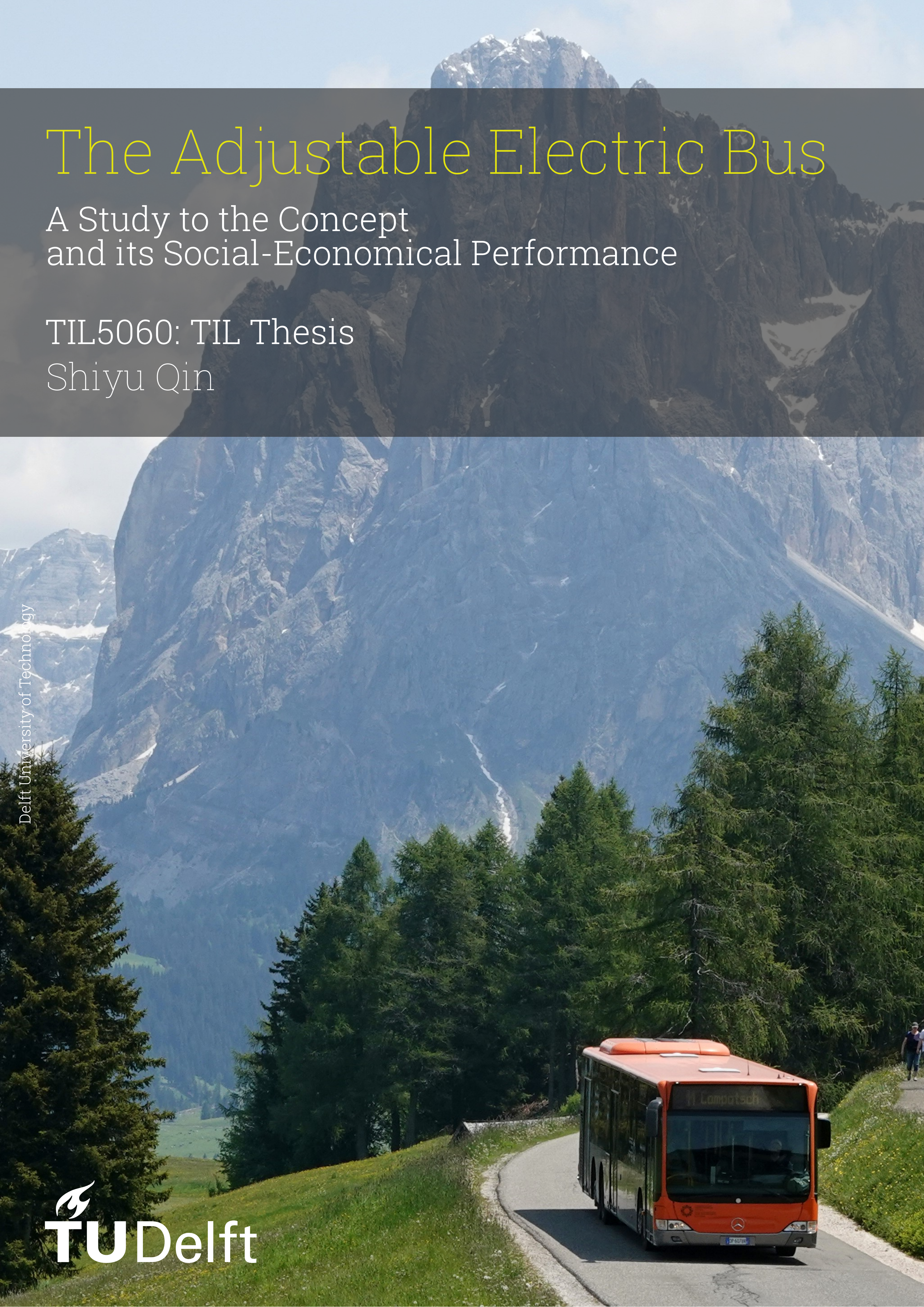
The Adjustable Electric Bus

A Study to the Concept and its Social-Economical Performance

TIL5060: TIL Thesis

Shiyu Qin



Delft University of Technology

The Adjustable Electric Bus

A Study to the Concept and its Social-Economical Performance

by

Shiyu Qin

Student Name	Student Number
Shiyu Qin	5458315

Supervision Committee

Chair:	Niels van Oort
Members:	Jan Anne Annema
	Arjan van Binsbergen
Project Duration:	5 Apr 2023 - 30 Oct 2023
Faculty:	Civil Engineering & Geography
Track:	MSc TIL (Transport, Infrastructure and Logistics)

Cover: Photo taken by the Author at Ortisei, Italy
Style: TU Delft Report Style, with modifications by Daan Zwaneveld

TU Delft

Preface

Completion of this Master thesis report marks the end of both my whole graduation research process and my Master Civil Engineering study in TU Delft. In this research, I explained and verified my idea of a special electric bus with adjustable configuration. I have selected this topic by myself based on my two-years study on the track of Transport, Infrastructure & Logistics and my real experiences on various types of buses across past years.

First of all, I want to thank to my Thesis Assessment Committee: Professor Niels van Oort (chair), Professor Arjan van Binsbergen and Professor Jan Anne Annema. I want to thank all of them for the feedback and suggestions from the beginning of my thesis on April to October when I write these words in the end. Your support keeps me on the right track and makes this idea gradually becomes widely understandable and as valuable as a real 'research'.

I would like to thank to Peirong Zhu from King Long Motor Group for his time and providing me with some key data that I am in need of. I want to thank my friends Tianyi Li (University of Stuttgart) and Hanxiang Zhang (RWTH Aachen University) whom I met and receive important information about buses from as I travel through Europe. Also, I would like to thank to (operators of) various bus-related websites, museums, exhibitions and non-profit organizations who provide bus information, preserve old timers and show new buses to expand my horizons on public transport.

Besides, I want to thank those who physically stayed in China but supporting me all the time. First and the most important are my parents and elders, they brought me up, paid for my study and travel and giving me advises for living abroad. I want to thank to my friends Ao Chen, Fan Zhang, Hao Wu, Haobo Qin, Ruoxiao Wang and many more of them who keeping linked with me online.

Finally, I want to thank myself for making through all those sunny and gloomy times through the past 788 days. Nothing could be achieved for both myself and the research without me keeping moving. Past has past and the future will always be in one's own hand.

Shiyu Qin
The Hague, October 2023

Summary

In recent years battery electric buses (BEB) are taking over bus networks from buses with internal combustion engines. These replacements happen on both city and regional networks. Considering the high purchasing cost of BEB, increasing the efficiency of applying BEB becomes important. Meanwhile, the volume and weight of batteries are causing limitations to driving range and capacity of BEBs. **The dilemma of current BEB is:** BEBs with city bus layout cannot hold too much battery in order to save energy and provide enough capacity; BEBs with ample batteries and high driving performance can only have high-floor layout capable for regional service.

The idea of research to an adjustable BEB

The dilemma above shows that currently it is hard to make all characteristics (driving performance, capacity, accessibility) available in one fixed BEB. This research proposes a possibility to make BEB characteristics show up on where and when they are needed.

A difference exists between peak time trips of city and regional bus network. Since peak time trips of regional lines are mostly earlier than trips of city lines in the morning, a chance of using one same BEB to operate both regional and city lines was seen (vice versa in the afternoon). It is possible to make BEBs adjustable to have appropriate advantages (while avoid disadvantages) to serve different lines on appropriate time and space. This is how the concept of an adjustable BEB come. However this concept was hardly found in existing literatures since it does not work for traditional internal combustion engines buses as they are so cheap and robust that they can overrun the dilemma of expensive BEB simply by using more vehicles.

Adjustable BEB with combined bus networks seems to be a new and useful concept to be researched. The research question is then proposed:

What could be a design for an adjustable BEB and how does this design perform in bus networks and cost-benefit analysis?

To reach the evaluation to cost-benefit performance of the adjustable BEB, firstly its operation feasibility need to be proved. This research, goes step by step, started from dispatching for simple networks and basic timetables in two situations: with and without adjustable BEBs. As complexity of target network grows, behaviour of the adjustable BEB and differences it brings are recorded by keep doing dispatching. Recorded behaviours of buses include minimum number of vehicles, daytime dwells, deadheading trips, transfers, delays, inter-network operations and charging operations. Useful general intermediate conclusions of opportunities of applying adjustable BEB are therefore discovered for later larger scaled network analysis. Meanwhile, operation feasibility of the adjustable BEB was evaluated. Characteristics (components, structure, capacity, driving range, weight, consuming rate, prices) of the adjustable BEB and other BEBs which are thought to be rivals of the former were defined by viewing private data collection and interviews with bus manufacturers. Vehicle investments, infrastructures, energy costs and exclusive operation costs of the adjustable BEB were selected as (monetary) criteria to evaluate its cost-benefit performance.

An archetype network with multiple lines, stations, different demand and supply across time reflecting typical existing regional and city bus networks was created. Research and reference cases pieced up by different types of BEBs were assumed according to typical organization of bus networks in reality. Using general intermediate conclusions to applying adjustable BEBs above, number of vehicles and infrastructures were calculated for each cases. Type and number of vehicles on each lines were then clarified so that operation cost was measured. Furthermore, passenger load and total driven kilometers in a complete weekday were calculated to handle energy consumption of different cases. As all cost factors and numerical operation results were ready, all cases was studied by a cost-benefit analysis (CBA) under an assumed 12-year concession period using one of the reference cases as basis. Therefore operation results were transferred to monetary values and cost-benefit performance of the adjustable

BEB was evaluated. Scenarios with different ridership and level of prices were set up considering inaccurate estimation to price factors. Sensitivity analysis was carried out by changing different factors in an amount in order to find out important factors influencing cost-benefit performance of the adjustable BEB.

The adjustable BEB named MBEBS

In this research the target adjustable BEB is named 'Multi-modal BEB System' in short MBEBS. MBEBS make use of developed 12-meters integral chassis structures of current BEBs on which motor was integrated into the rear axle and controlling were scattered in the corners. Limited number of batteries, pantograph charger and air conditioner were put on the roof. The middle part and rear overhang of the chassis are designed with 8 spaces for different units called interior modules to enter. These modules, homogeneous on sizes, have 5 different types according to function, floor height, seats and battery capacity. They can be installed from both left and right sides of the chassis like different people fitting in to a 'bierfiets' (Beer party bike). By installing indicated number and types of modules, a MBEBS can have two modes aiming for city or regional bus transport. At exclusive swapping stations located in big city hub stations where regional and city lines meet, modules are quickly exchanged by withdrawing or inserting movements so that MBEBS transfers between a regional- and a city BEB.

Based on this design, a rough operation storyline of MBEBS in a combined city and regional network throughout one working day was summarized. But it is unclear that whether this storyline is really executable. It has to be verified by timetabling to city and regional lines in a combined way: **If it is not verified on operation level, number of MBEBS and other types of vehicles needed would be unclear thus cost analysis would be nonsense.**

The opportunity of MBEBS in combined networks

Basic 5-stages timetables (Morning, morning peak, daytime, afternoon peak and evening) with exact departure times of bus lines were set up for regional and city lines. The trips are divided into peak ones and daily ones. Peak trips of regional lines are seen as sources of vehicles of city network (mainly serving city peak trips) as the following figure shows.

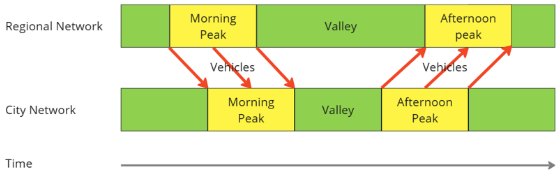


Figure 1: The flow of MBEBS in a combined network

The verification starts from a very basic formation consists of one regional line, one regular city line and one hub station connecting both. In this formation, MBEBS from regional lines have to get to the other end of the city line after transferred into city mode, causing wastes of time and a number of unfeasible connections. There also exists many deadheading (DH) trips and some MBEBS that have no city lines to drive with.

Next, formations with more than two lines are tried. In a formation with two regional lines each connected at one end of the city line, MBEBS can be put into city lines at both ends instantly so that DH trips are eliminated. Much more vehicles are saved but some are still unused.

The formation with 4 lines organized in the following structure, which can really be called a network, is able avoid DH trips while much more MBEBS are really working at daytime.

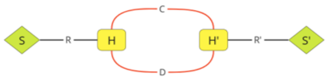


Figure 2: Formation 4 lines

From the verification process above, it could be shown that combining regional and city networks with MBEBS is feasible and helps the reduction of number of vehicles in this combined network. It also shows that **as the combined network becomes more complex, the regional lines and its MBEBS can be simply recognized as free to combine in or very close to a hub station without any waste especially when demand of city peak vehicles is more than supply from regional lines.** A symmetric allocation of MBEBS is more favourable for reducing DH trips and unused vehicles. Having cleared these features, modelling MBEBS for a more real network became easier.

The archetype network modelling
The archetype network created for this research includes 3 hub stations, 8 regional lines and 12 city lines. Frequency of these lines during different stages varies to make the network even more realistic. Considering the higher complexity of the archetype network and using the findings from previous step, no exact departure times are included. Only total number of departures of each lines are calculated according to frequency and driving duration for further statistics. Profile of each lines then only include direction, frequency, length, number of departures and average ridership.

Vehicles involved in this network for different cases are: city BEB, regional BEB, MBEBS and Utility BEB. City- and regional BEBs are designed to be directly replaced by MBEBS so they are included. Utility BEB is a kind of existing low-entry BEB with long driving range, higher floor in the rear and more seats. This layout and characteristics makes Utility BEB appropriate for both city and regional services and also favourable to the idea of combining networks so it becomes a rival of MBEBS. As the existing opponent of MBEBS, Utility BEB is involved in this research as a challenger. Characteristics of different BEBs are collected via private database, interviews with manufacturers and Dutch open RDW data. For the MBEBS, some of its characteristics were concluded based on assumptions of interior modules.

Using these vehicles and according to current operation structures of city and regional network, five cases are proposed. The first and second cases (A & B) are for reference. Case A reflects a typical separated city and regional operation while case B represents an improved whole-regional monopoly situation with Utility BEBs. The rest three (R1-R3) are research cases to MBEBS and Utility BEB as the rival: Case R1 for MBEBS-based combination, case R2 for MBEBS-monopoly combination and case R3 for Utility BEB-based combination.

By vehicle allocation under combined networks, 42 peak vehicles are supplied by 8 regional lines gathering at 3 different hub stations. They are completely absorbed by city lines with some extra city BEB as supplement and redundant vehicles. Therefore, number of vehicles needed in each cases were estimated as follows. It can be seen that combining networks have significantly reduced number of vehicles comparing with no combination, as it was proved in the part above.

Table 1: Vehicle usage by cases

Vehicles	A	B	R1	R2	R3
City BEB	83		46		46
Regional BEB	42				
Utility BEB		88			42
MBEBS			42	88	
Total	125	88	88	88	88
Combined network		x	x	x	x

Using profiles of lines and characteristics of vehicles, crowdness and the energy consumption in each cases over one working day was calculated. MBEBS in this research are designed to have similar capacity and seats layout in each modes so that difference of passengers' experience (city line crowdness and seats on regional line) between cases are relatively small. On the perspective of numerical energy consumption, cases with MBEBS takes advantage as MBEBS has the lowest energy consumption on both city and regional network.

CBA and analysis to MBEBS

The CBA uses derived operation data in previous part to verify the efficiency MBEBS in monetary values. Investment, energy, operation and infrastructure cost of MBEBS and other cases were measured. It takes case A as basis and considers a widely applied 12-years concession period in the Netherlands. Vehicle investments, infrastructure and operation cost are unified as costs. Energy costs would be the only benefit. The CBA grasps difference of these values between each cases. Minus difference in investments means a case spends less than reference case A. Positive difference in energy costs means it brings more benefits than reference case A. It can be seen that most research cases and reference case B are having positive NPV (net present value after the 12-years period) while case R3 partially using Utility BEBs for combining networks is the best among all. Result of passenger experience are displayed by a qualitative analysis: For city lines, all cases are performing worse than basis case A while case B with completely Utility BEBs is the worst; For regional lines, all cases are performing well.

Table 2: CBA result example

	A	B	R1	R2	R3	Unit
Crowdness on city lines	0	- - -	-	-	–	
Standing on regional lines	0	0	0	0	0	pax-km
Difference in investments (cost)		-8082	-2229	3153	-12774	x1.000€
Difference in energy costs (benefit)		900	1522	1773	1230	x1.000€
NPV		8981	3751	-1380	14000	x1.000€

The CBA result above was based on an intermediate investment price, electricity price and ridership level. Considering MBEBS as a new concept and fluctuating prices of energy at recent years, four different price levels for all aspects were set up for scenario analysis. Three different levels of ridership were set up since number of passengers directly influences electricity consumption of BEBs by changing loads on each vehicles. With 4 price levels and 3 ridership levels, 12 different scenarios were created. The result of comparing scenarios shows negligible effect of ridership and strong influence of investment and electricity price levels. As price level rises, inferiority of MBEBS enlarges and sometimes even gets higher costs comparing with reference case A. In another 3 extreme scenarios out of 12 regular ones with some extreme settings in favour of MBEBS, NPVs of MBEBS cases are still falling behind Utility BEB cases despite the decreased differences.

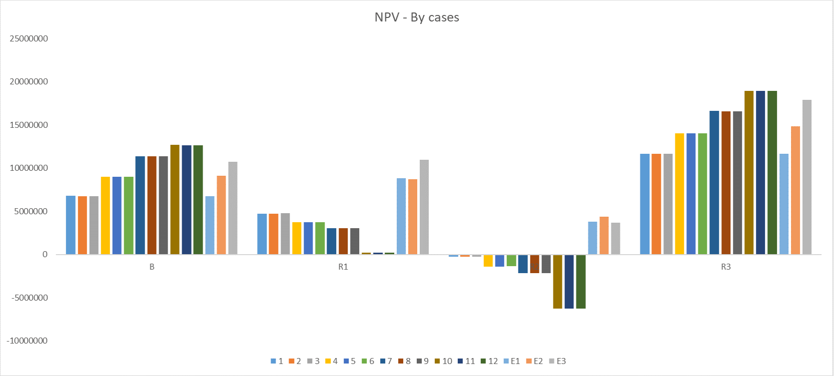


Figure 3: NPV by cases in each scenario

Which factors leads to this result? Why the benefit of MBEBS saving energy failed to make MBEBS more cost effective than Utility BEBs? Sensitivity analysis to factors for investments (costs), benefits and NPV based on an intermediate price level was carried out. For electricity price and operation cost, they were given both increase and reduction to show and compare the bandwidth of changes. It was observed that change of electricity price has relatively small effects to NPV comparing with operation costs under the same percentage of change.

Changing of vehicle single prices has positive effects to investments of each research cases with a magnitude less than 150%. Changing number of vehicles, although sounds having the same function as changing vehicle prices, exerts stronger negative influences to investments of all research cases. Sensitivity of MBEBS exclusive operation cost has an intermediate negative influence to to total investments of MBEBS cases.

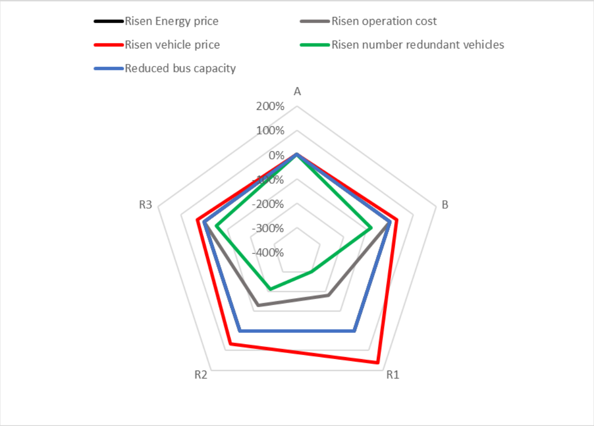


Figure 4: Investment change by cases of raising each factor

Benefits would be only related to energy price. 50% increase of energy price leads to 50% increase of benefits for all research cases. Sensitivity of these factors to NPV are similar as their sensitivity to investments. This result again reflects the low effect of energy costs. Increasing energy price and single vehicle prices do have positive effect to all research cases but operation cost and number of vehicles have much stronger negative influences.

General research findings

It has been proved that combining city and regional network with MBEBS is feasible on timetabling level. The bigger the networks will be combined is, the more flexible the combinations can be and the more vehicles can be applied effectively in both networks. These combinations were also proved to be robust to increasing wasted transfer time through an additional sensitivity analysis.

From the CBA, it was found that adjustable BEB is not the best vehicle to carry out such combining timetables due to its high investments and operation cost. Even in a extreme scenario with factors having unrealistic values in favor of the adjustable BEB, it had merely the same cost effectiveness as using Utility BEBs for combination. Considering Utility BEB as a mature technology, it is a stable and economic choice for combining network. The adjustable BEB might just be a concept in forseeable years. However in most scenarios all research cases (including adjustable BEB cases) have reached a positive NPV which means the idea of combining network is able to reduce total investment to such a big network significantly.

In conclusion, the adjustable BEB do save some energy cost, but this innovative concept has higher operation cost and vehicle investments compared to conventional Utility BEBs. Meanwhile, its high sensitivity to its own characteristics makes it easily becomes more expensive than using Utility BEBs. As for infrastructure investment of the adjustable BEB, they are not very important comparing with energy and operation costs which accumulates across days, months and years.

From this research, some advantages of an adjustable BEB can be summarized.

- Reducing vehicles for the network;
- Reducing energy consumption;
- Comfortable and capacity rides;
- Reducing deadheading trips and unused vehicle hours.

Involving Utility BEBs reveals the following disadvantages of the adjustable BEB:

- Too expensive vehicles;
- Unproven interior modules and operation costs;
- Extra and special infrastructures;
- Higher cost than existing BEBs in whole concession period;

Discussion & Recommendations
Some recommendations are given to MBEBS-related entities including bus manufacturer, concession manager and bus operators. Manufacturers of BEBs can consider to make small-scaled MEBES models and try its technological availability. Full-scale prototypes can be developed in cooperation with research institutes and vehicle managing departments. In a 3-5 years short experiment period, a few prototypes helps discovering real performances of MBEBS rather than just doing research on papers. On the other hand, the government in responsible for bus concession and services is suggested to merge city and regional networks especially in large cities to allow combination of networks. Accordingly, operators of city and regional networks can adjust timetable according to real distribution of lines, depots and demands to combine as much lines as possible. Low-entry Utility BEBs would be a more conservative and cost-efficient choice. The whole electrified combined network would probably consist of appropriate share of city, regional and utility BEBs. For other bus operators like subcontractors and rental companies, MBEBS might be useful in response to various demand from different scenarios.

To further understand the adjustable BEB and combined networks, researchers can choose to focus on dispatching algorithm considering adjustable BEBs in a combined network. The author proposes some extra ideas for the adjustable BEB. It can make use of recycled or worse-performance material, especially for batteries. They help adjustable BEBs becomes cheaper and more environmental friendly. The batteries that MBEBS has left during the day at hub stations can even work as part of energy storage. There can be different sizes of adjustable BEB chassis using same sets of interior modules. There can also be more types of modules for adjustable BEB rather than interior, doors and battery: fuel-cell modules, engine modules or battery-only modules gives adjustable BEB more changes and opportunities.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
BCR	Benefit-Cost Ratio
BEB	Battery Electric Bus
CBA	Cost-Benefit Analysis
EV	Electric Vehicles
FCB	Fuel Cell Bus
ICE	Internal Combustion Engine
MBEBS	The Multimodal BEB System
MPV	Multi-Purpose Vehicles
NG	Natural Gas
NPV	Net Present Value
RDW	Netherlands Vehicle Authority
TCO	Total Cost of Ownership
V2G	Vehicle to Ground

Symbols

Symbol	Definition	Unit
M	Mass of a vehicle	kg
r	Bus line	#
S	Stage of one day	#
V	Type of a vehicle	#
C_M^V	Energy consumption of vehicle type V at mass M	kWh/km
C_P^V	Capacity of vehicle type V	pax
C_S^V	Number of seats of vehicle type V	#
D_r	Single duration of bus line r	min
f_S^r	Frequency of line r at stage S	#/60 min
F_{rS}^V	Load rate of vehicle type V on line r at stage S	#

Symbol	Definition	Unit
G_S^r	Average number of passengers on each departures of line r at stage S	#
L_r	Single length of line r	km
N_S^r	Number of vehicles needed of line r at stage S	#
P_S^r	Number of departures of line r in stage S	#
T_S	Duration of stage S	min
W_{rS}^V	Energy consuming rate of vehicle type V on line r at stage S	kWh/km
Y_{rS}^V	Standing passengers of vehicle type V on line r at stage S	pax

1

Introduction

1.1. The developing electric bus

Battery electric buses (BEBs) have been widely applied for proceeding to carbon-neutral public transport target in countries over the world [25]. According to the vehicles' data provided by Busposities, 11 of total 12 provinces in the Netherlands are operating more than 5 BEBs by the year of 2022 [33].

