominant factor influencing e-bus energy consumption is gradient, that is, the terrain of the study area. Operational plans for mountain routes should be based on segment-level gradients rather than average route slopes, and should account for the energy recovered on long descents.

Passenger loading. Passenger loading was also found to influence consumption. However, within the range of loads observed, its coefficient was small enough not to make a material difference to estimates of e-bus energy consumption.

5.2 Limitations and future scope

The study had limited charging data across variations in battery and ambient temperature, which may lead to lower charging rates than estimated and longer-than-anticipated charging durations for the operator. The winter temperature range of the study area is a critical factor for e-bus batteries (Ge et al., 2016; Motoaki et al., 2018), and a similar study in winter conditions would support better policy recommendations.

For operational e-buses, more data on varying passenger loads and temperature conditions would help make more accurate predictions of their impact on energy consumption in the study area's terrain. Access to BMS data in a usable format would also allow continuous, higher-resolution measurement than the observation-based approach adopted in this pilot.

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Annexure A: Pilot Vehicle and Charger Specifications

The following specifications were reported by the manufacturer and operators at the time of the study and are reproduced for reference. They have not been independently verified by the pilot.

Table 9 E-bus specifications (PMI Foton, Leh fleet)

Parameter	Value
Manufacturer	PMI Electro Mobility Solutions (PMI Foton)
Length	8.5 m
Capacity	30 seated + 14 standing
Type	Air-conditioned
Battery capacity	150 kWh
Recommended SoC window	20% (min) – 100% (max)
Stated energy efficiency	About 1.2 km/kWh with A/C; 1.4 km/kWh without A/C
Stated range	About 120 km on 80% battery charge
Maximum speed	70–80 km/h
Fleet in Leh	10 buses

Source: SGArchitects (2022a), based on OEM information

Table 10 Charger specifications (Leh depot)

Parameter	Value
Type	DC fast charger (Luobinsen)
Rated output	180–200 kW (as reported in source documents)
Stated efficiency	90%
Operating temperature	–20 °C to 50 °C

Source: SGArchitects (2022a), based on OEM information



This case study documents pilot operations of battery-electric buses on non-urban mountain routes around Leh, Ladakh, and the analysis of how terrain, passenger load and temperature shape their energy use and charging. It forms part of a study exploring the role of the private sector as a catalyst for accelerating the transition to e-buses in India.

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