1.1.1. The price problem

Electric buses are more expensive than a diesel one of same size. Typical European 12-meter low floor BEBs costs between €500.000 and €600.000, while Chinese products are cheaper but still around €400,000 [39]. In comparison, a 12-meter diesel bus costs low as less than €200,000. Although the TCO across a BEB's 10-years-life is stated to be lower than a diesel bus [38], its kick-off investment is always a burden to the government and operators. Comparing with diesel buses, BEB takes longer time to recover the public investment.

The higher TCO of BEB comparing with diesel buses makes its social-economic benefits to be doubted and government subsidy would be necessary to cover the cost and boost its spread [18]. Between different types of BEB the cost also varies: the TCO between different charging modes are different [24]. Traditional analysis approaches like CBA would be able to be applied to compare economic efficiency between diesel buses and BEB which concluded that BEB has the best potential to reduce energy consumption and emissions [3].

1.1.2. BEBs' characteristics

The growth of number of BEBs leads to growth of demand of timely charging which requires high power output. Mathes et al's research [31] has proved that pantograph charging is a safe, healthy and high efficiency way to charge multiple types of BEBs with a power up to 350-600KW. Other different solutions are proposed including wireless moving charging, charging scheduling optimization, V2G and charging station load forecasting [46] to smooth this huge demand.

The charged electricity flows into battery packs, the mainstream of current BEBs' power storage which accounts a substantial portion of the size and weight of a BEB. They are hoped to be smaller and more powerful in order to improve performance of BEBs. [30] Not only the issue of weight, but also the capacity of battery packs are limiting all BEBs' driving range. For BEBs operating on different lines, they have different pattern of consuming, thus different choices of battery capacity should be considered. [8] On the other hand, driving technology also helps saving energy like extending range by regeneration brakes. By choosing more appropriate brake strategies, BEB can remove a number of battery sets without reducing driving range. [20]

Although all three main propulsion parts of an EV (Battery, motor, controller) matters, battery is the most important one on improving its operation performance. To decide the optimal battery capacity of target BEB strategically, there are available mathematical models that use location of chargers, passenger demand and also battery capacity as variables. In Korea, such model was applied to city tour buses [27]. Model developed by Gao et al proved the efficiency of high-power fast charging helps reducing battery capacity needed on BEBs in a transit network [44].

On the other hand, scheduling of battery swapping and/or fast charging (any method in contrast with overnight depot charging) for BEBs also have been studied. Combining with the electricity grid, Kocer et al's study provided a battery swapping scheduling method for BEBs that helps dealing with power demand peaks and valleys [10]. For en-route fast charging, Zhou et al formulated a deterministic robust optimization model for BEBs [43].

1.1.3. Passengers' demand and BEB

Passengers are not only simply taking buses to their destination, their demand is affected by multiple internal and external (in)direct aspects. Different interior (cabin composition) of buses has different effect to passengers, that's why city buses differed from intercity coaches in decades ago. Leyland, a famous British bus manufacturer, has studied floor layout of buses by a two-part investigation [9]. Their research has covered multiple design characteristics and dimensions of bus interior and showed strong preferences of passengers with different mobility and (safety, comfort) demand. According to research carried out by some private transport consultancies [6] [7], passengers' demand can be affected by:

- New or improved vehicles;
- Passenger service facilities in and out of vehicles;
- Comfort of different transport modes.

Meanwhile, passengers hope to improve some aspects and they are willing to pay more for that. Research to bus and railway service shows [7] [29], 30% of bus passengers in Washington want to improve comfort and reduce crowds and passengers of Swedish railways would like to pay around 10% more for extra comfort.

Passengers may notice a new BEB by their lower noise or ads from operators. The social influence of BEB has been investigated. Multiple factors of passengers including trip mode, attitude towards environment issues, ride comfort and social image are proven to be significant on the acceptance of BEBs [28]. There are also quantitative research to social-environmental benefits of BEBs despite the result was not transferred to monetary values [22] [21]. Going beyond investigation, Zhou et al's research directly developed an optimization model that considers balance between budget and environment equity of BEBs [47].

1.1.4. Summary

BEB, as a type of zero-emission bus, however costs noticeable quantity of money and resources replacing older traditional buses while keeping or increasing their level of service of the latter. Currently as supply chains in Europe becomes more fragile than previous years [17], minimizing and optimizing the use of all kinds of resources up to vehicles as a unit and down to every kilowatt of electricity or every gram of lithium becomes important. Meanwhile, passengers are watching and joining the transition to electric bus systems. BEBs' capacity on crowded lines and comfort on regional lines could be important factors that attract passengers and increase either their willingness to pay or operators' revenue.

1.2. The idea of an adjustable BEB

The author, having recorded and travelled with various types of buses in China and Europe since 2015, studies over 500 types of different buses and their technology. That includes from coaches, intercity, articulated, double-decker, standard bus and midibus to minibus. From the perspective of power, diesel, NG, hybrid (series, parallel and combined), super-capacitor, BEB and FCB buses are all in the author's collections. Meanwhile, as a frequent passenger on various bus lines, the author becomes sensitive to comfort and layout of buses. By learning his own collection and literatures, the author knows that layout of interior of a bus relates to power and/or demand of lines and operators, in which demand might be different at different times of a day.

From existing bus networks in the Netherlands, there exists a difference between peak times of regional and city bus lines. This difference was in fact generated naturally because commuters living in smaller towns have to depart earlier to catch up with city commuters and arrive at their work spaces at the same time with them. The following picture points out this difference.

↓ haltes van deze lijn
● 's-Gravendeel, H.Hamerstraat
○ 's-Gravendeel, Weegje
○ 's-Gravendeel, Smidsweg
○ 's-Gravendeel, Maasdamseweg
○ Maasdam, Provinciale Weg
○ Maasdam, Gemeentehuis
○ Puttershoek, De Grienden
○ Puttershoek, Sportlaan
○ Puttershoek, Kastanjelaan
○ Puttershoek, G. de Voslaan
○ Puttershoek, Suikerfabriek
○ Puttershoek, De Tol
○ Rotterdam, Zuidplein

maandag t/m vrijdag	
6	31
7	01 27 57
8	33
9	03

↓ haltes van deze lijn
● Oud-Beijerland, Rembrandtstraat
○ Oud-Beijerland, Maseratilaan
○ Oud-Beijerland, Koninginneweg
○ Oud-Beijerland, Sportlaan
○ Oud-Beijerland, Poortwijk Noord
○ Heinenoord, Tienvoet
○ Rotterdam, Zuidplein

maandag t/m vrijdag	
5	44^a
6	14^a 34^a 44^b 54^a
7	04^b 14^a 24^b 34^a 54^a
8	14^a 34^a 54^a
9	16^a 46^a
10	16^a 46^a
11	16^a 46^a
12	16^a 46^a
13	16^a 46^a

Maandag t/m vrijdag	Keizerswaard - Charlois																
Keizerswaard	V	...	...	06:09	06:24	06:34	06:44	06:54	07:04	07:14	07:23	07:28	07:35	07:42	07:49	07:56	08:03
Zuidplein Hoog	V	06:06	...	06:31	06:46	06:56	07:06	07:17	07:28	07:39	07:49	07:56	08:03	08:10	08:17	08:24	08:31
Garage Sluisjesdijk	A	06:20	06:30	06:45	07:00	07:10	07:21	07:32	07:45	07:56	08:06	08:13	08:20	08:27	08:34	08:41	08:47
Keizerswaard	V	08:11	08:19	08:27	08:35	08:43	08:51	08:59	09:07	09:15	09:22	09:32	09:42	09:54	10:06	10:18	10:30
Zuidplein Hoog	V	08:39	08:47	08:54	09:02	09:10	09:18	09:26	09:34	09:42	09:49	09:59	10:09	10:21	10:33	10:45	10:57
Garage Sluisjesdijk	A	08:55	09:03	09:10	09:17	09:25	09:33	09:41	09:49	09:57	10:04	10:14	10:24	10:36	10:48	11:00	11:12
Keizerswaard	V	10:42	10:54	11:06	11:18	11:30	11:42	11:54	12:06	12:18	12:30	12:42	12:54	13:06	13:18	13:30	13:42
Zuidplein Hoog	V	11:09	11:21	11:33	11:45	11:57	12:09	12:22	12:34	12:46	12:58	13:10	13:22	13:34	13:46	13:58	14:10
Garage Sluisjesdijk	A	11:24	11:36	11:48	12:00	12:12	12:24	12:37	12:49	13:01	13:13	13:25	13:37	13:49	14:01	14:13	14:25

Figure 1.1: Peaks and valleys in one working day

This difference becomes one of the basis notion of applying MBEBS.

There was a special type of adjustable bus that used to draw the author's attention. These were 4 BEBs operated by Dutch public transport operator Connexxion in Heinenoord depot from 2020. They became special hybrid buses by a fuel-cell trailer they carry in daily operation. The trailer was initially designed to be an environmental-friendly range extender that could be easily removable, but the function was never realized over the years before they were removed from service in 2022.

Figure 1.2: An electric bus with range extender

The author's bachelor thesis, developed in Beijing Jiaotong University trying to develop a system to deploy different types of buses according to demand of lines was not very successful due to limited knowledge at that time and lack of analyse to its benefits.
As a result of learning all those current developments of BEB and combining knowledge, inspirations and experiences, the author proposes the idea of an adjustable electric bus.

- **an adjustable BEB would be able to change the number of seats, quantity of battery sets and the height of floor (accessibility) to adapt to different types of lines. For example, in cities it will have low floor and carry hordes of passengers; but for regional lines, it will convert to a layout similar to intercity bus and provide seats to long-distance travellers. It makes use of difference of peak times between city and regional lines so that the departures normally need two buses (one regional and one city bus) can be covered with only one variable BEB. When converting the adjustable BEB to city bus layout, battery sets will be removed along with seats so that dead weight of the vehicle can be saved for carrying more passengers and reducing energy consumed.**

1.3. Research gap

As it was stated in the previous chapter 1, saving resources and materials makes BEB better adapt to current policy and economy trends. There have been plenty of research to saving number of BEBs by selecting appropriate features for BEBs, choosing fast charge to save time and batteries or simply apply more smarter dispatching logic. These approaches do make BEB procurement and operation more effective, but one common character of them is that they are always seeing vehicle as the minimum unit and seeing single-operator bus network as maximum structure. All changes were made in between the two levels on both real-world and digital aspects. In those research vehicles do come with more detailed factors like battery sets and interior layouts, but they work as fixed parts in the vehicle despite changing of those factors as result of the research.

This does not conclude that no research was done to changing vehicle themselves. On BEBs, swappable batteries has been studied and applied to both passenger cars and busses. From past to the future, there are plenty of mature research on interchangeable interior of various vehicles. The MPV or so-called minivan firstly independently developed by Renault in Europe in 1980s have had re-configurable interior to carry either passengers or cargo [41]. In the future of autonomous passenger cars, changing the configuration of (including driver's) seats is also considered possible and requires enhanced monitoring [5]. The mentioned research completed by Leyland [9] made use of a modified adjustable bus and some wooden models to simulate different floor height and cabin layout.

On other types of vehicles including airplanes, high-speed trains, their interior can also adjust between carrying cargo and people. Adjustable interior has been applied to diesel buses [9] too, although it was only an experimental design: nowadays most buses are developed for different demand and having a fixed layout, it seems unnecessary to spend more money to make it adjustable. Bus manufacturers have developed low-entry buses that has both seat platforms in the back and accessible cabin in the middle and front to face various demand.

Therefore, in real application adjustable bus interior was poorly applied. In 2001 Hess AG from Switzerland developed a Bustrain trailer to give extra capacity for single vehicle [19], which is a kind of external change to both passenger cabin and vehicle geometry size instead of only interior.

The idea of adjustable interior has not been widely studied on BEB. By combining swapping battery and adjustable interior, things may turn out to be unexpected. When talking about the idea of an adjustable BEB (MBEBS), there are still problems and characteristics to be discovered and solved. It is unclear if an adjustable BEB is feasible to some kind of timetable. Possibility to dispatch adjustable BEBs under a timetable and whether applying adjustable BEBs is better than traditional BEBs on economic perspective are unclear too. Is adjustable BEB able to replace all traditional BEBs, partially, or completely not favorable for some reason?

1.4. Research objective and questions

Having seen current research developments to (electric) buses and research gaps on adjustable BEB, the following main research question is brought to the table:

- **What are the design, estimation and assessment to the feasibility and cost-benefit performance of an adjustable BEB?**

The main research question can be divided into the following subquestions:

1. What makes an adjustable BEB?
    (a) -What substructures does an adjustable BEB have?
    (b) -How do these substructures organize and work as a complete vehicle?
2. Can the adjustable BEB be applied to bus networks?
    (a) -How does the adjustable BEB perform on simple networks?
    (b) -Is adjustable BEB feasible to networks?
    (c) -What intermediate conclusions of applying adjustable BEB can be concluded?

3. What are the operation cost and benefit of (the adjustable) BEBs?
    (a) -What does a complicated archetype bus network for the adjustable BEB look like?
    (b) -What are the characteristics of different BEBs to be applied?
    (c) -Which research and reference BEB vehicle cases should be adopted?
    (d) -Which factors will be taken to calculate cost of different BEBs?
    (e) -What are the values of cost and benefit related factors taken into account?
    (f) -What is the output of applying different cases to the archetype network?
    (g) -What is the general cost-benefit performance of the adjustable BEB?
4. What is the potential of the adjustable BEB?
    (a) -Which scenarios are created considering the change of factors?
    (b) -What is the result of cost and benefit comparison in different scenarios?
    (c) -How are the sensitivity of each factors in the cost-benefit analysis and for the adjustable BEB?
5. Other general questions:
    (a) -What is the general cost-benefit performance of the adjustable BEB among scenarios?
    (b) -What (dis)advantages of the adjustable BEB can be summarized?
    (c) -What conclusions are there for the application of (the adjustable) BEB?
    (d) -Are there any other limitations or opportunities for (the adjustable) BEB and its research?

To sum up, the objective of this research is:

- **Define a type of adjustable BEB, discover its application in timetable and compare its long-term cost-benefit performance with other existing BEB types under a set-up network.**

Research Delivery

This research delivers this full report itself and a scientific paper formatted summary which include the definition, modelling of an adjustable BEB and CBA comparison between reference fleet cases using adjustable BEBs and other related types of existing BEBs.

1.5. Methodology

According to research questions, the whole research will be divided into three phases. First, what an adjustable BEB is and how it works have to be clarified. Next, the adjustable BEB will be put into a mimic but realistic network to compare with some real reference and research cases using existing types of BEBs. Then, cost and benefit of each cases will be analysed based on data collection and a CBA. Data collection is always an important part of this research since it might be very sensitive to the result. This would also be quite time-dependent since data from multiple fields are needed like EV and BEB vehicle engineering. CBA will come with more than one numerical solution since there will be multiple scenarios for the network and inside which sensitivity of each factor will be analysed. Sensitivity analysis will be a considerable part of the content since the cost values might be highly variable. Beyond the three stages, a conclusion to the whole research and some recommendations to the adjustable BEB will be completed. The following figure shows the process of this research.

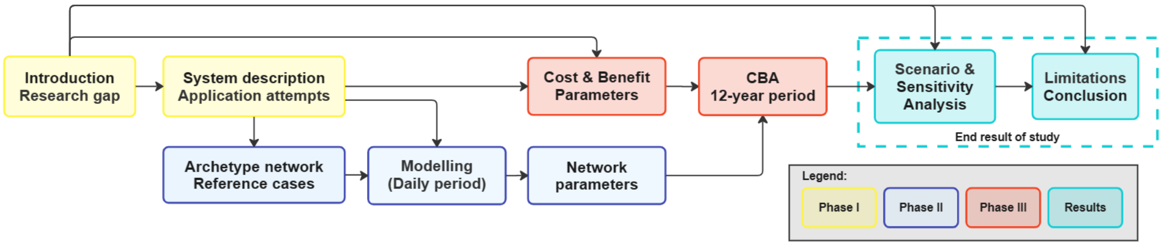


Figure 1.3: Flow chart of the research

1.5.1. Phase I – Basic research

In this phase the first series of research subquestions will be answered. To analyse the adjustable BEB, definition and mock-up design of the adjustable BEB will be proposed. Also, some basic regulations and principles for applying the adjustable BEB will be explored by timetabling from simple to relatively complex.

Expected methods and tools

This process is based on desk research and case studies that the author have had or having. Also, simple timetabling processes made by hand to calculate number of vehicles will be carried out to verify performance of the adjustable BEB and discover principles of applying the adjustable BEB in a more complex network.

Potential case studies and required data

The case study are focused on existing bus vehicles and networks. City, regional and combined networks and multiple types of busses are studied. Data are retrieved from websites, vehicle records, maps, papers and the Author's own collection, which includes types different BEB and their characteristics.

1.5.2. Phase II – Network modelling

This phase focuses on application of this variable BEB sticking to real cases. An archetype of bus network simulating real networks and meets the idea of this variable BEB will be set up. Research cases using different mix of BEBs and real cases using different mix of existing BEBs will be provided to the archetype network. Total number of vehicles needed for the network during a working day and other necessary parameters in each cases will be retrieved by modelling this network. Also, number of infrastructures and operation maneuvers (energy consuming, swapping, people transported) will be recorded.

Expected methods and tools

Interviews with bus manufacturers are carried out to help defining the parameters of variable BEB and existing BEBs to be modelled. Papers were read to backbone the calculation of bus energy consumption. The network will be developed based on desk research and case studies similar to those in phase I. Data processing tools like Excel will be applied to build and solve this network model to get number of vehicles. It will also be applied to estimation and statistics of operation maneuvers.

Potential case studies and required data

In this phase case studies to bus networks are needed but useful information can also be found in case studies completed in phase I. Knowledge on building and solving bus network models are studied from previous phases of research and literature.

1.5.3. Phase III – CBA Analysis

In this phase, pricing parameters like vehicle prices and energy price needed in CBA will be collected. Based on pricing data and result of modelling, the daily operation and infrastructure cost of this system will be calculated. Social benefit and total cost-benefit performance will also be analyzed in this phase. When all social-economic performances of different research and reference cases are clear, a long-term CBA of all cases will be completed. The result of CBA will answer the feasibility of this variable BEB comparing with existing BEBs. Since data from multiple external fields are needed, sensitivity and scenario analysis will be carried out in and after the CBA. Therefore, research questions in the third series and some of which in the fourth series will be answered.

Expected methods and tools

Appraisal methods Cost-Benefit Analysis (CBA) and its analysis executed by data processing software like Excel will be used. As a new concept of bus system, innovation theories will be applied to help prove (or deny) the adjustable BEB's feasibility after completion of CBA.

Potential case studies and required data

In the interview with bus manufacturers, pricing of variable BEB and existing BEBs are learned. Previous CBA cases from lectures are studied in order to better perform CBA of this research. Data of different fields varies in the CBA research period and the adjustable BEB itself is a new product with unknown exact prices. Papers will be read in case they are needed to backbone the situation in each scenario.

2

The adjustable BEB System

In chapter 1, how come of the idea of an adjustable BEB and a rough description to the concept itself have been delivered to let readers know what this research is focused on. In this chapter, more detailed information of components and operation environments of the adjustable BEB can be found.

2.1. Vehicle & infrastructure

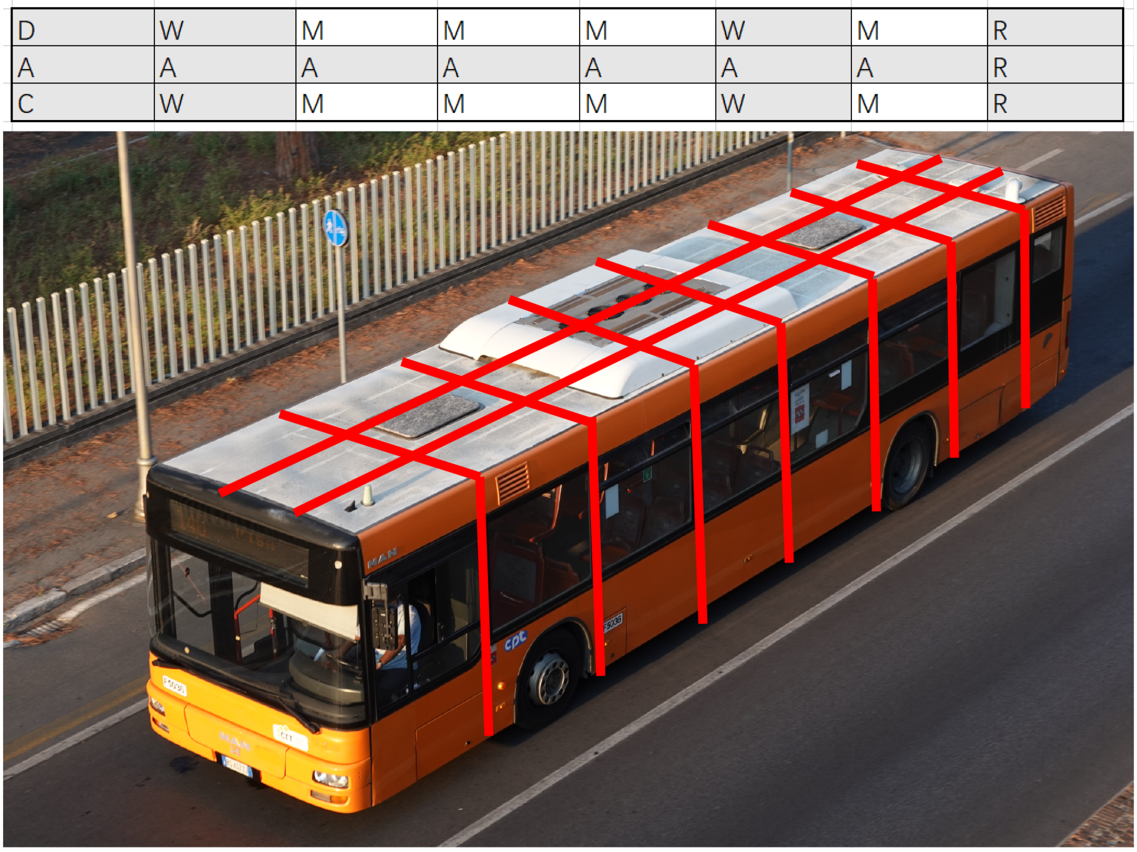
2.1.1. Adjustable BEB chassis & bodywork

Completed vehicle of the adjustable BEB would be a two-axle BEB with an approximate 12-meters length. It would be named ’MBEBS’ taking the first letters of ’Multi-modal BEB System’. It makes use of current in-wheel driven motors which do not occupy any extra space in other parts of the vehicle. As a result, there are two spaces in this bus that keeps an accessible low floor at a full width: behind the rear driving axle and between the two axles.

Figure 2.1: A BYD-brand in-wheel driven BEB

The MBEBS chassis itself can be divided in the following manner. The letter of each part of the cabin means:

- A: Aisle that goes trough the bus
- C: Driver’s cabin
- D: Door
- M: Low-floor spaces
- R: Rear part of the cabin with seats and mechanic spaces
- W: Wheel as a bulge in the vehicle



D	W	M	M	M	W	M	R
A	A	A	A	A	A	A	R
C	W	M	M	M	W	M	R

Figure 2.2: Parts of the MBEBS refer to a real bus

2.1.2. Interior module

With the low floor spaces marked by letter 'M' above available, this vehicle can be filled by a number of standardized interior modules. The interior module can consist of a battery pack and seats above it, a door or a few seats with standing spaces aside. There are 5 types of modules:

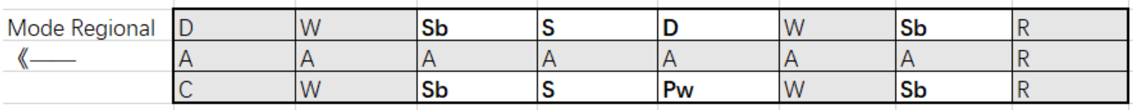
- D: Door
- P: Standing place with one seat
- Pw: Standing place accepts wheelchair
- S: Raised platform with seats
- Sb: Raised platform with seats and battery underneath

For each type of modules, they exact number of space they provide are as follows:

Table 2.1: Characteristics of different interior modules

Type	Meaning	Seats	Stands	Other
D	Door	0	8	1 door
P	Place	2	6	
Pw	Place wheelchair	2	6	1 wheelchair
S	Seats	4	0	
Sb	Seats & battery	4	0	

The module can be inserted or removed from the chassis on both sides. As a result, when more 'S' or 'Sb' modules are inserted, the bus would gain higher floor, more seats and more battery. In the figure it will replace 'M' spaces as follows:



Mode Regional	D	W	**Sb**	**S**	**D**	W	**Sb**	R
⟪——	A	A	A	A	A	A	A	R
	C	W	**Sb**	**S**	**Pw**	W	**Sb**	R

Figure 2.3: Layout of MBEBS in regional mode

This figure of the 'Bierfiets' (beer party bike) shows how the MBEBS is composed of. Being vertical to the driving direction of vehicle, different people with different characteristics (cycling power, weight, drinking) can seat into the vehicle and thus forms different combination of a complete loaded Bierfiets. The structure of the MBEBS is the same but simply replacing people and their characteristics with interior modules and their functions.

Figure 2.4: A Bierfiets helps explanation to components of a MBEBS

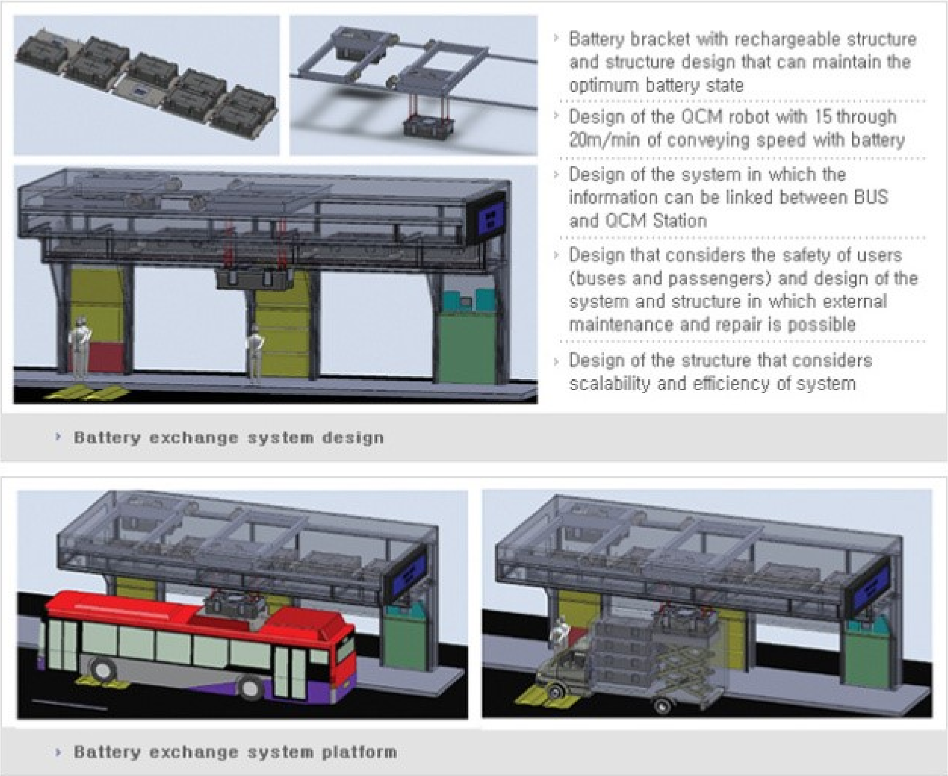
2.1.3. Battery packs

Like any BEB, MBEBS chassis will include a number of fixed standard battery packs to provide a basic driving range. These battery packs would be located on the roof or in the rear 'R' part of the bus. But for MBEBS, battery packs can also be inserted to the chassis as a part of interior module 'Sb'. In this way, the battery packs work as both fillings to raise floor height and driving range providers.

2.1.4. Swapping & interior transfer mechanics

For more than ten years battery swapping have been applied to multiple BEB systems, and there are quite developed research results. Ayad proposed an optimization model for battery swapping BEB systems that considers complex physical and operation constraints which helps the utilizing and decision making process of setting up battery swapping BEB system [1]. Xie used a column generation algorithm to model scheduling of BEBs with different charging modes including battery swapping and plug-in charging [42]. It was also stated that battery swapping would be cost efficiency for high speed and low frequency network, comparing with plug-in charging and moving charging [12].

Since battery packs and seats are included in one interior module, charging to battery packs in this module can work together with transfer (insert and removing) of modules. Modules with used batteries roll out from both side of the bus and transported to a storage with charging function, just like an ordinary automatic battery swapping station for EVs. After 'S' and 'Sb' module are rolled out, other modules (mainly 'P') will enter and the bus becomes a spacious lighter short-ranged city bus.



- Battery bracket with rechargeable structure and structure design that can maintain the optimum battery state
- Design of the QCM robot with 15 through 20m/min of conveying speed with battery
- Design of the system in which the information can be linked between BUS and QCM Station
- Design that considers the safety of users (buses and passengers) and design of the system and structure in which external maintenance and repair is possible
- Design of the structure that considers scalability and efficiency of system

Figure 2.5: A battery swapping station for BEB [35]

In reverse, the bus can remove its 'P' modules and add fully charged 'Sb' modules so that the bus becomes a long-range regional bus ready for use.

2.1.5. Pantograph chargers

Pantograph charger is the second way of charging MBEBS and all the other BEBs in a network. This is a mature technology that has been applied to many BEB systems like Veluwe area in the Netherlands. As it was introduced, pantograph charging can easily reach a high power of 300KW. Bus-down pressing pantograph charging is selected to reduce complexity of charging devices that have to be installed on vehicles.

Figure 2.6: A BEB equipped with bus-down charging rail [37]

Summary

This section gives a brief description to key mechanical parts and the concept of MBEBS as a vehicle and its supporting infrastructures. It can be seen that except the interior module (as a single equipment), other parts make use of mature existing BEB technology that rich experiences can be found as reference. The research will not go deeper on industrial design and realize of the MBEBS chassis and modules. Due to high level of maturity of its subsystems, they are considered ready for use.

2.2. Network elements

2.2.1. City & regional lines

MBEBS will be applied to a bus network consists of both city and regional lines. City lines drive trough city areas that are not covered by other modes of public transport like tram. These lines have at least one of their ends, or an intermediate stop attach to a hub station. For regional lines, they always start at a town surrounding the city and ends at a city hub station.

2.2.2. City hub stations

In city hub stations, there are interior module swapping stations mentioned in previous part to support MBEBS. Space for storage and charging of interior modules are involved. A few pantograph chargers are also installed as a reinforce to any BEB that are in need of fast charging. Totally, besides platforms for passenger boarding and alighting, the hub station will include a bus parking and working area. The following figure shows a sample city hub station for MBEBS.

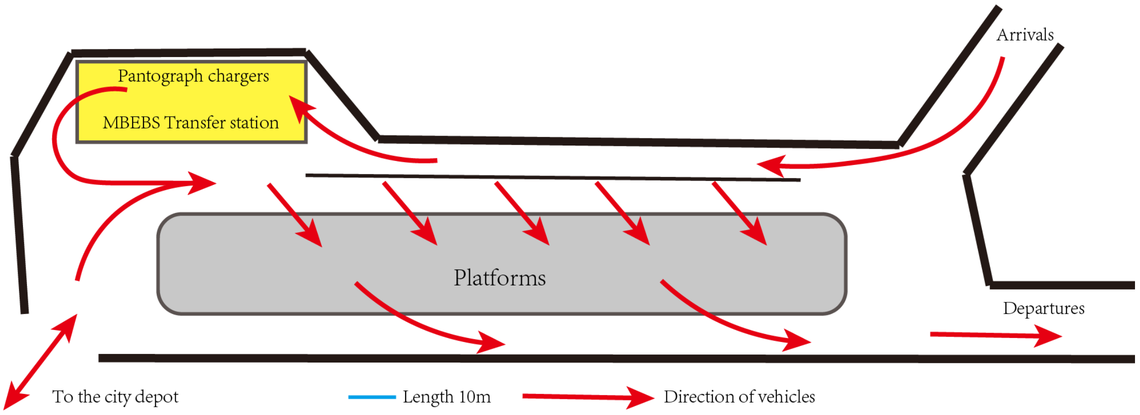


Figure 2.7: A sample MBEBS hub station

2.2.3. End station & depots

On the other end of city lines, pantograph chargers are set up as necessities. BEBs would easily make use of fast charging and regain driving range in a short time. Near the city area a small depot is needed to support all BEBs. It contains vehicles at night along with hub stations. Spare parts storage, repairing and maintenance teams are located in that depot as the same they behave in existing networks. In the suburban area, each depots at the end of regional lines would be provided with slow plug chargers. They guarantee vehicles to have a place to spend the night in suburban area for early departures tomorrow of course but also work as a backup plan for any charging or operation failure.

Summary

These network elements can be represented by the following figure. The structure is essentially a combination of city and surrounding regional network in which infrastructures are edited for operation of MBEBS.

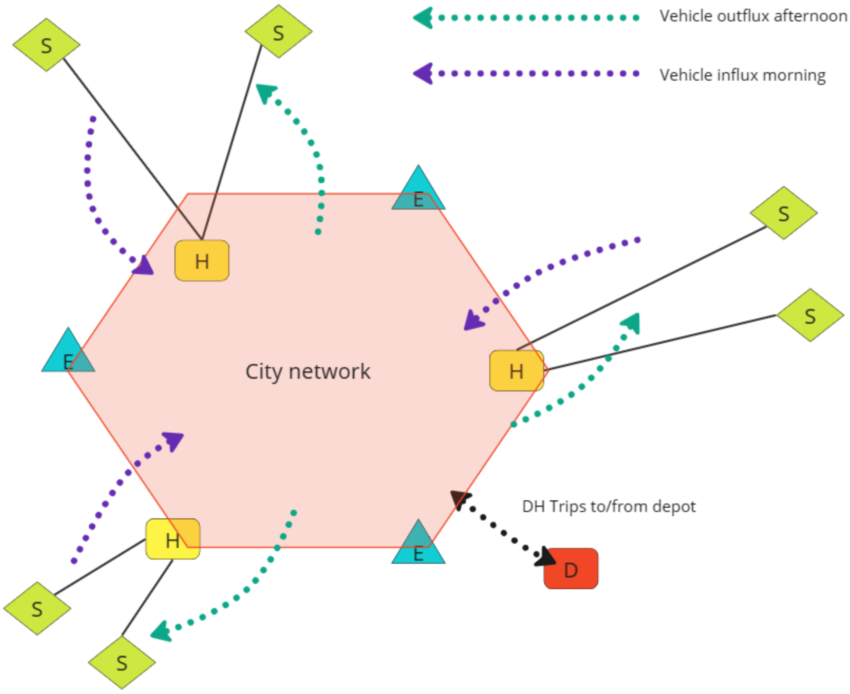


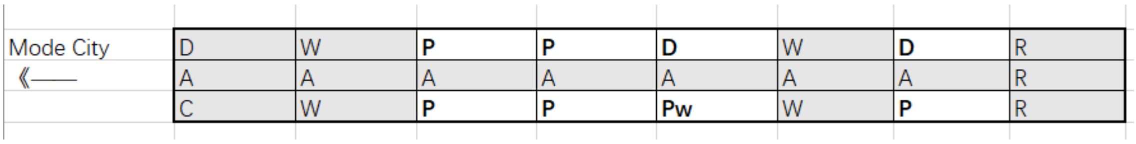
Figure 2.8: A sample operation network of MBEBS

2.3. Operation modes

The MBEBS is assumed to operate with two different modes: city mode and regional mode as it was stated. In this part, the two modes will be described.

2.3.1. Mode 1: City

In this mode, the BEB comes with less battery, less seats, 3 doors and a complete low floor with wheelchair accessible. This mode is designed for city lines which require large capacity and high boarding/alighting efficiency. On city circulations, it uses bus-down pantograph fast charging to drive between end or hub stations. Layout of the interior in this mode is shown as follows.

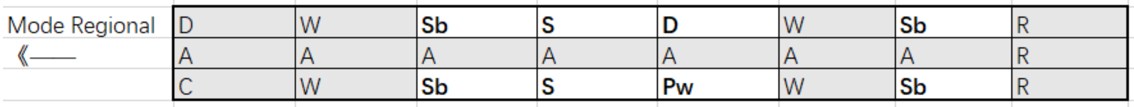


Mode City	D	W	**P**	**P**	**D**	W	**D**	R
《——	A	A	A	A	A	A	A	R
	C	W	**P**	**P**	**Pw**	W	**P**	R

Figure 2.9: Interior layout of BEB interior in Mode 1

2.3.2. Mode 2: Regional

In this mode, the BEB will equip seat modules to make it a high-floor bus with 2 doors, 4 columns of seats throughout the vehicle and more battery packs. This mode is designed for regional lines requiring comfortable seats, high stability and long driving range. When the BEB in this mode comes to city hub stations, it can choose to transfer to city mode, swap used battery modules or use pantograph recharge to keep operating on regional lines. Layout of the interior in this mode is shown as follows.



Mode Regional	D	W	**Sb**	**S**	**D**	W	**Sb**	R
《——	A	A	A	A	A	A	A	R
	C	W	**Sb**	**S**	**Pw**	W	**Sb**	R

Figure 2.10: Interior layout of BEB interior in Mode 2 (the same as chapter 2.1.2)

2.3.3. Transition between the modes

Clearly, there are 4 possible transitions when a MBEBS vehicle enters a city hub station as the following table shows. The first and last transition may not be involved by any movements of interior modules since only charging is needed. The rest two transitions will be described.

Table 2.2: Transfer between modes

Previous service	Next service	Operation
City	City	Pantograph charging
City	Regional	Module exchange
Regional	Regional	Module exchange/Pantograph charging
Regional	City	Module exchange

City to regional

During the peak hours in late afternoon, some commuters leave the city for their home and departures of regional lines increase. Vehicles are needed on those lines while there comes MBEBS vehicles in city mode. As they end city line service at a hub station, they head toward swapping station and exchange city modules with fully charged interior modules during the day. Then they can head for regional line departure platforms for their following trips.

Regional to city

During the peak hours in the morning, people come to the city from suburban towns by regional lines. They and the BEB they are sitting in will arrive into city hub stations when departures of city lines just begin to increase. More city vehicles are needed on city lines as regional mode MBEBS ends regional line service at the hub station. They go to swapping station and change into city interior modules. Then it can drive to city line departure platforms for its day trips. The regional interior models ('S' and/or 'Sb'), left at the swapping station, will be charged and receive possible maintenance until their next use in the afternoon.

2.4. Operation storyline

In this part, a hypothetical brief storyline of one BEB in the MBEBS is provided to better understand operation of the system.

- In the early morning, MBEBS starts at a suburban depot in regional mode;
- MBEBS drives a regional line and reaches a city hub station;
- MBEBS goes to swapping station and transfer to city mode;
- MBEBS runs on city lines during peak hours while interior modules are charged at the hub station;
- In the afternoon, MBEBS returns to a city hub station after some peak rides on city lines;
- MBEBS goes to swapping station and transfer to regional mode by loading fully charged interior modules;
- MBEBS departs from the city hub station for a regional line;
- In the evening, MBEBS ends up at a suburban depot.

2.5. Discovery of MBEBS combined operation

The hypothetical timeline gives an example of co-operating between city and regional lines. The first step of trying MBEBS is to begin with simple multi-vehicle formations composed of those operation timeline above.

Basic service stages

To apply vehicles, a basic timetable must be decided. Except normal double-peaked city lines, two types of city lines namely plateau and daytime lines are proposed. Plateau lines with frequent departures across the day while daytime lines only run in between the two peaks with a fixed frequency. Regional peak lines with and without daytime departures are proposed. Totally, 5 different types of lines are defined. The following table dividing a working day into 5 stages points out transition time of each type of lines (e.g. at 7:00am the line enters morning peak).

Table 2.3: Stage time strips of defined lines

Pattern	Morning	Morning peak	Day	Afternoon peak	Evening	Last departure
Regional line (in)	5:50	6:00	7:30	—	17:30	22:00
Regional line (out)	—	—	7:00	16:30	18:00	23:00
Reg. peak line (in)	5:50	6:00	7:30	—	17:30	22:00
Reg. peak line (out)	—	—	7:00	16:30	18:00	23:00
City line	6:00	7:20	9:30	15:20	17:10	23:00
City plateau line	6:00	—	7:20	—	17:10	23:00
City daytime line	—	—	7:10	—	—	17:10

Basic service frequencies

For each bus lines, during each stages of its operation it has fixed frequency. The following table shows basic frequencies of each types of lines by number of departures per hour.

Table 2.4: Stage frequency of defined lines

Pattern	Morning	Morning peak (MP)	Day	Afternoon peak (AP)	Evening
Regional line (in)	2	6	2	2	1
Regional line (out)	2	2	2	6	1
Reg. peak line (in)	0	2	0	0	0
Reg. peak line (out)	0	0	0	2	0
City line	2	6	3	6	2
City plateau line	2	6	6	6	2
City daytime line	0	3	3	3	0

Having decided frequencies of lines across one (working) day, a basic timetable including exact departure times was drawn up for each lines. To prove these timetables' authenticity, comparison between real and these drawn-up timetable of city and regional lines can be found in the appendix.

Basic timetabling principles

According to the departure times of each lines in the basic timetable, loops of vehicles are divided into the following two parts:

- Daily loops. One or several vehicles runs between the two ends of the line from begin of service till the end. Several daily loops then guarantee a basic level of service of the route.
- Peak loops. Several vehicles sets off only for morning and afternoon peaks so that frequency of lines increase at peak hours.

This is a very traditional approach of scheduling making the timetable neat and easily executable. In the basic timetable, 8 peak rides are added into the regional line in both directions, while totally more

than 10 peak rides are added to a normal city line. Eight extra vehicles are confirmed for single regional line peak service. City lines have symmetric peak rides and shorter duration requires fewer vehicles, but city line loops are more complex than regional line loops since there are multiple types of them. For example, loops of city daytime lines begins later than loops of normal double-peaked city lines.
As a result, considering the both ends of a city line that may not be a hub station or close to one of them, several different approaches of combining city and regional lines are generated. Each combination becomes one formation for MBEBS network timetabling verification. In this process, two cases are applied for each formation in order to show effort of reducing number of vehicles:

- -Case 'I' using city BEB and regional BEB, non-combined service;
- -Case 'II' using city BEB and regional BEB and MBEBS for combined service.

2.5.1. Formation I: One-One Normal

In this formation, one regional line and one city line are combined. The two lines comes with both morning and evening peaks, while for the regional line peaks are single-directional. The exact departure times can be found in the appendix.

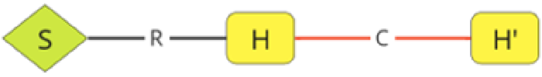


Figure 2.11: Formation I

The result of manual scheduling following loop principles in the beginning of this section, states a minimum of 20 vehicles are needed under Case I (without MBEBS). In Case II, peak rides of both lines are completely covered by 4 MBEBS available at daytime (10:00-15:00). Therefore, the other 4 MBEBS running on regional peak loops (totally 8) are put aside. The regional line will keep using regional BEBs for regional daily loops in order to save vehicle operation complexity. An extra city BEB was added especially for two peak rides that are not able to be covered by MBEBS. It can be solved by adjusting timetable and reducing turnaround times, but in the research they are not considered. Then, a minimum of 17 vehicles are needed in case II. Detailed scheduling of each vehicles can be found in the appendix, while the following table shows number and home depot of them.

Table 2.5: Vehicle usage & allocations in Formation I and II

Vehicle plan		Case I	Case II
	City	8	5
	Regional	12	8
	MBEBS		4 (Any)
	Total	20	17
	DH	16	10
	Shifts		8

Vehicle allocation		H1	H2	S8
Case I	City	4	4	
	Regional			12
Case II	City	3	2	
	Regional			8
	MBEBS			4

2.5.2. Formation II: One-One Plateau

In this formation, one regional line combines with one plateau city line. Difference between Formation I and II is the usage of MBEBS instead of minimum number of vehicles needed. Plateau on the city line allows MBEBS to operate during the whole day before they are transferred back to regional mode. The demand to each type of vehicles in both cases would remain the same as it was formation I. Detailed scheduling of each vehicles can be found in the appendix.

2.5.3. Formation III: One-One Daytime Line

This formation is seen as a variant of Formation II. Being the same as Formation I and II but less vehicle needed in the city line, 16 vehicles are needed in Case I.
A total number of 12 vehicles are needed in case II. MBEBS is able to carry out all services of at least one daytime line by replacing same number of city BEBs. No city BEB can do this in Case I since they are occupied at the same period. In this way, MBEBS crates an opportunity of saving number of city buses on network level. Detailed scheduling of each vehicles can be found in the appendix, while the following table shows number and home depot of them.

Table 2.6: Vehicle usage & allocations in Formation III

Vehicle plan		Case I	Case II
	City	4	
	Regional	12	8
	MBEBS		4
	Total	16	12
	DH	16	8
	Shifts		8

Vehicle allocation		H1	H2	S8
Case I	City		4	
	Regional			12
Case II	City			
	Regional			8
	MBEBS			4

2.5.4. Formation IV: Two-One variants

In Formation I it was stated that under the set-up interval of city and regional lines, there exists surplus of regional peak extra MBEBS while deadheading trips are necessary to send MBEBS away from city hub stations for city peak rides on the other side. However, most city lines lies between two hub stations for better connection to regional services. These facts brings two possibilities of putting more lines into one combination:

- One regional line combining two city lines with different patterns at one hub station;
- Two regional lines combining both ends of one city line at two different hub stations.

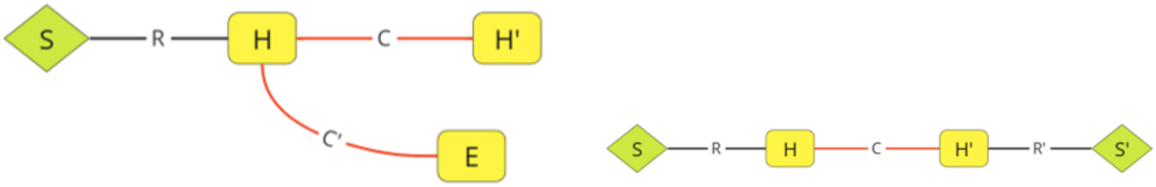


Figure 2.12: Two variants of Formation IV

In the first situation, one normal city line and one daytime city line are combined to one regional line at one hub station. The rest 4 unused MBEBS in Formation I can be used for the daytime line now.

The timetable allows daytime line operates between 7:30am and 16:50pm with MBEBS. Comparing with totally 24 vehicles without MBEBS in Case I, only 17 vehicles are needed for the same timetable in Case II. Detailed scheduling of each vehicles can be found in the appendix, while the following table shows number and home depot of them.

Table 2.7: Vehicle usage & allocations in Formation IV-1

Vehicle plan		Case I	Case II
	City	12	5
	Regional	12	4
	MBEBS		8
	Total	24	17
	DH	16	2
	Shifts		16

Vehicle allocation		H1	H2	S1
Case I	City	6	6	
	Regional			12
Case II	City	3	2	
	Regional			4
	MBEBS			8

The second situation mainly helps reducing deadheading trips of vehicles, improving symmetry of vehicle deploying and more compact connection between departures. Another regional line was added to the other side of the city line in Formation I (Hub station H1). To operate the three lines separately, 32 vehicles are needed which is simply adding 12 from Formation I. With the application of MBEBS, peak rides of the city line is completely taken by MBEBS instead of two departures left aside in Formation I. Thus, 4 vehicles are saved while there are still lots of vacancies for more city lines to be combined. Detailed scheduling of each vehicles can be found in the appendix and the following table shows number and home depot of them. Noticeably, some vehicles does not have to return to their beginning depot in one day, they are having two-day loops.

Table 2.8: Vehicle usage & allocations in Formation IV-2

Vehicle plan		Case I	Case II
	City	8	4
	Regional	24	20
	MBEBS		4
	Total	32	28
	DH	32	24
	Shifts		8

Vehicle allocation		H1	H2	S1	S8
Case I	City	4	4		
	Regional			12	12
Case II	City	2	2		
	Regional			10	10
	MBEBS			2	2

2.5.5. Formation V: Multi-Multi variants

Starting from this formation, pairing of lines rises to network level. Considering a combination of two different situations in Formation V. Using two low-frequency regional lines to combine both ends of more than one high-frequency city lines at two different hub stations helps both saving deadheading trips and creating chances for MBEBS inter-modal application. Some city lines connected to only one hub station can also be seen as a compensation to this formation.

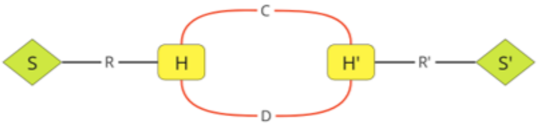


Figure 2.13: Formation V

For example, adding one daytime line operating at both sides from 7:30 to 17:10 to the second situation in Formation IV-2 does not effect the total number of vehicles needed. But without MBEBS, 4 extra vehicles are for sure needed for it. Detailed scheduling of each vehicles can be found in the appendix and the following table shows number and home depot of them.

Table 2.9: Vehicle usage & allocations in Formation V

Vehicle plan		Case I	Case II
	City	12	4
	Regional	24	16
	MBEBS		8
	Total	36	28
	DH	32	16
	Shifts		16

Vehicle allocation		H1	H2	S1	S8
Case I	City	6	6		
	Regional			12	12
Case II	City	2	2		
	Regional			8	8
	MBEBS			4	4

Summary

From simple to complex, 6 formations of network combining have been discovered for MBEBS by timetabling. These combinations has proved the reduction of vehicles that MBEBS can make. As long as they are connected to one hub station, lines can be combined and vehicles will be saved. It also shows the availability of adding vehicles at both ends of a line in a 2+2 simple network. It can be concluded that if the network becomes more complex, the lines (and its adjustable vehicles) can be simply recognized as free to combine in or very close to a hub station without any calculations. Besides, a symmetric allocation of MBEBS is more favourable for reducing deadheading trips and uncombined departures. Having cleared these points, modelling for the archetype network would become much easier for execution.

Table 2.10: Vehicle usage in each formations

Formation	I & II	III	IV-1	IV-2	V Network
No combination	20	16	24	32	36
Combined	17	12	17	28	28
Difference	-3	-4	-7	-4	-8

3

Modelling Preparation

Modelling of a bus network is necessary for quantitative analysis to application of MBEBS. First, structure and demand of the 'real' archetype network that MBEBS will apply to is described. Then, selection and characteristics of vehicles including both MBEBS and competitors are proposed. Next, modelling of number of vehicles and other factors that are in the range of statics will be executed and values will be derived. Finally, the derived values will be transferred to costs by a series of analysis and estimation. In this chapter, the preparation of modelling including data calibration, cases and network building are presented.

3.1. The archetype network

As it was stated, MBEBS works by combining city and regional lines. Thus, a rough structure of the archetype network was set up as the following figure shows:

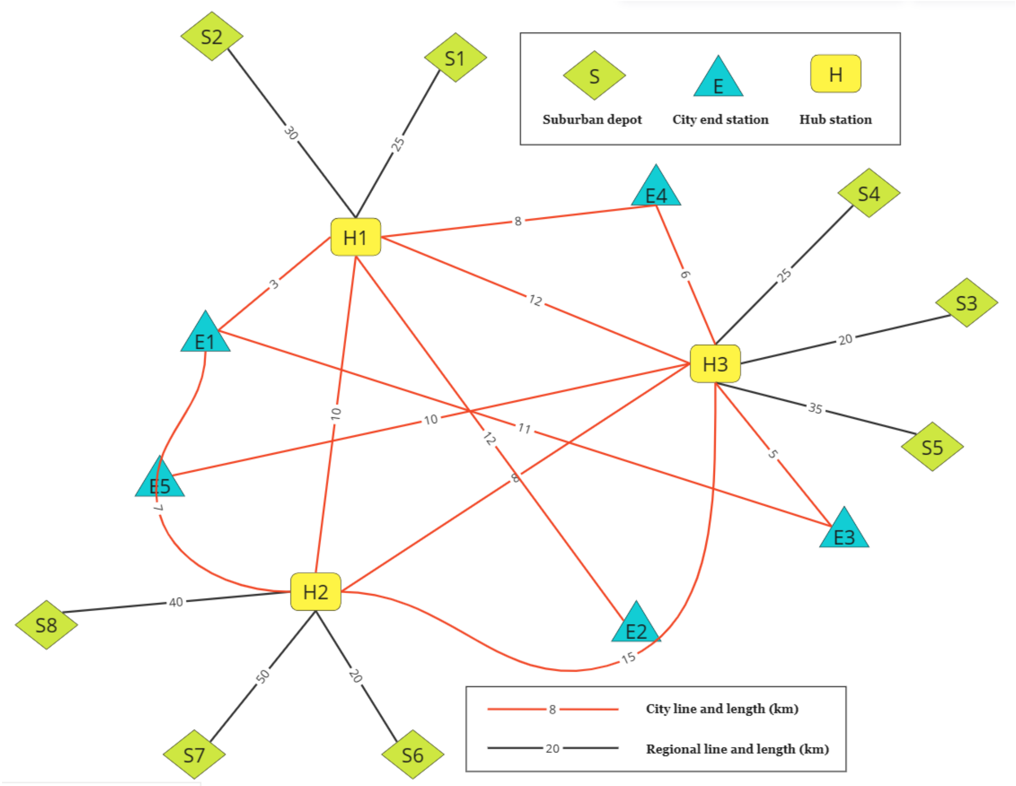


Figure 3.1: Structure of the archetype network

This is a large-scale network centered by a dense city with noticeable internal passenger demand (e.g. commuting, shopping, tourists, entertainment) and commuting demand from 8 satellite towns (each with a bus station namely S1-S8). Around the city center lies 3 transit hubs (H1, H2 and H3) where bus lines depart and end. Between the hub stations and 5 other locations in the city (refer to end stations E1-E5), 12 city lines forms city bus network. The following table shows name, direction, type and length of all the 20 lines:

Table 3.1: Lines in the archetype network: length and connection

Line number	Length (km)	End 1	End 2	Type
11	3	H1	E1	C
12	10	H1	H2	CH
13	12	H1	E2	C
14	12	H1	H3	CH
15	8	H1	E4	C
16	6	H3	E4	C
17	10	H3	E5	C
18	8	H3	H2	CH
19	15	H3	H2	CH
20	5	H3	E3	P
21	7	H2	E1	D
22	11	E1	E3	CE
31	25	H1	S1	R
32	30	H1	S2	R
33	20	H3	S3	R
34	25	H3	S4	R
35	35	H3	S5	R
36	20	H2	S6	R
37	50	H2	S7	R
38	40	H2	S8	R

3.2. Timetable

In this network, timetable of city and regional lines resembles how they were organized in reality. These timetable will not be accurate to every departure, but using the same 5-stage separation in Chapter 32.5.

3.2.1. Standardization of lines

Since different regional lines have different length, their vehicles need to depart at different times according to how far they are away from city hub station in order to take people to the city on time. Considering they arrive and leave at/from city hub stations at same peak time strip, they are standardized to have the same transition time between stages. The standardization of city lines works in the same way as regional lines do since they also answer regular demand at city hub stations. All city lines in the archetype network will use same transition times only with difference of ride duration and frequency at each stages in one day. The following table summarizes frequency and single ride duration of each line at different stages of a day. Noticeably, for regional lines (Line 31-38), the values in peak columns (MP: morning peak & AP: afternoon peak) show number of total PEAK EXTRA departures over the whole peak hours instead of frequency in that hours. The 'Day' column of them refers to its basic service frequency from morning to the end of afternoon peak.

Table 3.2: Lines in the archetype network: frequency and duration

Line	Morning	MP	Day	AP	Evening	Duration (min)
11	2	6	3	6	2	10
12	3	8	4	8	3	30
13	2	5	3	5	2	40
14	3	8	5	8	3	40
15	2	3	2	3	2	25
16	2	4	3	4	2	20
17	2	6	4	6	2	30
18	3	8	5	8	3	30
19	2	3	2	3	1	40
20	0	3	0	3	0	15
21	0	3	3	3	0	20
22	2	5	3	5	2	30
31	2	6	3	6	1	35
32	2	4	2	4	1	35
33	3	8	4	8	2	30
34	2	5	3	5	1	35
35	0	4	0	4	0	40
36	2	6	2	6	1	30
37	1	3	1	3	0	60
38	2	6	2	6	1	50

From this table, number of departures for each city lines at each stages can be calculated using the following equation:

$$P_s^r = \lceil 2f_s^r * (T_s - 60/f_s^r)/60 \rceil$$

Where:

P refers to number of departures;
f refers to frequency of a line at one stage of a day;
T refers to duration of that stage.

Therefore, a table of number of departures of each lines at each stage can be summarized as table 3.3 shows:

3.2.2. Demand

Passenger demand of each rides in specific stage of one day are assumed to be fixed. They are displayed as average in-vehicle load so that intermediate stops will not be involved in the network. There were troubles acquiring real passenger records from operators, so in this research passenger demand was generated by the author. For different types of lines, different number of travellers were assumed. An overview of passenger demand in a low situation can be found in the following table.

Table 3.4: Average ridership by line type and stage

LOW	Morning	MP	Day	AP	Evening
C	3	15	8	12	5
CH	5	30	20	25	10
P	0	10	0	10	0
D	0	10	20	15	0
CE	5	20	10	20	5
R	0	30	20	25	15

Table 3.3: Lines in the archetype network: number of departures

Line	Type	Morning	MP	Day	AP	Evening
11	C	6	28	32	28	22
12	CH	8	37	44	37	32
13	C	6	24	32	24	22
14	CH	8	37	56	37	32
15	C	6	15	20	15	22
16	C	6	19	32	19	22
17	C	6	28	44	28	22
18	CH	8	37	56	37	32
19	CH	6	15	20	15	12
20	P	0	15	0	15	0
21	D	0	15	32	15	0
22	CE	6	24	32	24	22
			MP Extra	Daily Promised	AP Extra	Evening Promised
31	R		6	48	6	12
32	R		4	48	4	12
33	R		8	72	8	12
34	R		5	48	5	12
35	R		4	48	4	12
36	R		6	72	6	12
37	R		3	24	3	0
38	R		6	48	6	12
	Total	66	336	808	336	324

For example, normal city lines in the morning stage has a number of 10, meaning over the whole route of the bus in the morning, there are on average 10 passengers in the bus. The mass of one passenger is set to be 80 kilogram[13].

3.3. Vehicles

Besides MBEBS, other existing BEBs that are widely used currently need to be involved for research case and reference cases. For fair and reasonable comparison, all vehicles are introduced as a 12-meters two-axle version. In this section, technical characteristics of each types of BEB including MBEBS are confirmed. For these BEB vehicles parameters, an interview was carried out with a technician from Chinese bus & coach manufacturer King Long. Useful data were also retrieved from the open RDW information of all kinds of vehicle registered in the Netherlands.

3.3.1. Estimation to energy consuming rate

According to BYD K9A 12-meter city BEB's test rides in 2015 [23], it do has an average consuming of 1,41KWh/km while the maximum consuming rate 1,77KWh/km.

According to the interview with King Long, consuming rate of a standard 12-maters BEB with 350KWh battery rates between 0,8 to 1,2KWh per kilometer.

According to the test to a 12-meters city BEB made by [2], it will consume on average 1,35KWh per kilometer under urban main line conditions and 0,98KWh per kilometer under regional line conditions while fully seated. The fully seated mass of the BEB being tested was 17.554kg.

According to the research carried out by [26], energy consuming rate rises approximately in a linear manner with increase of vehicle mass. Their test shows on a 8,1km long bus line, consuming rate changes between 0,033KWh/100kg and 0,028KWh/100kg. In this research, a fixed value of 0,03KWh/100kg was taken. Therefore, for each kilometers driven, the slope of increasing energy consumption would be 0,0037KWh/100kg*km.

Based on this slope, consuming rate of different types of BEB with different loads can be calculated.

3.3.2. Standard City BEB

City BEBs are equipped with a complete low floor and three doors to increase boarding efficiency. When reinforced by fast charging, they do not need very large battery capacity to operate on short city lines.

Demand of Range

According to the length of lines in the archetype network, in this research city BEBs are required to have a minimum driving range of 30km which is slightly over the round-trip length of the longest city line. By giving a 40% battery capacity redundancy to unexpected temperature, crowdness and traffic jam, the battery capacity of this city BEB would be:

$$(1,4 * 30)/0,6 = 70kWh$$

The design of 70KWh battery fulfills its demand even with high consuming rate.

Weight

From RDW data, it can be concluded that the empty (unladen) vehicle weight of a typical city BEB would be around 13 tons. The following table shows some of these vehicles' empty and maximum weight.

Table 3.5: Weight of different existing BEBs

Type	Empty weight (kg)	Maximum weight (kg)
Volvo 7900 Electric	12.940	19.000
BYD K9A	12.600	18.000
BYD K9UB	13.650	19.000
VDL Citea SLF-120 Electric	13.935	18.745
Ebusco 2.2 12m	12.750	19.000

Taken 13.200kg as the weight of a standard bus with 350KWh of batteries and 19.000kg as the maximum weight of any BEB in this research. From the interview, the weight of battery pack would be 230kg per pack with 35KWh. Therefore, the empty weight of this city BEB would be 11.360Kg.

Capacity & Performance

Difference between empty weight and maximum weight of a bus is its available load. For this city BEB, it has a load of 7.640kg, which equals to 95 passengers having weight of 80kg each [13]. Now look at the layout of the bus. This figure shows a common layout of low floor city bus with 3 doors:

Figure 3.2: Layout of a city BEB

29 passenger seats and 1 wheelchair space are installed. Therefore, city BEB in this research would be able to carry 95 people and 29 seats. A comfortable 80% load of this BEB would be 76 people.

3.3.3. Regional BEB

Regional BEBs have high floor, less doors and more seats to increase comfort. Meanwhile, they equip more battery sets under the seats to operate on long distance lines.

Demand of Range

The longest route in the archetype network is line 37 with single length 50km, therefore the regional BEB in this research is granted to have a 120 kilometer driving range. According to that test of XE40 BEB [2], regional BEBs may have average consumption rate of 0,9KWh/km. By giving a 40% battery capacity redundancy to unexpected temperature, crowdness and traffic jam, the battery capacity of this regional BEB would be:

$$(0,9 * 120)/0,6 = 180kWh$$

Considering more unexpected circumstances and saving of battery life, the regional BEB would be equipped with 210KWh battery, exactly 6 sets of 35KWh battery packs.

Weight

Currently regional BEB have not showing up in the Netherlands frequently, therefore its mass can be estimated from normal 12-maters diesel regional bus.

Figure 3.3: A 12-meters diesel regional bus

This 12,1-meters Mercedes regional bus has a weight of 12.420kg. However, the 12,3-meters long MAN regional bus weights only 11.360kg when empty while 12,3-meters Van Hool regional bus weights 13.090kg. It can be observed that weights of regional bus may vary. On the other hand, according to bus manufacturer Yutong, their 12-meters regional BEB with 295KWh battery has an empty weight of 13.300kg [16]. Therefore, the empty weight of regional BEB in this research will be set to 13.500kg as a high estimation.

Capacity & Performance

The diesel regional buses mentioned above provides at least 50 seats. Therefore, exact 50 seats are promised for the regional BEB in this research according to its 12-meters length (slightly shorter than ones above). There is no worry for 50 passengers to reach weight limit:

$$13.500 + 80 * 50 = 17.500kg < 19.000kg$$

In fact, they can carry another 18 standing passengers before reaching maximum weight. A comfortable 80% load of this regional BEB would be 55 people.

3.3.4. Utility BEB

Sourcing from diesel buses, low-entry buses has accessible low floor at the front and more seats high above in the rear part. Combining the advantages of both city and regional buses, low-entry diesel and electric buses have been widely applied across the Netherlands. This type of bus is considered as another solution to combining city and regional networks as its name 'utility' states. It would be the most direct rival of MBEBS.

Figure 3.4: A Low-entry utility BEB

Demand of Range

The bus is required to have the same range as regional BEB has (120km), while it should be able to deal with urban service with higher energy consuming rate. Taking consuming rate 1,4KWh per kilometer and 40% battery capacity redundancy, the battery capacity of this utility BEB would be:

$$(1,4*120)/0,6 = 280KWh$$

Which is exactly 8 packs of 35KWh battery sets.

Weight

Typical 12-maters low-entry utility BEB made by Ebusco weights between 12.500kg and 13.100kg according to RDW information. Taking 11.200kg as empty weight of a diesel utility bus, the weight of bus with 8 sets of battery would be:

$$11.200 + 230 * 8 = 13.040kg$$

which is reasonable. Therefore, the weight of utility BEB in this research is set to 13.000kg. In fact, it would be very similar to existing low-entry utility BEBs.

Capacity & Performance

For this utility BEB, only 6.000kg would be available for loading passengers which equals to 75 people. For this research, the layout and number of seats can be directly adopted from rea life due to utility BEBs' high similarity with those vehicles. It will be granted with 42 seats. A comfortable 80% load of this utility BEB would be 60 people.

3.3.5. The MBEBS

Functions of the MBEBS vehicle have been described in very details. Here, its characteristics will be confirmed. Basically, in each mode MBEBS would reach a similar or same performance as the type of vehicle it refers to.

Demand of Range

In Mode 1, MBEBS would equip 70KWh of batteries on the roof, refers to city BEB's performance in chapter 3.3.2. In mode 2, when 4 'Sb' modules each with a 35KWh battery set replace 'P' modules, MBEBS would have 210KWh of batteries which is less than that of a regional BEB in chapter 3.3.3.

Weight

The weight of MBEBS in mode 1 would be hard to estimate. Considering the extra weight of interior modules and related structures on MBEBS chassis, it is set to 11.500Kg. In mode 2, the weight is estimated to be:

$$11.500 + 230 * 4 + 50 * 6 = 12.720kg$$

In which 230kg refers to unit weight of battery packs and 50kg refers to extra structural weight of 'S' interior modules comparing with 'P' modules.

Capacity & Performance

According to the layout in both modes proposed in chapter 2.2.3, in mode 1 MBEBS provides 31 seats; in mode 2, MBEBS provides 45 seats. The limit of 19.000kg total weight to all buses allows MBEBS to carry:

$$(19.000 - 11.500)/80 = 93$$

people in mode 1;

$$(19.000 - 12.720)/80 = 78$$

people in mode 2.

A comfortable 80% load of MBEBS would be 74 and 62 people in mode 1 and mode 2 respectively.

Summary

From all analysis to vehicles above, a summary to characteristics of all BEBs that will be involved to this research can be found in the table below:

Table 3.6: Characteristics of BEBs involved

	Doors	Wheelchairs	Seats	Stands	Capacity	80% Capacity	Stands at 80% capacity
(Units)	#	#	Pax	Pax	Pax	Pax	Pax
Standard	3	1	29	66	95	76	47
Regional	2	0	50	18	68	55	5
Utility	3	1	42	43	75	60	18
MBEBS-City	3	1	31	62	93	75	44
MBEBS-Regional	2	1	45	33	78	63	18

	Demanded driving range	Consuming rate low	Consuming rate high	Battery capacity	Battery weight	Body weight	Max. weight
(Units)	km	KWh/km	KWh/km	KWh	kg	kg	kg
Standard	30	1,42	1,7	70	460	11360	19000
Regional	120	1,13	1,33	210	1380	13500	19000
Utility	120	1,11	1,33	280	1840	13000	19000
MBEBS-City	30	1,43	1,7	70	460	11500	19000
MBEBS-Regional	120	1,1	1,33	210	1380	12720	19000

And all real vehicle data values and its sources can be found in the appendix.

3.4. Research cases

The vehicles provided in section 3.3 can be combined in different ways. Firstly, a very basic reference case reflecting current concession-based operation in and around large cities is proposed. In this case, the network is strictly divided into two parts: all regional lines are using normal regional BEBs, while all city lines are using standard city BEBs. Operation of these vehicles do not exchange and interfere with each other. Daytime dwelling of regional buses in city depots are not allowed.

The second reference case is based on another type of existing bus concession in which all bus lines in a whole region are operated by a single operator using utility BEBs. In this case, vehicles are allowed to operate across city and regional network and dwelling at any depot in any time-of-the-day are open for all vehicles.

Three research cases are provided besides the two reference cases. The main research case (naming case R1) of the research would be a combine of traditional city BEB, regional BEB and MBEBS. This case aims to introduce as many traditional (city and regional) BEB as possible to save purchasing cost and the else of the fleet will be MBEBS. The 'as many', refers to using traditional bus on loops that have full usage sticking to one type of line. Daytime dwelling of regional buses in city depots are allowed.

Another research case is to replace the whole system completely with MBEBS, aiming to compare with the reference case of utility BEB on network level.

The last research case is to use limited number of utility BEB. It would be a combine of traditional city BEB, regional BEB and utility BEB. This case aims to introduce as many traditional (city and regional) BEB as possible to save purchasing cost and the else of the fleet will be utility BEBs. The 'as many', refers to using only utility buses that the peak of regional lines provide. Daytime dwelling of regional buses in city depots are allowed. Summary and naming of the 5 cases are shown below:

- Basic reference case, separated operation, city and regional BEB, case A.
- Reference case, combined operation, only utility BEBs, case B.
- Main research case, combined operation, city, regional BEBs and MBEBS, case R1.
- Research case, combined operation, only MBEBS, case R2.
- Research case, combined operation, city, regional and utility BEBs, case R3.

In all reference cases, traditional BEBs are able to use pantograph chargers at end stations or stops in the city and occasional optional cable chargers at suburban stops. Under Zhang et al's assumptions with an 8km short-turning route and 120KW charging power, the bus only needs to stay at the charging station for 5 minutes [45]. So, it can be easily derived that with high power pantograph charging at end stations, buses can regain a considerable driving range enough for city operation cases in a short time, keeping the whole BEB system healthy for residents. The following table shows comparison between organization of all 5 cases.

Table 3.7: Vehicles allowed in each cases

Vehicles	A	B	R1	R2	R3
City bus	x		x		x
Regional bus	x		x		x
Utility bus		x			x
MBEBS			x	x	
Combined city & regional lines		x	x	x	x

There is no reference group with buses using other power sources like diesel, FCB or hybrid buses.

3.5. Other aspects

From the perspective of existing bus network structure, this network would be realistic. In the Netherlands, it can be found in Rotterdam and surrounding areas. However, this network is operated by two operators: RET for Rotterdam city bus and Connexxion for regional lines at southern area.

Figure 3.5: Rotterdam south and its bus network

In the northern part of the Netherlands including Groningen, Friesland area and Zwolle, such combination of regional and city lines can be found. Some of those regional lines do not run on expressway and have slightly more stops but the vehicle will stop only if there is demand.

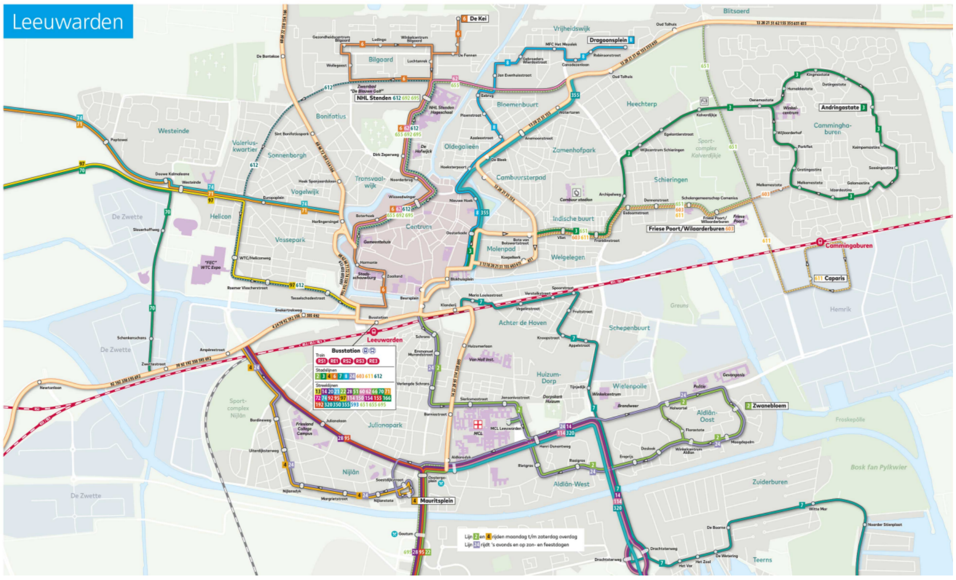


Figure 3.6: Bus network at Leeuwarden: city and regional lines

With the application of MBEBS, this network will be awarded to a single operator. It is possible that the network can be put under one flag. Groningen, Friesland area and Zwolle network are only held by

Qbuzz, Arriva and EBS as above shows. In Belgium, bus transport was united in Region level with sub-operators on regional lines (but operation in provincial level).

Figure 3.7: De Lijn and operators

Based on reality and model requirements, a few more model regulations are added as follows:

1. The model does not consider special, school services and any BEB other than 12-meters length;
2. The model does not consider scheduling of drivers. It is only for modelling vehicles.
3. Variable departure times and ride duration are not considered.

3.6. Summary

In this chapter, in order to prepare for modelling a 'real' archetype network with 20 lines and 3 hub stations was set up. MBEBS and 3 other types of BEB are selected and their characteristics are confirmed. One research case and 4 reference cases are introduced for modelling and following CBA. All these settings are based on real-world data so that the model itself do resembles real situation. The next step is to make use of conclusions in discovering simple MBEBS models to solve this real model and acquire critical parameters as CBA input.

4

Modelling

Serving the CBA, the aim of network modelling is to calculate number of vehicles needed for the network of each cases and record a series of factors including electricity consumption. The following modelling process was based on the research case 'R1': Make use of city BEB, regional BEB and as much MBEBS as possible so long as there is a chance of line combination.

4.1. Vehicle allocation

The vehicle supply from regional lines to three hub stations are as follows:

Table 4.1: Vehicle supply from regional lines

Line	H1	H2	H3
31	6		
32	4		
33			8
34			5
35			4
36		6	
37		3	
38		6	
Total	10	15	17

Before combining lines at hub stations, the number of extra vehicles demand of each city lines also have to be estimated. This cannot be perfectly accurate since in real operation all vehicles will be adjusted according to real departure times of each lines. There might be impossible combinations due to inappropriate arrival times of extra departures on regional lines and extra vehicles are probably needed. A simple formula was applied to estimate number of extra peak vehicles demand of single line [11]:

for conservative estimation:

$$N_c^r = \left\lceil 2(f_p^r - f_d^r) * (D^r + 10)/60 \right\rceil$$

in which:

N refers to number of vehicles,

f refers to frequency of a bus line at a specific stage of one day,

D refers to single trip duration of a bus line,

the number 10 in $D^r + 10$ refers to 10 minutes turnaround time, in the end it was divided by 60 to transfer form minutes to hours.

This formula considers daytime stage as basic service level of a city line. At morning and evening stages, vehicles are partially deployed.

for high estimation:

$$N_c^r = \left\lceil 2(f_p^r - f_m^r) * (D^r + 10)/60 \right\rceil$$

This formula considers the lowest service level during early morning and evening as basis of a city line. Vehicles which are not outsourced will be fully deployed. The result of demand estimation is shown as the follows.

Table 4.2: Peak vehicle demand of each city lines

Line	Low estimation	High estimation	End
11	2	3	H1
12	6	7	H1H2
13	4	5	H1
14	5	9	H1H3
15	2	2	H1
16	1	2	H3
17	3	6	H3
18	4	7	H3H2
19	2	2	H3H2
20	3	3	H3
21	0	3	H2
22	3	4	EE
Total	35	53	

High estimation was adopted for further vehicle allocation process in order to fullt use MBEBS supply. As total demand and supply of vehicles are clear, the next step is to distribute the demand fairly to meet the fixed supply at each hub station. From the summary to formations in chapter 2.5.5 it can be seen that for one city line connecting to two hub stations at both ends, combination becomes more efficient. So firstly, vehicle demands are separated equally for each hub station which forms the first iteration of allocation plan as table 4.3 shows. It can be seen that H2 has a spillage of MBEBS supply of 4 and H1 has a very large shortage of 8 vehicles.

Vehicles balancing situation of long city lines is shown as follows:

Table 4.4: Allocation of important (sets) of city lines in the beginning

Lines	H1	H2	H3
12	3.5	3.5	
14	4.5		4.5
18		3.5	3.5
19		1	1
15&16	2		2
11&21	3	3	

Table 4.3: Vehicle allocation in the beginning

Type	Line	SUPPLY	Hub	DEMAND	Line	Type
MBEBS	31	6	H1	3	11	MBEBS
MBEBS	32	4	H1	3.5	12	MBEBS
			H1	5	13	MBEBS
			H1	4.5	14	MBEBS
			H1	2	15	MBEBS
	Total	10	H1	18	Total	
MBEBS	36	6	H2	3.5	12	MBEBS
MBEBS	37	3	H2	3.5	18	MBEBS
MBEBS	38	6	H2	1	19	MBEBS
			H2	3	21	MBEBS
	Total	15	H2	11	Total	
MBEBS	33	8	H3	4.5	14	MBEBS
MBEBS	34	5	H3	2	16	MBEBS
MBEBS	35	4	H3	6	17	MBEBS
			H3	3.5	18	MBEBS
			H3	1	19	MBEBS
			H3	3	20	MBEBS
	Total	17	H3	20	Total	
			E	4	22	MBEBS
	Total	0	E	4	Total	

This does not match the supply of MBEBS to each hub station by regional lines. In the following iteration, number of vehicles are changed into integer, moving away from H1 and moved to H2 to fill the gap. This causes an uneven vehicle allocation for line 12.

Table 4.5: Vehicle allocation iteration 1

Type	Line	SUPPLY	Hub	DEMAND	Line	Type
MBEBS	31	6	H1	3	11	MBEBS
MBEBS	32	4	H1	0	12	MBEBS
			H1	5	13	MBEBS
			H1	4	14	MBEBS
			H1	2	15	MBEBS
	Total	10	H1	14	Total	
MBEBS	36	6	H2	7	12	MBEBS
MBEBS	37	3	H2	4	18	MBEBS
MBEBS	38	6	H2	1	19	MBEBS
			H2	3	21	MBEBS
	Total	15	H2	15	Total	
MBEBS	33	8	H3	5	14	MBEBS
MBEBS	34	5	H3	2	16	MBEBS
MBEBS	35	4	H3	6	17	MBEBS
			H3	3	18	MBEBS
			H3	1	19	MBEBS
			H3	3	20	MBEBS
	Total	17	H3	20	Total	
			E	4	22	MBEBS
	Total	0	E	4	Total	

The second iteration has balanced total demand by making some of the lines unevenly gaining their MBEBS vehicles:

Table 4.6: Allocation of important (sets) of city lines iteration 1

Lines	H1	H2	H3
12	0	7	
14	4		5
18		4	3
19		1	1
15&16	2		2
11&21	3	3	

Extra vehicles are always needed in the high estimation. In this iteration, extra vehicles flows into H1 and H3. 7 standard buses are added in which four pieces to line 14 at H1 and the rest three goes to H3 for branch line 20. In this way, line 12 was again balanced.

Table 4.7: Vehicle allocation iteration 2

Type	Line	SUPPLY	Hub	DEMAND	Line	Type
MBEBS	31	6	H1	3	11	MBEBS
MBEBS	32	4	H1	3	12	MBEBS
Standard	Depot	4	H1	5	13	MBEBS
			H1	4	14	Standard
			H1	2	15	MBEBS
	Total	14	H1	18	Total	
MBEBS	36	6	H2	4	12	MBEBS
MBEBS	37	3	H2	4	18	MBEBS
MBEBS	38	6	H2	1	19	MBEBS
			H2	3	21	MBEBS
	Total	15	H2	12	Total	
MBEBS	33	8	H3	5	14	MBEBS
MBEBS	34	5	H3	2	16	MBEBS
MBEBS	35	4	H3	6	17	MBEBS
Standard	Depot	3	H3	3	18	MBEBS
			H3	1	19	MBEBS
			H3	3	20	Standard
	Total	20	H3	20	Total	
			E	4	22	MBEBS
	Total	0	E	4	Total	

Table 4.8: Allocation of important (sets) of city lines iteration 2

Lines	H1	H2	H3
12	3	4	
14	4 (Standard)		5
18		4	3
19		1	1
15&16	2		2
11&21	3	3	

In the last iteration, more vehicles are added to fill the last gaps and extra MBEBS vehicles at H2 are moved to nearby end stations by short deadheading trips. As line 17 receives MBEBS from H2 at E5, it is well balanced and 3 MBEBS at H3 can work for line 20; 4 standard buses are added to both sides of line 22.

Table 4.9: Vehicle allocation iteration 3

Type	Line	SUPPLY	Hub	DEMAND	Line	Type
MBEBS	31	6	H1	3	11	MBEBS
MBEBS	32	4	H1	3	12	MBEBS
Standard	Depot	4	H1	2	13	MBEBS
Standard	Depot	3	E2	3	13	Standard
			H1	4	14	Standard
			H1	2	15	MBEBS
	Total	17	H1	17	Total	
MBEBS	36	6	H2	4	12	MBEBS
MBEBS	37	3	E5	3	17	MBEBS
MBEBS	38	6	H2	4	18	MBEBS
			H2	1	19	MBEBS
			H2	3	21	MBEBS
	Total	15	H2	15	Total	
MBEBS	33	8	H3	5	14	MBEBS
MBEBS	34	5	H3	2	16	MBEBS
MBEBS	35	4	H3	3	17	MBEBS
			H3	3	18	MBEBS
			H3	1	19	MBEBS
			H3	3	20	MBEBS
	Total	17	H3	17	Total	
Standard	Depot	2	E1	2	22	Standard
Standard	Depot	2	E3	2	22	Standard
	Total	4	E	4	Total	

Considering the possible DH trips problem and time constraints of city branch lines and for redundancy, 5 more standard BEBs are prepared for each city end station. A final summary for vehicle numbers and allocation are as follows.

Table 4.10: Final vehicle allocation of city lines

Lines	H1	H2	H3
11_21	3	3	
12	3	4	
13	2	3 (E2 Standard)	
14	4 (Standard)		5
15_16	2		2
17		3 (E5)	3
18		4	3
19		1	1
20			3
22	2 (E1 Standard)	2 (E3 Standard)	
Extra	5 (Standard)		

For the research case, the usage of each type of vehicles can be summarized as follows:

Table 4.11: Vehicle usage case R1

Vehicles	H1	H2	H3	City depot	Total
City BEB	11	9	10	16	46
MBEBS	10	15	17		42

The vehicle demand of each cases are shown in the following table. Case R1 uses 46 city BEBs, 42 MBEBS and a number of region BEBs to support daily loops of regional lines.
For case A, 42 regional BEBs and 46 city BEBs are added to compensate the absence of MBEBS. For the theoretical 46 city BEB, the five redundant vehicles can be removed since all vehicles for city lines are ready in the city depot without worry about failed connections. Therefore in total 46+42-5=83 city BEBs goes to city network for both daily and peak rides;
For case B, 88 utility BEBs replace all vehicles in case R1;
For case R2, 88 MBEBS replaces all vehicles in case R1;
For case R3, the number of city BEBs does not change, but the 42 MBEBS in case R are replaced by utility BEBs.

Table 4.12: Vehicle usage in all cases

Vehicles	A	B	R1	R2	R3
City BEB	83		46		46
Regional BEB	X+42	X	X	X	X
Utility BEB		88			42
MBEBS			42	88	
Total	X+125	X+88	X+88	X+88	X+88

It is noticeable that there is no accurate statistics to regional BEBs operating daily loops of regional lines since they are all the same in different research and reference cases, from number of vehicles and infrastructures to departures. They were finally cancelled out in the CBA process. In order to reduce complexity of calculation, those regional BEBs are ignored by removing that 'X' value in the table above.

Table 4.13: Vehicle usage in all cases except basic regional BEBs

Vehicles	A	B	R1	R2	R3
City BEB	83		46		46
Regional BEB	42				
Utility BEB		88			42
MBEBS			42	88	
Total	125	88	88	88	88

Based on this vehicle allocation plan and timetable of each lines, the share of each type of vehicles of each lines at every stage-of-the-day was calculated.

4.2. Vehicle consuming

4.2.1. Operation trips

It has been clarified that energy consuming rate of a BEB depends on route profile and load[2]. So in order to calculate energy consumption, the total kilometers driven by each type of vehicles of each lines at every stage-of-the-day should be derived. Again, according to the research carried out by [26], the relationship between vehicle load and average kilometer energy consumption is approximately linear. Therefore, the research considers average kilometer energy consumption at a specific load with the following equation:

$$C_M^V = C_{min}^V + M \frac{C_{max}^V - C_{min}^V}{M_{max}^V - M_{min}^V}$$

For the load of a specific type of vehicle on a specific line during a specific stage, it is calculated using the following equation:

$$M(r) = P_r * 80$$

Where P is the number of passengers.

As a developed country, population of the Netherlands grows in a slow but steady pace[34]. In this research, passenger demand remains the same across time, but 3 different scenarios are given for different level of willingness of using buses as the following table shows.

Table 4.14: Average ridership low

LOW	Morning	MP	Day	AP	Evening
C	3	15	8	12	5
CH	5	30	20	25	10
P	0	10	0	10	0
D	0	10	20	15	0
CE	5	20	10	20	5
R	0	30	20	25	15

Table 4.15: Average ridership intermediate

MED	Morning	MP	Day	AP	Evening
C	5	25	12	20	10
CH	15	50	35	40	20
P	0	20	0	20	0
D	0	15	30	20	0
CE	8	30	15	35	30
R	0	40	25	35	18

Table 4.16: Average ridership high

HIGH	Morning	MP	Day	AP	Evening
C	10	40	20	35	15
CH	20	70	50	60	30
P	0	30	0	30	0
D	0	20	40	25	0
CE	10	40	20	35	10
R	0	50	30	50	20

Therefore the load and driving distance can be used for energy consumption calculation. The single trip energy consumption of a specific type of vehicle on a specific line during a specific stage is calculated using the following equation:

$$W_{rS}^{V} = C_{M(r)}^{V} * L_r$$

Where:
W refers to energy consumption of one type of vehicle with assigned load,
C refers to average kilometer energy consumption at this load,
L is the length of that ride.

For some stages of some lines that are run by more than one type of vehicle, number of departures of each type of vehicle are simply divided by fraction of that type of vehicle in the fleet of that line in that stage. Adding all types of vehicles, lines and stages together, the total energy consumption of each cases over one working day at indicated ridership can be derived as the following table shows:

Table 4.17: Daily energy consumption in each cases

LOW RIDERSHIP	A	B	R1	R2	R3
Energy (KWh)	47.579	48.249	47.490	47.184	47.840

4.2.2. Deadheading trips

In all cases vehicles are forced to come from or return to depot when it begins or ends peak service. In reference case A where there is no combination between regional and city network, the peak vehicles have to return to suburban depots. Therefore, for each peak vehicles in case A, the length of its deadheading trip equals to length of the regional line it serves.

In other cases, peak vehicles are allowed to park at the city depot. The length of their deadheading trips is set to 10km. Each peak vehicle would drive two deadheading trips per day, one from city hub station to suburban or city depot, the other vice versa. Total distance they drive can therefore be calculated and it is known that they drive with empty vehicles. Using the same way of calculating consumption of operation trips, the energy consumption of deadheading trips in each cases can be calculated as follows:

Table 4.18: Daily deadheading energy consumption in each cases

kWh	A	B	R1	R2	R3
Number of DH	84	84	84	84	84
Vehicle	Regional	Utility	MBEBS	MBEBS	Utility
Consumption	2.723	932	924	924	932

Result

By adding energy consumption of operation trips and deadheading trips up, total energy consumption of each cases in one day can are shown as follows:

Table 4.19: Daily total energy consumption in each cases

LOW RIDERSHIP	A	B	R1	R2	R3
Energy (KWh)	50.302	49.182	48.414	48.108	48.773

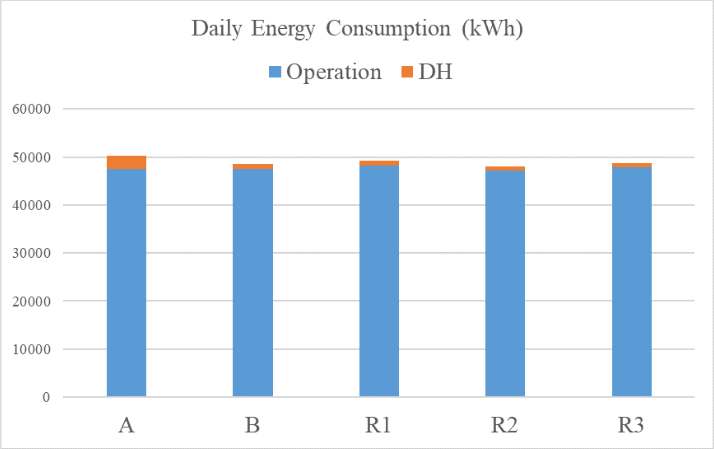


Figure 4.1: Daily energy consumption of each cases, low ridership

4.3. Infrastructure

Considering the maximum frequency would be 6 departures per hour among all city lines, one pantograph charger will be granted to each city lines at city end stations except line 12, 14 and 18 having 8 departures per hour. To support MBEBS, special swapping stations are needed at all three city hub stations. Meanwhile, at city end stations, it was stated that pantograph chargers are necessary since MBEBS will have to use them for city lines. These will be the same for both case R1 and case R2. As a result, the number of pantograph chargers and redundant cable chargers in all cases would remain very little differences. These would also be cancelled as well as background regional BEBs. The only difference is number of vehicles that are equipped with vehicle side plugs. Total number of infrastructures that are taken into account is as follows.

Table 4.20: Number of infrastructures in each cases

Item	A	B	R1	R2	R3
Swapping stations	0	0	3	3	0
Pantograph rails on vehicles	125	88	88	88	88
Cable charging plugs	42	88	42	88	42

4.4. Passenger effects

Passengers choose to stand or seat in the bus during the trip. Crowd in city lines and standing for a long distance on regional lines influence passengers' experience. In this research, load rates and number of standing passengers are measured for further analysis. Standing and seat capacity of each type of BEBs have been provided in chapter 3.3 defining vehicles while 3 levels of ridership has been clarified in section 4.2.1.

On city lines, crowdness would be of more importance than seats since people mostly travel with lower speed and shorter distance than regional lines. In contrast, granting seats would become an important indicator of regional service. Statistics aiming at these two indicators will be elaborated separately on each parts of the network. Considering unchanged passenger demand across the whole period and the low difference of capacity performance between vehicles (and cases), a qualitative analysis is executed. The following result would become references for CBA analysis.

The way of calculating load rate of a specific type of vehicle on a specific line during a specific stage would be similar as calculating vehicle mass:

$$F_{rS}^{V} = G_{S}^{r}/C_{P}^{V}$$

Where:

F refers to load rate;

G refers to number of passengers;

C_p^V refers to capacity of one type of bus.
This value will be used for weighted calculation to average load rate in each stages of each cases.

Using number of seats minus number of passengers, number of people without a seat on a specific line during a specific stage in a specific type of vehicle is as follows:

$$Y_{rS}^V = \max(0, G_S^r - C_s^V)$$

Where:
C_s^V refers to sitting capacity of one type of bus.

With a low level of ridership, the weighted ridership in each stages of one day for each cases is as follows. The weighted ridership is calculated by averaging load rate of each lines according to total distance driven:

$$F_S = \left(\sum_{r \in city}^{r} \sum^{v} F_{rS}^v * L_r * P_S^r \right) / \left(\sum_{r \in city}^{r} L_r * P_S^r \right)$$

A simple qualitative rating to each cases is performed in the last column.

Table 4.21: Crowdness of city lines in each cases

LOW RIDERSHIP	Morning	MP	Day	AP	Evening	Rating
A	5.6%	29.8%	21.7%	25.5%	9.9%	+
B	7.1%	37.8%	27.5%	32.4%	12.6%	- - -
R1	5.6%	30.0%	21.8%	25.7%	9.9%	0
R2	5.7%	30.2%	22.0%	25.9%	10.1%	-
R3	5.6%	33.5%	23.0%	28.7%	9.9%	- -

On regional lines, there is no standing passengers at low ridership for any cases. In the following chapter of CBA, a qualitative analysis to ridership parameters in all 3 scenarios will be carried out.

4.5. Summary

From the perspective of number of vehicles, three out of four cases ('B', 'R2' and 'R3') are having the same value as the research case 'R1'. However, they come with different mix of utility BEB, regional BEB and MBEBS. These vehicles may differ in price, energy consumption and capacity so that these cases are necessary to be presented. Their (dis)advantages will be revealed in the CBA process.

Since vehicles in this research are designed to have similar capacity and seats layout, difference of passengers' experience between cases are relatively small. The result will not be discarded but restored as qualitative reference of cost parts of CBA.

Before entering the energy price and receiving monetary result of the CBA, MBEBS already shows its potential on saving energy. However, its operation cost and infrastructure cost are still big issues to be measured and it is yet unknown that if MBEBS's advantage of saving energy would cover any other hidden extra costs.

5

CBA Analysis

In a CBA process, parameters will be transferred into monetary values for comparison. In the first section of this chapter cost of all network elements will be estimated.

5.1. Cost Parameters

5.1.1. Vehicle & Parts

During that interview with a technician from King Long, pricing information of modelled BEB vehicles and parts were also collected. Besides, pricing information of completed BEB vehicles are collected from the Internet and an interview with one of the author's friends from University of Stuttgart. As a mostly classified information, real price of batches of buses are hard to estimate which is only possible via news and occasionally found procurement presentations. Procurement presentation of 10 Standard BEBs (with chargers) in Novi Sad of Serbia gives an average price of less than €0,6M per vehicle [14]. In Belgium, De Lijn bought Van Hool A12 with a single price of €0,55M. In Germany, the single VDL-branded bus purchased by the city of Neuss was also €0,55M. These buses are equipped with large capacity batteries (>300KWh) and do not have to charge during operation. Through the interview, the author was informed for such a long-range bus, battery sets takes up about 30% of the total price.
It can be estimated that for the standard BEB in this research with 70KWh battery, the price will be as low as to €0,4M-€0,45M. For regional BEB in this research, price was set to €0,45M-€0,5M considering similar battery capacity as listed standard BEBs but cheaper parts (axles) and vehicle body. The price of utility BEB, having a relative high battery capacity and a low entry, was set to €0,5M-€0,55M.
For MBEBS chassis, the situation is more complex. It has similar but simpler structure than a complete standard BEB, but its structure should be strengthened and customized for interior modules. It is estimated the price of chassis varies also between €0,4M-€0,45M.
Price of an interior module varies. It includes:

- (0-1) battery packs and its cables;
- Rigid structures, seats and overall decoration;
- Joints and rails for connection and transfer.

To fulfill MBEBS operating in both modes, not only 8 but at least 10 interior modules are needed. Pricing of each types of module and its reason is written in the following table. By adding up these value, price of a full MBEBS with all modules would be €0,5M-€0,55M.

Table 5.1: Costs of interior modules

Type	Cost (€)	Quantity	Reason
D	10.000	2	Door mechanics worth extra 5.000
P	5.000	5	Structure
Pw	5.000	1	Structure
S	6.000	2	Structure and seats
Sb	12.000	4	Battery system extra 6.000
Total	110.000	14	

The author assumed the range of prices for each type of BEB with all information above.

Table 5.2: Prices of BEBs in each level

Unit: €x1000	Cheap	Medium	Expensive	Supreme
City BEB	350	400	450	500
Regional BEB	400	450	500	570
Utility BEB	450	500	550	620
MBEBS full	460	515	570	650

5.1.2. Infrastructure & operation

Cost of different infrastructures are also based on the interview and occasional open-sourced data. For normal cable chargers, both vehicle- and land-side price were set to €1.500-€3.000. For press-down pantograph chargers, the vehicle-side price is also €1.500-€3.000, but land-side price would be €15.000-€25.000 due to much larger size and pressing functions. A module swapping station would be very expensive. According to NIO company, a passenger BEV manufacturer concentrates on battery swapping, battery swapping for passenger BEV costs €0,5M [32]. The price of module swapping station is then set to €0,6M. Using number of infrastructures derived in chapter 4.3, total infrastructure cost in a medium case is calculated in the following table.

Table 5.3: Prices of infrastructures in each level

Unit: €x1000	A	B	R1	R2	R3
Swapping stations			1.800	1.800	
Pantograph rails	250	176	176	176	176
Cable charging plugs	84	176	84	176	84
Total	334	352	2.060	2.152	260

In this research, maintenance cost and redundant parts of interior modules would be included. An interior module is set to have a lifetime of 1000 cycles (including 1000 insert and 1000 removing movements). The structure of one interior module costs €5.000, so each cycle cost of EACH module is set to be €5. Therefore, to exchange one MBEBS throughout between two modes, 5*8=€40 would be spent. Due to expected automation level of swapping station and other mechanical aspects, 4 scenarios are set up for this part of cost as follows:

Table 5.4: MBEBS operation cost in each level

€/Swap	Cheap	Medium	Expensive	Supreme
Price	3	5	7	10

No operation cost of charging infrastructures are involved since all vehicles except some MBEBS would use pantograph chargers for almost the same times across all cases. For necessary maintenance cost of any vehicles and labour costs, they are also not involved since these costs are completely the same among different cases: they always cover the same network (although in some cases separately), the same passenger demand and the same driven kilometers.

5.1.3. Energy price as benefits

In this research, costs on energy are seen as benefits that different types of BEBs can bring to the whole network. If one research case uses more electricity than the reference case, it will gain a minus benefit. Over these years, energy price fluctuates. The following figure provided by ANWB shows a increasing estimate to fixed long-term electricity price. It is observable that recently the dynamic energy price are reaching a relative high but stable value of €0,2 per KWh [4].

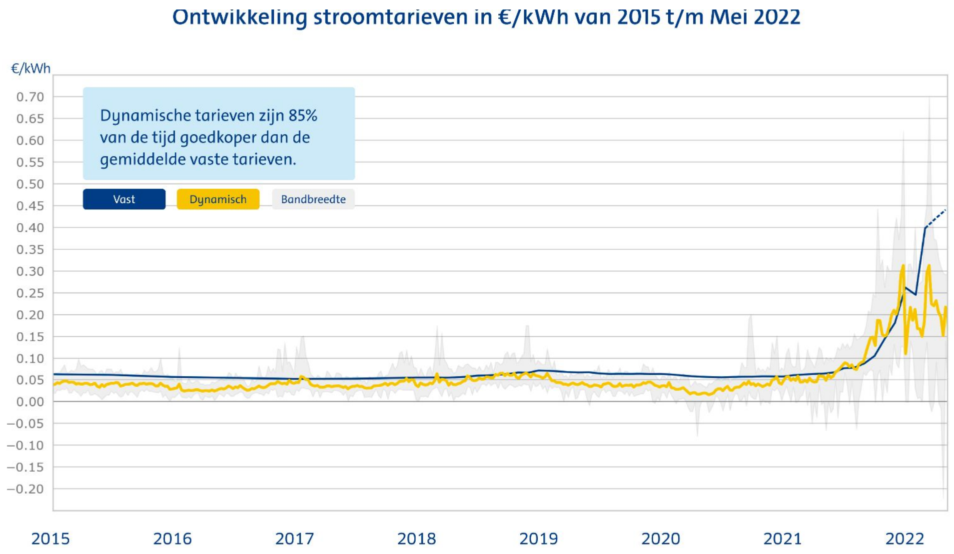


Figure 5.1: Change of electricity price across years in the Netherlands

For a 12-years long CBA process, energy price would be very hard to estimate, but in a estimable short future it would remain in a high level. Therefore, 4 different scenarios are set up for average energy price over the period.

Table 5.5: Electricity price in each level

€/KWh	Cheap	Medium	Expensive	Supreme
Energy price	0,15	0,25	0,4	0,5

The discount rate of energy cost as benefits depends on multiple aspects. In this research a constant monthly discount rate of %0.1 is applied.

5.2. CBA Result Example

An example of the CBA calculation table can be found in the appendix. The CBA begins in January 2022 and takes 12 years as research period since it is a typical duration of bus service concession in the Netherlands. One-go investment of vehicles and infrastructure happens on the first month of application (January 2022). Over years, operation cost of swapping interior modules and electricity cost are included. Here, a CBA result table under intermediate price level and ridership is presented. The benefits for passengers are listed qualitatively as a reference due to the low difference across cases. The following table shows comparison of result between 5 cases. In the first half, real costs of each cases and aspects are displayed. In the second half, difference between cases of each aspects are calculated.

Table 5.6: Example CBA result table under intermediate settings

Scenario: MED price level, MED ridership						
↓↓↓ Numerical results ↓↓↓						
Cases (see section 3.4)	A	B	R1	R2	R3	Unit
Vehicle investments	52,1	44	40,03	45,32	39,4	M€
Infrastructure costs	0,33	0,35	2,06	2,15	0,26	M€
Operation costs MBEBS	0	0	8,11	8,11	0	M€
Total investments	52,43	44,35	50,20	55,59	39,66	M€
Energy costs over 12 years	41,24	40,34	39,71	39,46	40,01	M€
↓↓↓ CBA Results ↓↓↓						
Crowdness on city lines	0	- - -	-	-	–	
Standing on regional lines	0	0	0	0	0	pax-km
Difference in investments		-8,08	-2,23	3,15	-12,77	M€
Difference in energy costs		-0,90	-1,52	-1,77	-1,23	M€
NPV		8,98	3,75	-1,38	14	M€

BCR is absent from the table. Since cost and benefits are having both positive and negative values in this research, BCR of each cases (benefit divided by cost) would be unreliable when cost value is small. Therefore BCR is ignored, the cost, benefits and NPV will be used for the following scenario analysis.

5.3. Scenario Analysis

In section 4.2.1 demand was set to have 3 different levels while unit operation cost, vehicle price and energy price are set to have 4 different levels written in the section before. The recent situation of supply chain and inflation shows not only energy prices are increasing, but also products are becoming increasingly expensive [17]. Since in this research the unit operation cost is related to the lifespan and price of interior modules, they are seen as having the same trend as the prices of vehicles and energy. Therefore, 4 synchronized cost scenarios are set up for the network while ridership is seen as independent from costs. It is then decided to perform 3 different ridership levels for every cost levels, which then leads to 4*3=12 different scenarios. Besides, some extreme scenarios that are likely to happen are proposed. A summary to all scenarios can be found in the following table:

Table 5.7: Situation of each scenarios

Scenario	Cost	Demand	Exceptions
1	Low	Low	
2	Low	Midi	
3	Low	High	
4	Midi	Low	
5	Midi	Midi	
6	Midi	High	
7	High	Low	
8	High	Midi	
9	High	High	
10	Supreme	Low	
11	Supreme	Midi	
12	Supreme	High	
E1 Reliable modules	Low	Low	Very low operation cost
E2 Energy crisis	Low	High	Super high energy price
E3 Lithium scarcity	Low	Midi	Super high vehicle price

By applying different scenrio factor settings to the CBA model, its output will be comparison between cases in that scenario. To be remembered, these factors are always the ’distance’ between research and reference cases. It measures how ’far’ they are from reference cases, so they can be compared across scenarios. In a expensive scenario, total real costs of any cases will certainly become more expensive than that in other scenarios which is less meaningful than ’differences’ that directly shows how better or worse a case is.

5.3.1. Set-up scenarios

The following scatter plot shows values of costs and benefits of each cases in all scenarios.

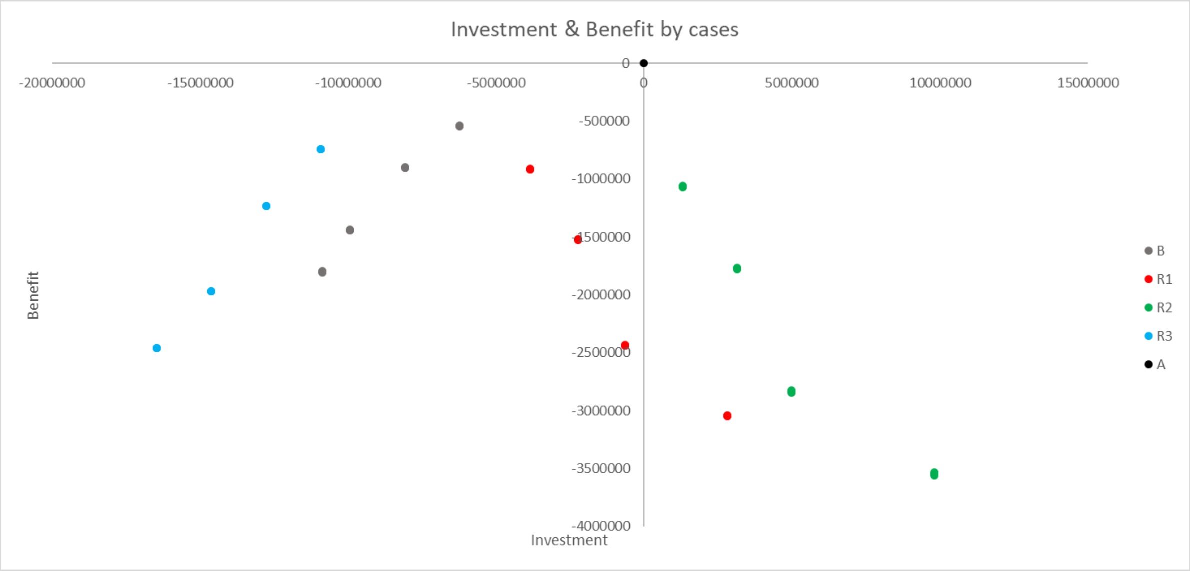


Figure 5.2: Difference of investment and benefits for each cases in each scenario

Dimension of ridership

The expected number of data points in this figure should be 4*12=48 despite only 16 are seen. This is because they are always gathered in triple as the following figure shows.

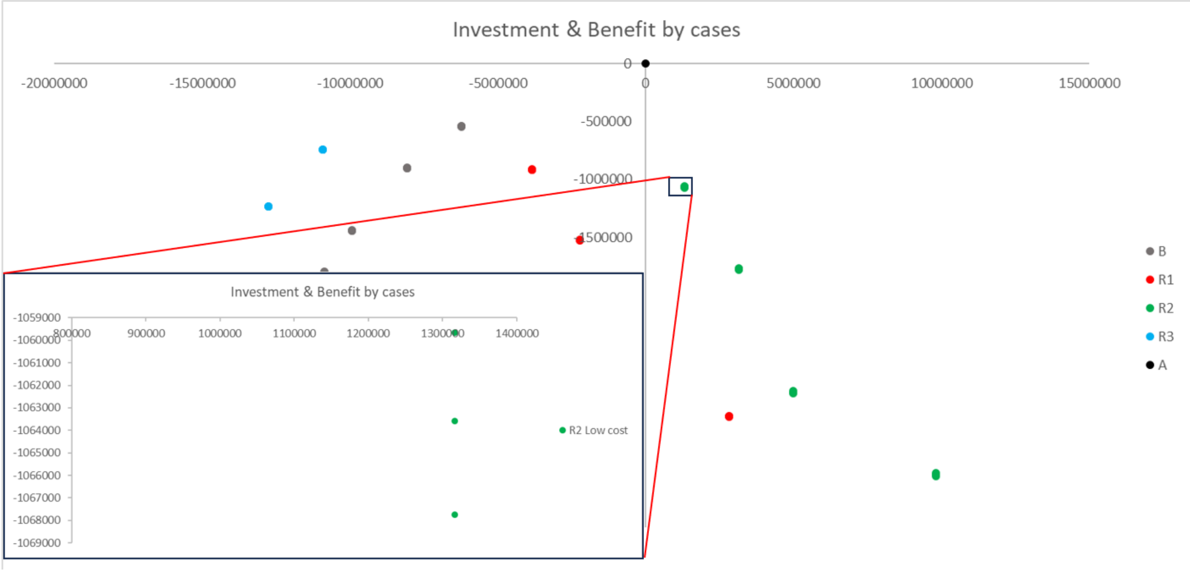


Figure 5.3: Magnified scatter plot

Having the same cost, any three gathered points like these reflect change of benefits in different level of ridership for one case. The showing up of these 'groups' reflects the small changes that demand can influence benefits. These values are indeed very small comparing with which other factors has made. But for different cases their placement in that group are different. For case B and R3, the lower the ridership is, the more benefit the system can get; For case R1 and R2 (MBEBS cases) it reverses: the higher the ridership is, the more benefit the system can get.

The difference of city lines' load rate and number of standing pax-km on regional lines are listed below.

Table 5.8: Difference of crowdness on city lines in each level of ridership

LOW	Morning	MP	Day	AP	Evening	Unseatted paxkm
A	0.0%	0.0%	0.0%	0.0%	0.0%	0
B	1.5%	8.0%	5.8%	6.8%	2.6%	0
R1	0.0%	0.2%	0.1%	0.2%	0.0%	0
R2	0.1%	0.4%	0.3%	0.3%	0.1%	0
R3	0.0%	3.7%	1.3%	3.1%	0.0%	0

MED	STAGE I	STAGE II	STAGE III	STAGE IV	STAGE V	Unseatted pax-km
A	0.0%	0.0%	0.0%	0.0%	0.0%	0
B	3.7%	13.2%	9.6%	10.8%	6.1%	0
R1	0.0%	0.3%	0.1%	0.3%	0.0%	0
R2	0.2%	0.7%	0.5%	0.5%	0.3%	0
R3	0.0%	6.1%	2.0%	5.0%	0.0%	0

HIGH	STAGE I	STAGE II	STAGE III	STAGE IV	STAGE V	Unseatted pax-km
A	0.0%	0.0%	0.0%	0.0%	0.0%	0
B	5.3%	18.9%	13.9%	15.9%	7.8%	38560
R1	0.0%	0.4%	0.1%	0.4%	0.0%	24100
R2	0.3%	0.9%	0.7%	0.8%	0.4%	24100
R3	0.0%	8.8%	2.9%	7.8%	0.0%	38560

Dimension of costs

The following bar charts shows NPV in each case and scenarios. It can be seen that the difference between the best and worst cases increase when level of costs gets higher, but the best and worst one does not vary in different scenarios. That is, case R3 (Utility, regional and city BEBs) always have best NPV while case R2 (full MBEBS) is the worst.

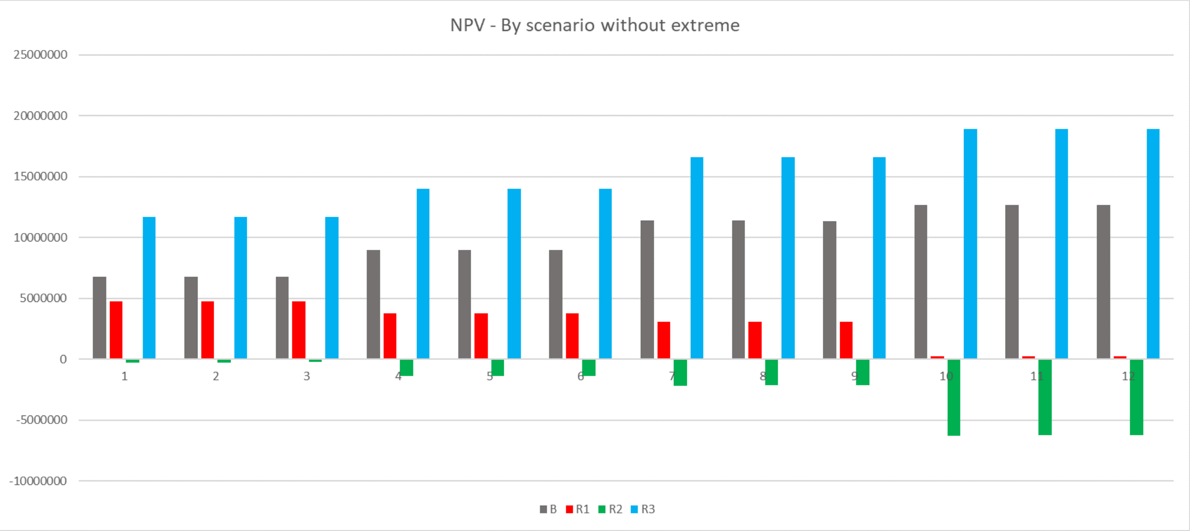


Figure 5.4: NPV by scenario

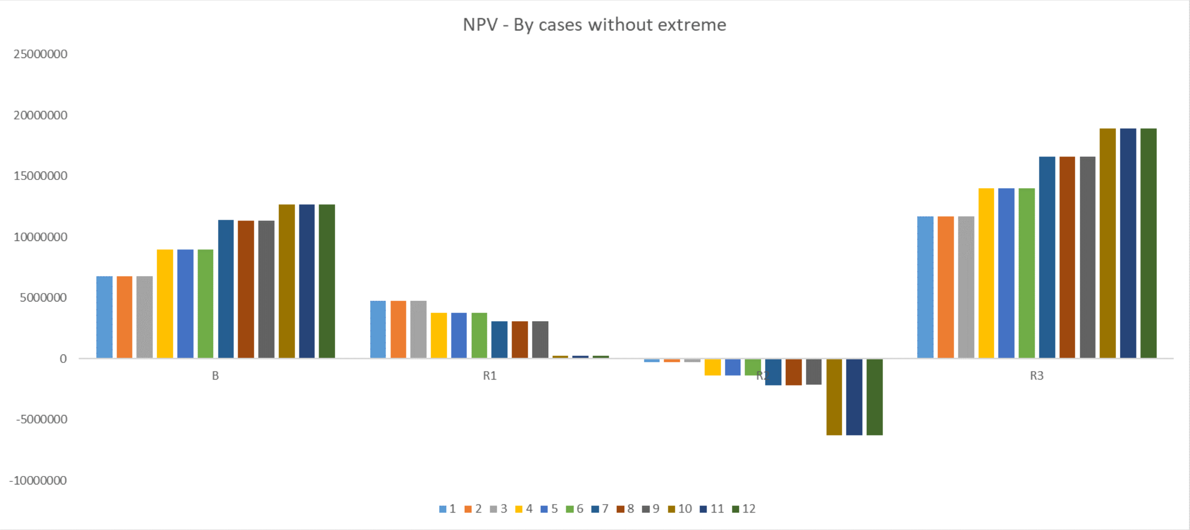


Figure 5.5: NPV by cases

The scatter plot also shows this trend: in higher cost scenarios, difference of cost difference between each cases are magnified as these arrows showing them gradually being separated. A high cost scenario does not change ranking of cases, but dividing them more clearly: using utility BEBs to combine timetables brings observable benefits.

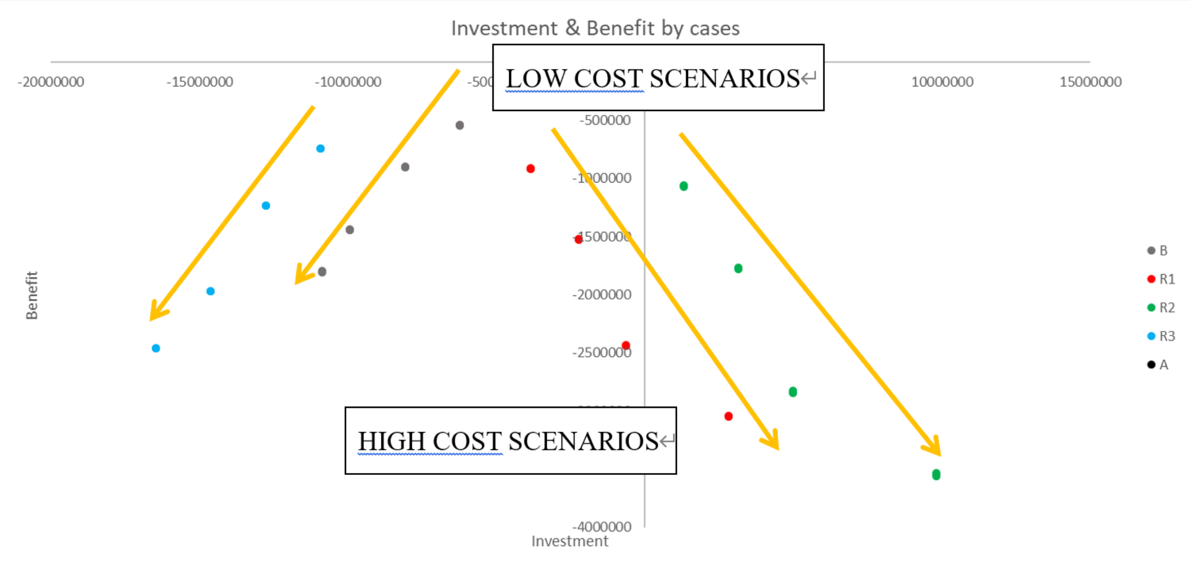


Figure 5.6: Trends can be seen as level of price rises

Commons
Common conclusions can always be found among these 12 scenarios.

- Case R2 (full MBEBS) leads to positive cost and negative NPV while other cases can always reduce cost (except R1 in supreme cost scenario);
- All cases have benefits to energy consumption;
- Without exceptions, case R3 using utility BEBs to combine timetable would be the best choice;
- Case R1 (MBEBS combined timetable) always brings positive NPV;
- Case B (full Utility BEB) reaches better NPV than MBEBS;
- ……

5.3.2. Extreme scenarios

The following bar chart shows NPV of each cases under extreme scenarios. It can be seen that under some exceptional extreme assumptions all cases are having positive NPVs and their difference has reduced while case R1 begins to catch up with case B (which even overtaken case B in E1 and E3). However, case R3 is still the best performed one and R2 the worst.

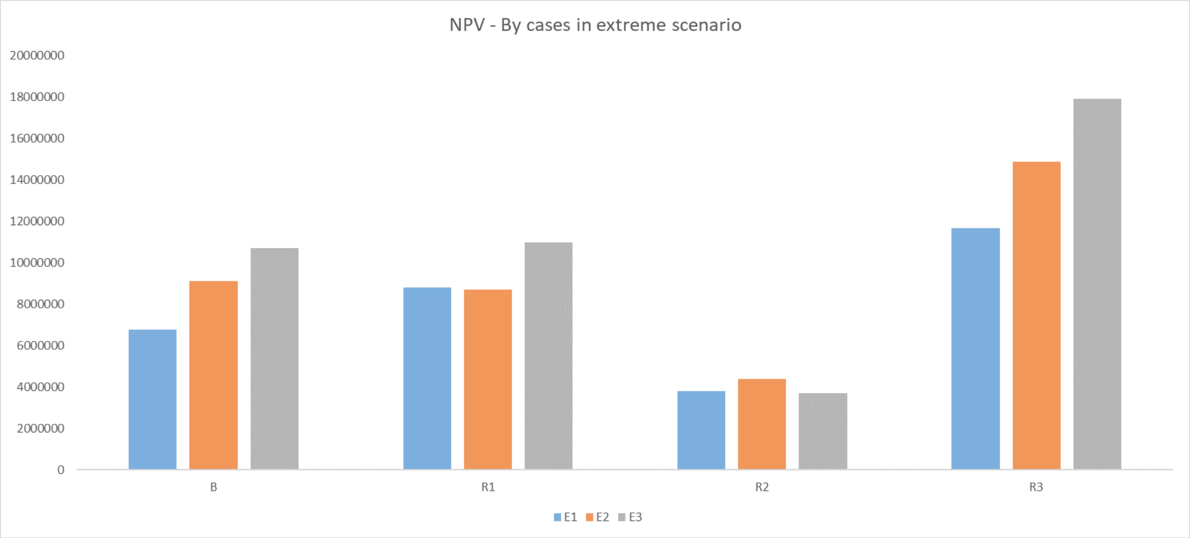


Figure 5.7: NPV by cases under extreme scenarios

The following bar chart (5)containing all 15 cases shows these changes. The three extreme cases as 'outliers' do shows very different trend comparing with regular cases.

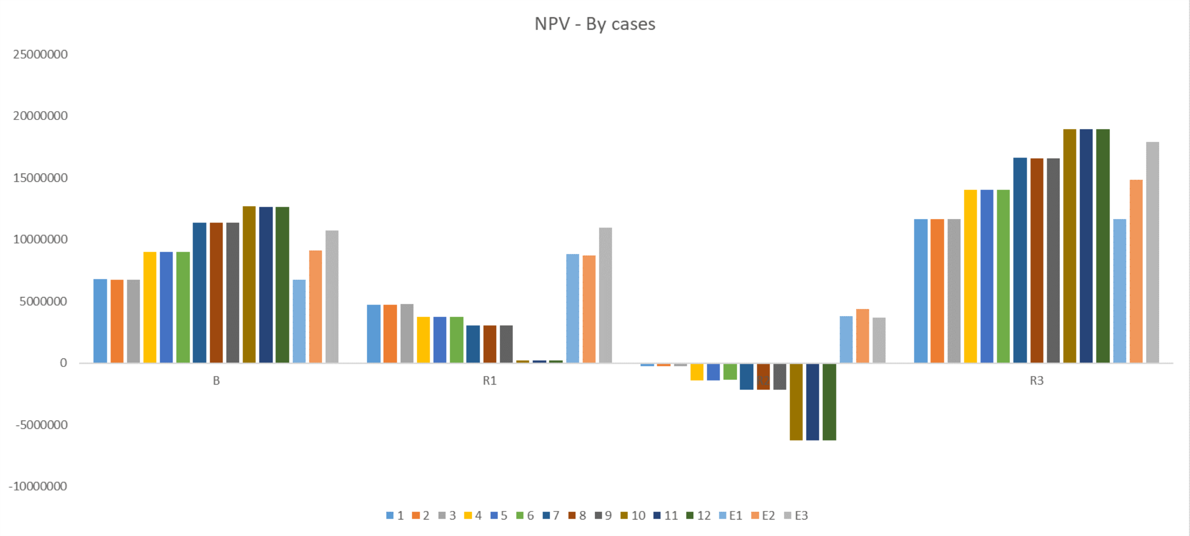


Figure 5.8: NPV by cases in all scenario

The following scatter plot of extreme cases and case 2 as comparison shows the effects of extreme values of factors. It can be seen that for most cases extreme values enhances their advantages of saving cost (E1 & E3) or making more benefits (E2) while pricing of vehicles effecting all cases significantly but reducing operation cost only helps cases with MBEBS (R1 & R2).

Figure 5.9: Difference of investment and benefits by cases under extreme scenario

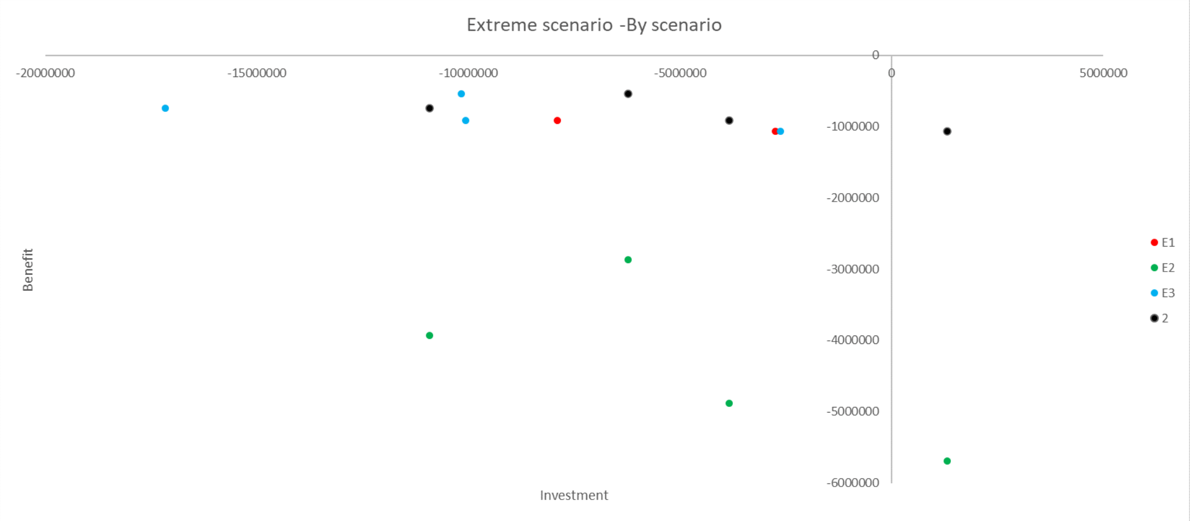


Figure 5.10: Difference of investment and benefits under each extreme scenario

Summary

In this section, under different scenarios, performances of each research cases are analysed. Result shows ridership of the network does not exert significant effect to benefits in any scenario, but using utility BEBs under high ridership may increase load rate of the network up to 20% during peak hours. Considering this research has taken average demand of the whole stage, increase of ridership might be higher than the value in this estimation. Furthermore, under high ridership scenarios some of the lines using Utility BEBs have reached a load rate of over 100% (over 80% of vehicle maximum capacity). This is noticeable but not a big problem for multiple reason:

- High ridership scenarios are not very likely to happen;
- It can be solved by simply adding more vehicles which does not effect the NPV ranking of Utility BEB cases very much;
- MBEBS cases can handle this very high ridership.

For the monetary values, it can be summarized as follows. The NPV ranking of cases in each scenario does not vary. High cost scenarios would increase the advantage of Utility BEB cases (B and R3) while making MBEBS cases (R1 and R2) more unfavourable while under some extreme scenarios MBEBS cases are likely to win. For most research cases, thanks to combined timetables they are always having positive NPV comparing with the non-combined reference case.

Numerical results (cost, benefit, NPV and BCR) of all 15 scenarios can be found in the appendix.

5.4. Sensitivity Analysis

From the very beginning of timetable analysis, the concept of MBEBS is sensitive to many factors. For example, if there is a system without peak timetables and regional express lines, MBEBS would be completely useless. This makes timetabling factors the same as, or even more important than cost factors.

5.4.1. Analysis to a Timetable Factor

Going into core, MBEBS catches the difference between peak departure times of city and regional lines. In between, it takes some time to transfer between modes and then will be put back to another service. If the transfer takes two hours, a MBEBS coming at 7:00 will not be ready until 9:00 which is already the end of city peak hours. Originally, transfer time of MBEBS was set to 10 minutes. In this section, two variants of transfer times will be tested with Formation I and Formation V in chapter 2.5 to observe the sensitivity of timetable constraints.

Transfer time 20 minutes

For Formation I combining one city and regional lines, combinations in the morning remains completely executable (with one extra city BEB). However in the evening one outbound ride (from the hub station to the other side) of the city line is not constrained and another one extra city BEB with one deadheading is needed.

For Formation V working as a mini network, due to reduction of deadheading trips, no extra vehicles are needed. The latest outbound departures of regional lines (to the suburban area) are used to contain last city line peak departures.

Transfer time 30 minutes

For Formation I, two more city BEBs are added for one unconstrained morning peak ride and two unconstrained afternoon peak rides. 3 DH trips are added. The existing extra city BEB need to drive for one more peak ride and one DH.

For Formation V, in each direction one morning and one afternoon peak rides are unconstrained. Two extra city BEBs are needed and they do not have to perform DH trips.

Summary

The following table shows number and share of extra vehicles needed in different transfer times.

Table 5.9: Sensitivity of vehicle demand to different delays

Formation I			
Transfer time (min)	Extra vehicles	Spilled trips	DH
10	1	2	0
20	2	3	1
30	3	6	4
Formation V			
Transfer time (min)	Extra vehicles	Spilled trips	DH
10	0	0	0
20	0	0	0
30	2	4	0

Transfer time is not considered to be longer than 40 minutes since it is not likely to happen on a 12-meter bus and it demands higher capacity for swapping stations, making MBEBS costs too high to further loss its advantages. However, MBEBS would be resilient to changes of transfer times in the range of 10 to 30 minutes. It can be concluded that under network level operation, only one extra vehicle is needed among 20 vehicles which is only 5% increase when transfer time triples. However, slight increase will certainly lead to unconstrained departures and extra vehicles and the best solution is still to limit the transfer time under or equal to 10 minutes.

5.4.2. Analysis to CBA Factors

Many factors like operation costs and energy price come with uncertainty and might vary in a bandwidth. The sensitivity analysis to each parameters would be performed based on Scenario 5 with both medium costs and demand. The following table shows the variables to be analysed and their bandwidths of changing.

Table 5.10: Changes for sensitivity analysis

Factor	Lower bound	Upper bound	Clarification
Energy price	-50%	50%	Fluctuation of energy price
Operation cost	-50%	50%	Fluctuation of MBEBS operation cost
Vehicle price	0	30%	Vehicles might be more expensive
Number of MBEBS and utility BEB	0	30%	Possible demand of extra vehicles
Vehicle capacity	-50%	0	Restricted load rate

In the bandwidth of energy price and operation cost

The following radar figures shows changes of NPV of each cases when energy price and unit operation cost of MBEBS changes. From the very first glance it can be seen that of energy price is less sensitive than operation costs. 100% (up +50% and down -50%) changes of energy cost effects all cases (except reference case A) in a small scale, while operation costs has influenced MBEBS cases (R1 and R2) significantly.

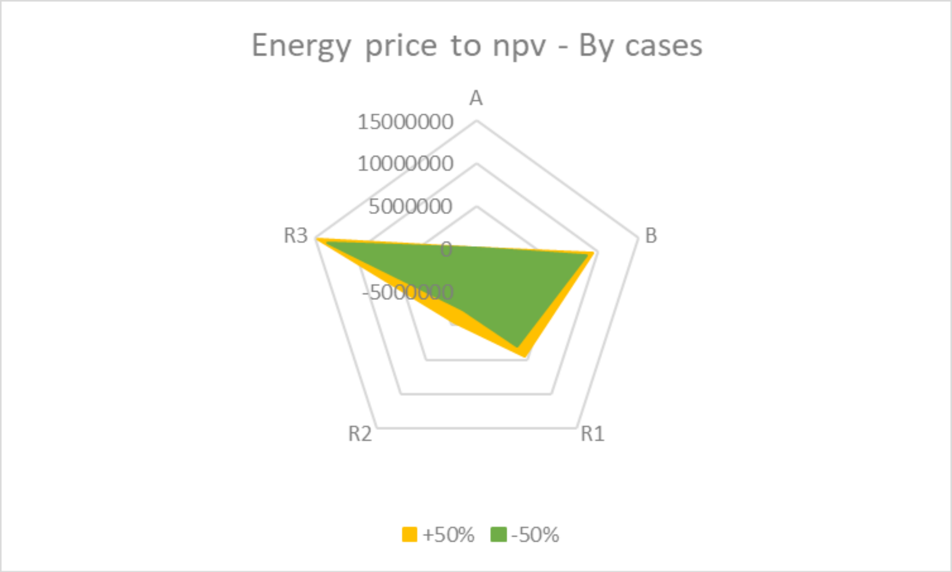


Figure 5.11: NPV bandwidth of changing energy price by cases

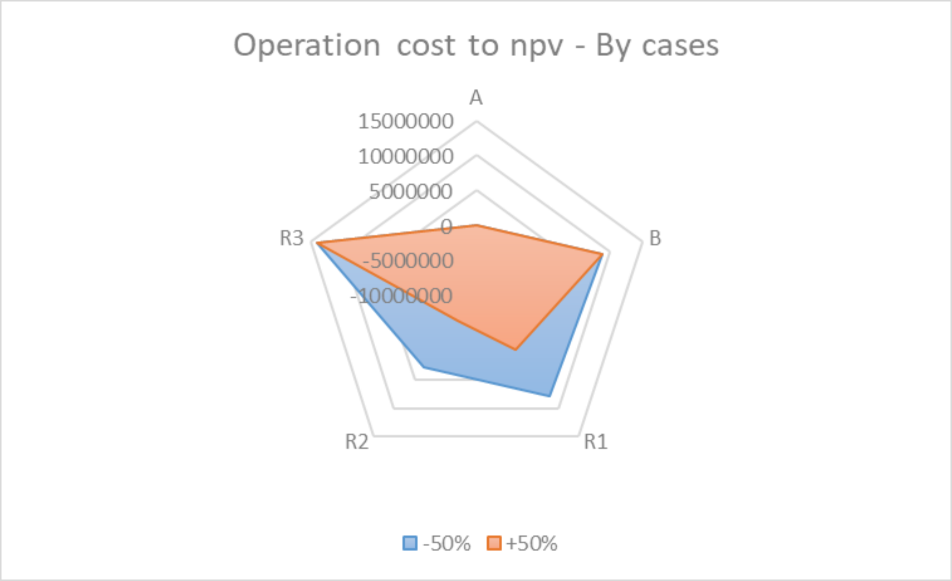


Figure 5.12: NPV bandwidth of changing operation costs by cases

Secondly, the direction of effect should be noticed. Increasing energy price leads to higher NPV for all research cases but increasing operation cost makes NPV of MBEBS cases to reduce. Totally, operation cost is a unknown, highly variable and a very sensitive factor. Although energy price is also hard to estimate due to global developments, it is not that of importance.

Comparison between different risen factors

In this section, all 4 positive changes are applied to compare their effects and importance. The following figure shows percentage effect to costs of each cases by these changes. Energy price has no effect to costs so it has an overlap with reference 0% circle. Changing of vehicle single prices has positive effects to costs of each research cases with a magnitude less than 150% while changing of number of vehicles, although sounds having the same function as vehicle prices, exerts strong negative influences to costs of all research cases as low as to -300%. Sensitivity of operation cost to total costs is in between the two mentioned above, it has an intermediate negative influence to MBEBS cases as low to -100% and -200%.

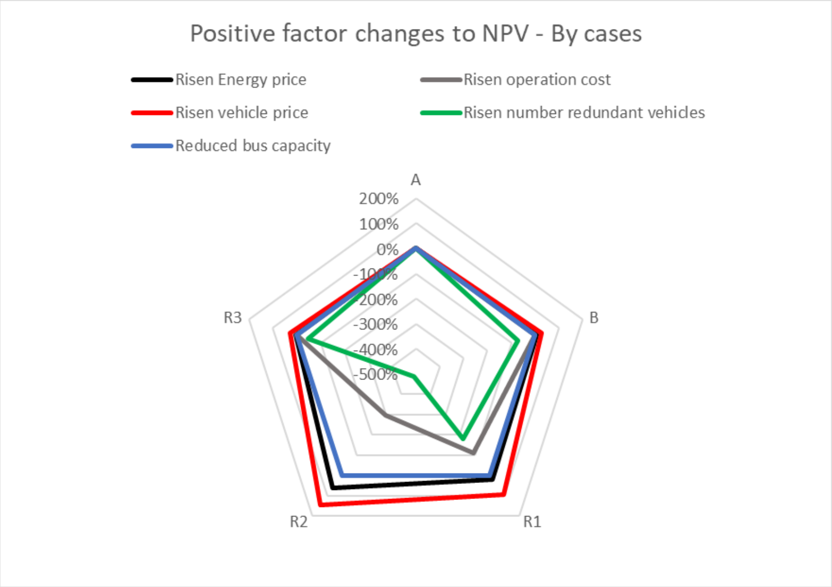


Figure 5.13: Investment change by cases of rising each factor

The following figure shows effect to benefit of each cases by these changes. As section 5.3 has shown, ridership is completely not a sensitive factor to benefits. Beside ridership, benefits would be only related to energy price. It can be simply seen that 50% increase of energy price leads to 50% increase of benefits for all research cases.

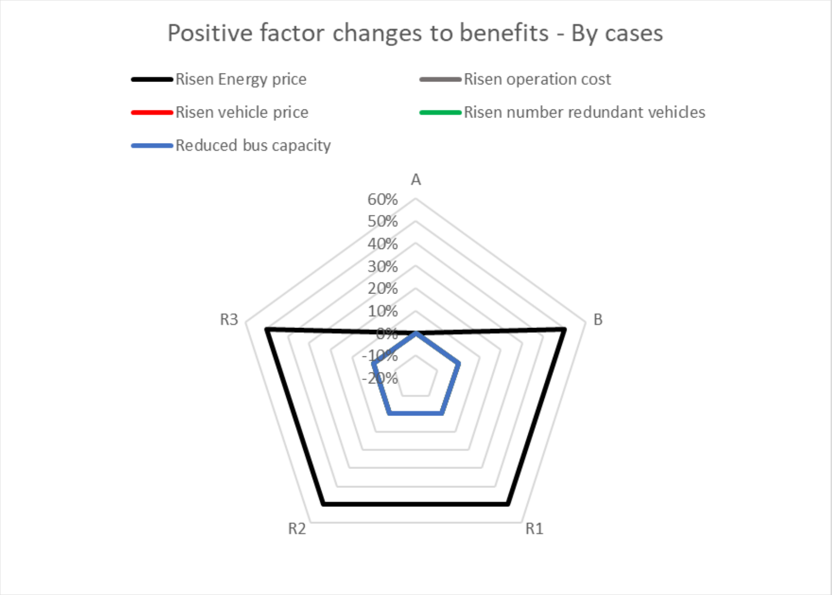


Figure 5.14: Benefit change by cases of rising each factor

The following figure shows effect to NPV of each cases by these changes. Sensitivity of these factors to NPV has a similar trend as them to costs. Increasing energy price and single vehicle prices have positive effect to all research cases while operation cost and number of vehicles has stronger negative influences.

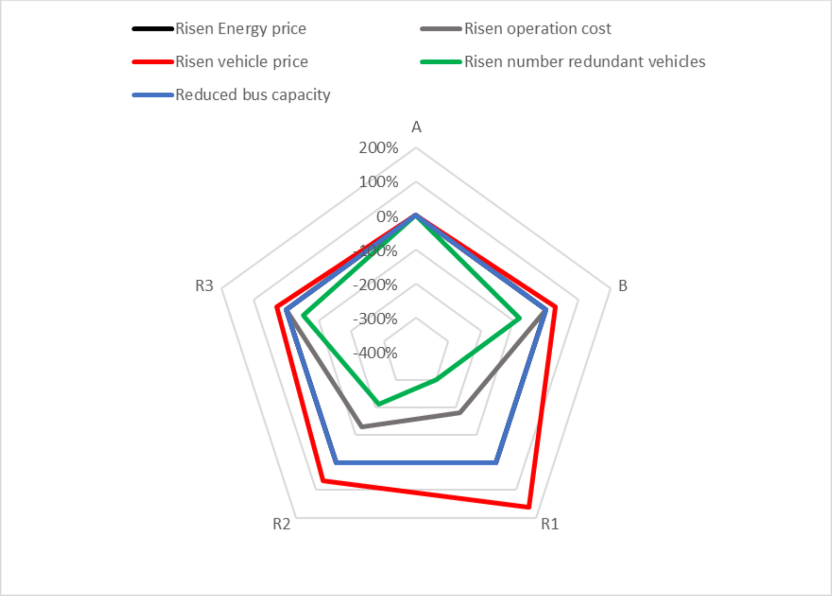


Figure 5.15: NPV change by cases of rising each factor

Summary

In can be observed that either on numerical or on percentage level, number of vehicles and operation cost of MBEBS are the most sensitive factors. single price of vehicles and energy cost also effect values of cases in one scenario, but they have weaker sensitivity.

Not only sensitivity of the numbers to factors can be seen, but also the sensitivity of cases to changes can be observed. Costs of case R1 is very sensitive while NPV of case R2 is sensitive to external changes comparing with other research cases. Totally, MBEBS (and the cases it has involved) is sensitive to external environment as a new type of bus solution. Data of sensitivity analysis can be found in the appendix.

The following figures shows the share of each categories of costs and investments in scenario 5. It can be clearly seen that it is operation cost that has lifted total cost of MBEBS cases significantly.

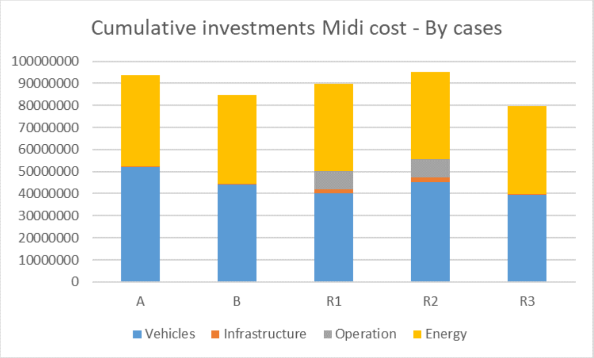


Figure 5.16: Cumulative graph of costs by cases, intermediate price level

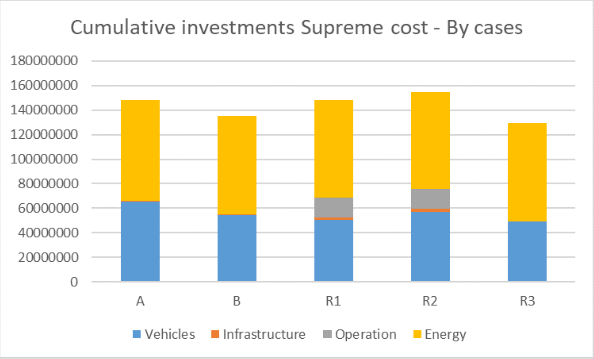


Figure 5.17: Cumulative graph of costs by cases, super price level

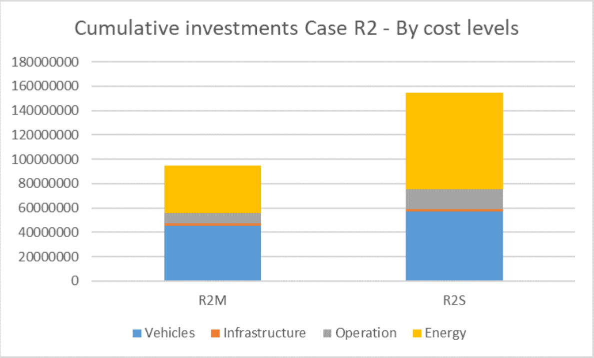


Figure 5.18: Cumulative graph of costs Case R2, different price levels

This figure comparing different costs in each cases shows the low difference in between. Although energy cost takes up almost half of the total cost in midi cost scenario and more than half of total cost in supreme cost scenario, they differ so less that the winner would clearly depends on other three types of costs. Sensitivity analysis to operation cost and vehicle cost factors also support this point. As for infrastructure costs, they are not very important comparing with energy and operation costs which accumulates across days, months and years.

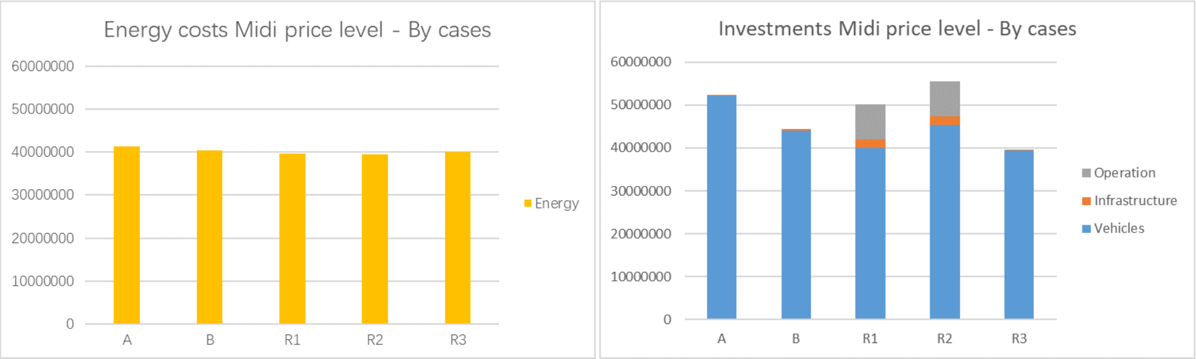


Figure 5.19: Energy costs and investments by cases in same magnitude

6

Discussion, Conclusion & Recommendations

In this chapter, conclusion to the whole research process was made according to research questions. Then, the research process including modelling CBA and sensitivity analysis and limitations in this process was discussed. Finally, some recommendations are given for further research and related stakeholders.

6.1. Conclusion

In this section, a final conclusion was made for the whole research except the idea of MBEBS which can be found in chapter 1 and 2 so that there is no need to further conclude it. Splitting to four main subquestions, they are first addressed to better reflect to the main research question.

MBEBS setting off from a concept

Research subquestion:

- What makes an adjustable BEB?

The adjustable BEB, naming MBEBS in this research, is an half-completed electric bus chassis with spaces for different interior modules to insert and form a BEB with adjustable layout. The interior modules themselves have different characteristics. Some modules are equipped with only low floor and a few seats; some have high floor, seats and battery at the bottom. These modules have same sizes from the outside so that they can be inserted into MBEBS chassis at will. Outside the MBEBS vehicle, pantograph chargers and exclusive module swapping stations support its operations. By making use of difference between peak times of regional and city network, MBEBS drives in both networks at different times with different layout. This process is therefore called combining network. Combining network and the innovative structure of MBEBS makes an adjustable BEB possible.

Feasibility and general performance of the MBEBS and its rivals

Research subquestion:

- Can the adjustable BEB be applied to bus networks?

During timetabling and comparing to created simple networks with and without combining timetable, it was discovered that combining regional and city networks with MBEBS (or any vehicles) is feasible and helps the reduction of number of vehicles in this combined network. It also concludes that as the combined network becomes more complex, the lines (and its MBEBS) can be simply recognized as free to combine in or very close to a hub station without any waste especially when demand of city peak vehicles is more than supply from regional lines. A symmetric allocation of MBEBS is favourable for reducing DH trips and unused vehicles. These general intermediate conclusions were applied to further modelling of more complex and realistic networks. After iterations of balancing vehicles, a clear reduction of vehicles was also seen in an bigger archetype network consists of 20 lines and 3 hub stations.

Cost-benefit performance of MBEBS and its rivals

Research subquestion:

- What are the operation cost and benefit of (the adjustable) BEBs?

Not only number of vehicles in the archetype network, but also its energy consumption and infrastructure demands are calculated. The result of energy consuming is summarized that MBEBS cases are energy-efficient. For infrastructures, MBEBS requires 3 exclusive swapping stations at each hub stations. After transferring these characteristics into monetary values a CBA process was set up. Vehicle investments, infrastructure costs and MBEBS operation costs are taken into account as costs while difference of energy costs between reference cases and research cases are seen as benefits. The CBA result above was based on an intermediate price and ridership level. For the generated 12 different scenarios with different price and ridership level, the result of comparing scenarios shows negligible effect of ridership and strong influence of price levels. As price level rises, inferiority of MBEBS enlarges and sometimes even gets negative costs comparing with case A. In 3 extreme scenarios out of 12 regular ones with some extreme settings in favour of MBEBS, NPV of MBEBS cases are still falling behind Utility BEB cases despite the decreased differences. Case R3 using Utility BEB to combine networks are having on average the best NPV. The second one is reference case B with monopoly of Utility BEBs. MBEBS cases took the last 2 positions. Passengers' experience did not differ so much as the CBA table shows. For city network, all cases are performing worse than reference case A while case B with completely Utility BEBs is the worst; For regional network, all cases are performing well as there is no standing passengers across the day on all lines in each cases. It can be concluded that MBEBS has generally worse cost-benefit performances in all scenarios. Even extreme scenarios with unrealistic factor values in favour of MBEBS cannot make it overrun Utility BEBs.

Analysis to MBEBS and its rivals

Research subquestion:

- What are the important factors influencing the adjustable BEB?

Bandwidth sensitivity analysis to energy price and operation costs concludes that change of energy price has relatively smaller effects to NPV comparing with operation costs. Risen value sensitivity analysis to four model factors (energy price, number of vehicles, vehicle prices, MBEBS operation cost) results that changing of vehicle single prices has positive effects to investments of each research cases while changing of number of vehicles, although sounds having the same function as vehicle prices, exerts stronger negative influences to investments of all research cases. Sensitivity of MBEBS exclusive operation cost to total investments has an intermediate negative influence to MBEBS cases. Sensitivity of these factors to NPV has a similar trend as them to investments. Increasing energy price and single vehicle prices have positive effect to all research cases while operation cost and number of vehicles has stronger negative influences.

General conclusion

Now, the main research question can be answered:

- **What are the design, estimation and assessment to the feasibility and cost-benefit performance of an adjustable BEB?**

Following the distribution of existing city and suburban commuters' demand across time, a difference of time was found to let peak vehicles for regional network enter city networks. Therefore, structure of an adjustable BEB with changeable cabin layout and battery capacity to adapt to both short city and long regional lines was designed. Seeing interior and battery as a unified nodule, it changes the cabin layout meanwhile adjusts its battery capacity to run both short city and long regional lines with different modes.

By generating timetables from existing services, trials was completed from simple structure to small networks. It was proved that combining regional and city lines from both ends of the latter helps saving both number of vehicles and deadheading trips. By expanding this result to a more complex network with similar structure, it is believed that adjustable BEB or any vehicle can be effectively inserted into city lines to reduce minimum total number of vehicles of the whole combined network. The combination was also proved with appreciable resilience which allows regional vehicles to delay up to 30 minutes with only a demand of less than 10% redundant vehicles.

From the perspective of operation, an adjustable BEB is able to save up to one third of total number of vehicles in a typical combined city and regional network and observable amount of electricity, comparing with current separated operation using existing BEBs. Due to its own structural limitations, it does not promise as perfect services as separated operation modes using city and regional BEBs, but performs better services than utility BEBs.

From the perspective of costs and benefits, the adjustable BEB would have significantly higher investment than existing BEBs. Its exclusive operation costs brought by transferring between modes makes it less profitable than using low-entry Utility BEBs over long concession periods in most of the realistic scenarios. Meanwhile, the economical effectiveness of the adjustable BEB is sensitive to its single price, operation cost and vehicle redundancy. Energy price (cost) has relatively much smaller influence despite its great share in total costs.

It can be concluded that combining network is feasible on operation and very profitable on economics, but adjustable BEB is not primary choice rather than Utility BEB to be applied on the perspective of cost effectiveness. From both perspectives of economic and service quality the adjustable BEB stands in the second place, but the great economical advantages, low technological threshold and higher application adaptability always let Utility BEB overrun the adjustable BEB.

6.2. Discussions & limitations

Discussion to CBA analysis and results

All CBA results in each scenarios indicate that MBEBS is not very likely to win Utility BEB under the given archetype network in economical level, despite proving its better performance on saving energy and level of service (capacity on city lines and seats on regional lines).

However, an optimistic thing is that in most scenarios all research cases except R2 (full MBEBS) have reached a positive NPV which means the idea of combining network is able to reduce total investment to such a big network significantly. Using MBEBS, it saves up to 5 Million Euro across 12 years while with Utility BEBs the amount of saving will be 10 to 20 Million Euro. It has been proved that combining timetables is not very sensitive, in other words, robust to extending of transfer duration, so these savings are promised.

Discussions on MBEBS as an innovation

According to Planing's theory [36], the adjustable BEB meets an opportunity vacuum in the field of bus transport. From his criteria, a transport innovation like the adjustable BEB must be positive on three aspects: technically feasible, financially viable and society adoptable. This research has proved the technical feasibility of adjustable BEB. For society, the main subject of the adjustable BEB would be passengers. MBEBS did not show strong negative influences to passenger experiences so it is recognized to be social adoptable. However, both aspects are not positive in solid. Technically, adjustable BEB does not fit to all kinds of timetable and travel behaviour of passengers; On the aspect of passengers, MBEBS does not differ so much to other research cases. Furthermore, MBEBS is financially viable but it is not the best one. It is also sensitive to external changes. Therefore, adjustable BEB is not an ideal tool filling this vacuum for individual actors like bus operators.

So, what is the feasibility of the best case stated in this research e.g. Utility BEB for combining networks? Under the framework of Political Economy of Transport Innovations [15], Utility BEB has passed the CBA so it is technical feasible. Due to the limitation of vehicle structure, it is social feasible for passengers with only a little bit worse performance. To make it feasible politically, it (mainly the idea of combining network) has to consider the interests of industry and non-business groups. This research cannot confirm if non-business groups like the government would support Utility BEBs. On the side of industry, bus manufacturers may stand against it since they would sell much less vehicles to a combined network.

Contributions of this research

This research on innovative new adjustable BEB design proposes a new aspect of designing electric buses by making exact use of electric driving systems' advantages. By seeing interior as a non-fixed characteristic on the level of vehicle inner space, this research has expanded the modularized, multi-purposed and flexible design logic from other types of vehicles to buses. This research opens a new field of researching interactions of traditional human-driven BEB and bus networks. It will always provide a reference for anyone who wants to start their research in or from this concept.

Practically, this research gave an approximate estimation to price of such an adjustable BEB, and denied this innovation to some extent from the perspective of costs. It tells readers and related stakeholders that currently BEBs with traditional structure is still the most efficient choice. However, the research has proved the necessity of combined usage of increasing expensive vehicles and the reduced importance of energy prices when bus systems turning to electricity driven. This research will always provide a reference for anyone who would like to create real model, prototypes or products of an adjustable BEB.

(Dis)advantages of MBEBS

From this research, some advantages and disadvantages of MBEBS were summarized.

Advantages

- Less vehicle for the network: By combining networks with MBEBS or other appropriate vehicles, vehicles can be used at once when they are needed, instead of preparing extra buses that runs only a few trips per day.
- Less energy consumption : When interior modules with battery packs are removed from the vehicle, the MBEBS becomes lighter, so less energy are wasted for it propelling itself, especially in city lines with more sharp acceleration and braking movements. The more MBEBS put into use, the more energy it will save.
- Comfortable and capacity rides: On city lines, the MBEBS provides low-floor and high standing capacity (with a number of seats). On regional lines, MBEBS provides high floor and more seats to make long-distance trips more comfortable. MBEBS can perform just like exclusive city and intercity BEBs and better than low-entry Utility BEBs.
- Less DH and unused vehicle hours: Buses in combined network do not have to return to depot after the morning peak. They run more in the network and only have to return to city depot or stay at hub stations thus both empty rides and static vehicle hours are reduced as much as possible.

Disadvantages

- More expensive vehicles: The MBEBS is required to use a wheel-driven motor axle, and a specially designed chassis that cope with interior modules. These new and special structures will increase single price of MBEBS vehicles.
- Unproven interior modules: Interior module is a new concept that has never been put into mass production in any bus system. Economical efficiency of MBEBS is very sensitive to lifespan and operation cost of this unclear interior module.
- Extra and special infrastructures: The MBEBS swapping station in hub stations serves interior modules. It must handle charging and storage of interior modules. This necessary working equipment brings extra cost and unknown land use and safety problems.
- Total cost more than existing BEBs: According to the result of network modelling and CBA, extra costs have overrun MBEBS's advantages. MBEBS might be less effective than using Utility BEBs to the same combined network.
- Transition from/to traditional systems: Assuming MBEBS will be adopted. Then, MBEBS has to run the whole concession period and new infrastructures must be installed. By the end of the concession, disposal of used MBEBS is also a problem since it cannot be sold casually like normal buses without support of infrastructures.

Limitations of the archetype network modelling

The tests to effectiveness of MBEBS and its idea of combining network is always based on the archetype network. On the develop and modelling of this network, there are still many limitations.

The first limitation is about the network itself. In reality, bus lines may not depart from hub stations and ridership profiles of each lines might vary more than just a few simple types in this research. This network, based on Rotterdam and surrounding regional lines, is backboned by tram lines in the city so that not too much lines are involved.

Lack of ridership profiles directly lead to inaccurate statistics of passenger effects including load rate (crowdness), average standing pax-km and following monetize process. To avoid this instability further disturbing CBA, merely a qualitative analysis was proposed.

Another limitation in this archetype network is modelling of number of vehicles. An assumption was made through simple network modelling in chapter 2.5, which is all regional peak vehicles can be assigned to a city service. In reality it might be difficult to assign all of them because it can already be seen that earliest and latest entry and leaving times of regional peak rides are used up. In other words, other vehicles coming later and leaving earlier are not that easy to 'use' just like a bad student. This limitation was compensated to some extent in the sensitivity analysis: a situation with 30% more vehicles was proposed.

Before proposing the archetype network, the proving of combining simple networks were so simple that was seen as a limitation, too. It is possible that by swapping some departure times of peak and daily loops, more vehicles might be saved. Adjustable departure times was also not considered although it has been researched in the well-known book for bus operations[11].

Limitations of the CBA process

The CBA has considered some necessary and variable factors, but there are far more factors that can be taken into account. The first ignored factor was monetary value of passenger experiences which has already explained in section 5.3.

The second factor with limitations is the real accurate price of swapping station for MBEBS. It functions like a battery swapping station for BEVs, but the structure is larger and much more heavier than a simple battery pack. Besides, interior modules are designed to have different types, which increasingly demand a delicate design for the exclusive swapping station. Based on the design and size of swapping station, land use of MBEBS is also an unstable factor especially in city hub stations.

The accurate pricing of MBEBS and other BEBs on the market are part of the limitations. Pricing of existing city and utility BEBs are good since there are ample cases and information sources like public transport expo to refer to. For MBEBS the problem is bigger because it is a completely new structure of BEB while lines of production have to be built from zero, so that its prices might be even higher and hard to estimate.

Another big limitation is the accurate cost of MBEBS swapping operations which has been mentioned for multiple times in the chapters before. Its high sensitivity makes it even more important, but due to lack of research in this aspect it is still a limitation leaving unsolved.

Lack of ticket income, personnel cost, charger maintenance cost and deduction of daily Regional BEBs are thought to be unimportant limitations since they are basically the same in each cases. Vehicle basic operation costs have been seen as the reverse of extra MBEBS operation costs.

6.3. Recommendations

In this section, recommendations are given to MBEBS-related entities including bus manufacturer, concession manager and bus operators. Although it has been proved that MBEBS has no significant economical advantages and may not become mainstream of future BEBs, some further ideas of MBEBS and recommendations for researchers interested in this topic are still proposed.

Recommendations for further research

Considering the limitations in this research, to better understand MBEBS and combined networks, researchers can choose to focus on dispatching algorithm considering adjustable BEBs in a combined network. Constraints of variable charging times, variable departures, detailed combination of city and regional departures accurate to departure times helps further improving the efficiency of combining.

From the perspective of hardware, calculation and computer modelling to MBEBS on mechanic engineering and scaled model of MBEBS can be made. Prototypes of MBEBS chassis and interior modules helps defining real costs, weight, lifespan, comfort, malfunction and energy consumption of MBEBS.

Investigation to different bus systems should be made in a range to discover potential of combining networks and market and costs of applying MBEBS, not only sticking to the archetype network in this research. If there are various opportunities for MBEBS, it can be considered to have more plans of interior layout not only strictly city and regional, this change of adaptability or application range can be studied. Transition to or from MBEBS or any adjustable bus is the last thing to be studied before applying them: how to deal with disposal of MBEBS, or transition from fixed BEB or other types of vehicles?

Meanwhile, the author proposes some extra ideas for MBEBS not only as a 12-meters BEB. It can make use of recycled or worse-performanced material, especially for batteries. MBEBS does not depend very much on performance of batteries, it helps BEBs becomes cheaper and more environmental friendly. The batteries that MBEBS has left during the day at hub stations can even work as part of energy storage. There can be different sizes of MBEBS using same sets of interior modules. From 6-meters with merely 2 modules to 18-msters with 10 modules, MBEBS can be more flexible to various demand in different (combined) networks. There can also be more types of modules for MBEBS rather than interior, doors and battery: fuel-cell modules, engine modules or battery-only modules gives MBEBS more changes.

Recommendations for bus manufacturers

Manufacturers of BEBs can consider to make small-scaled MEBES models and try its technological availability. Then, full-scale prototypes can be developed in cooperation with research institutes and vehicle managing departments (VVD in the Netherlands). In a 3-5 years short experiment period, a few prototypes helps discovering real performances of MBEBS rather than doing research on papers. The story of the famous Superbus [40] shows an example of this cooperation (only institution and government, without manufacturers). For MBEBS developing from existing BEB, involving of manufacturers helps.

Recommendations for the government and operators

The government is responsible for bus concession and services is suggested to merge city and regional networks especially in large cities to allow combination of networks. On the other hand, operators of city and regional networks can adjust timetable according to real distribution of lines, depots and demands to combine as much lines as possible. For (combined) bus network operators, low-entry Utility BEB would be a more conservative choice and the whole electrified network would probably consist of city, regional and utility BEB. The monopoly of any type of BEB is not suggested. For other bus operators like subcontractors and rental companies, MBEBS might be useful for response to demand from different scenarios.

It is hoped that these conclusions, recommendations and ideas can help expanding the horizon of variable parts as a concept for any buses, BEB systems and MBEBS itself. Even if the MBEBS has become something useless by the end, the basis of applying it: combining networks will least making the current bus network more energy efficient.

Bibliography

[1] A. Abdelrahman, N. A. El-Taweel, and H. E. Z. Farag. “Optimal Design of Battery Swapping-Based Electrified Public Bus Transit Systems”. In: *IEEE Transactions on Transportation Electrification* 7.4 (2021). Cited by: 12, pp. 2390–2401. doi: 10.1109/TTE.2021.3083106. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85107181554&doi=10.1109%2fTTE.2021.3083106&partnerID=40&md5=b0aba5de797fa6859ae99aaf31614a0e.

[2] Altoona and Pennsylvania Transportation Institute. *Federal Transit Bus Test, Manufacturer: New Flyer, Model: XE40*. 2015. url: https://www.altoonabustest.psu.edu/bus-details.aspx?BN=1405 (visited on 09/06/2023).

[3] L. Antti. “Energy consumption and cost-benefit analysis of hybrid and electric city buses”. In: *Transportation Research Part C: Emerging Technologies* 38 (2014). Cited by: 254, pp. 1–15. doi: 10.1016/j.trc.2013.10.008. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84888071130&doi=10.1016%2fj.trc.2013.10.008&partnerID=40&md5=9bec5dfdb2b3ab73716f1aa20f61082e.

[4] ANWB. *Hoe hoog zijn de risico’s van een dynamisch tarief?* 2023. url: https://www.anwb.nl/huis/energie/hoe-groot-zijn-de-risicos-van-dynamische-prijzen (visited on 09/06/2023).

[5] P. Avinash et al. “Peek into the Future Camera-based Occupant Sensing in Configurable Cabins for Autonomous Vehicles”. In: vol. 2021-September. Cited by: 1; All Open Access, Green Open Access. 2021, pp. 3321–3327. doi: 10.1109/ITSC48978.2021.9564420. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85118425399&doi=10.1109%2fITSC48978.2021.9564420&partnerID=40&md5=66b4b4ff1055d83ce82d9fedc2413d3f.

[6] R.J. Balcombe and Transport Research Laboratory (Great Britain). *The Demand for Public Transport: A Practical Guide*. TRL report. Transport Research Laboratory, 2004. url: https://books.google.nl/books?id=sOpeHAAACAAJ.

[7] Transportation Research Board, Engineering National Academies of Sciences, and Medicine. *Elements Needed to Create High-Ridership Transit Systems: Interim Guidebook*. Washington, DC: The National Academies Press, 2005. doi: 10.17226/22052. url: https://nap.nationalacademies.org/catalog/22052/elements-needed-to-create-high-ridership-transit-systems-interim-guidebook.

[8] D. Bongkotchaporn. et al. “Battery Sizing for Electric Vehicles Based on Real Driving Patterns in Thailand”. In: *World Electric Vehicle Journal* 10.2 (June 2019), p. 43. issn: 2032-6653. doi: 10.3390/wevj10020043. url: http://dx.doi.org/10.3390/wevj10020043.

[9] B.M. Brooks. “An investigation into aspects of bus design and passenger requirements”. In: *Ergonomics* 22.2 (1979). Cited by: 9, pp. 175–188. doi: 10.1080/00140137908924602. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0018438848&doi=10.1080%2f00140137908924602&partnerID=40&md5=dce25bef150e372ce676c8d060f401fb.

[10] K. Mustafa Cagatay et al. “Optimization of multiple battery swapping stations with mobile support for ancillary services”. In: *Frontiers in Energy Research* 10 (2022). Cited by: 1; All Open Access, Gold Open Access. doi: 10.3389/fenrg.2022.945453. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85139829386&doi=10.3389%2ffenrg.2022.945453&partnerID=40&md5=08716c1144f6f65e7644c2c2520dcde1.

[11] A. Ceder. *Public Transit Planning and Operation: Modeling, Practice and Behavior, Second Edition (2nd ed.)* CRC Press, 2015. doi: https://doi.org/10.1201/b18689. url: https://www.taylorfrancis.com/books/mono/10.1201/b18689/public-transit-planning-operation-avishai-ceder.

[12] Z. Chen, Y. Yin, and Z. Song. “A cost-competitiveness analysis of charging infrastructure for electric bus operations”. In: *Transportation Research Part C: Emerging Technologies* 93 (2018). Cited by: 102, pp. 351–366. doi: 10.1016/j.trc.2018.06.006. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85048892270&doi=10.1016%2fj.trc.2018.06.006&partnerID=40&md5=e740fa9e5bed0d995a2bd9d32060c545.

[13] EASA. *EASA review of standard passenger weights in 2022 shows no significant change*. 2022. url: https://www.easa.europa.eu/en/newsroom-and-events/news/easa-review-standard-passenger-weights-2022-shows-no-significant-change (visited on 09/06/2023).

[14] ECEPP. *Serbia: Procurement Of 10 New Low Floor 12 M Standard Electric Buses And The Related Charging Stations*. 2022. url: https://ecepp.ebrd.com/delta/viewNotice.html?displayNoticeId=20685521 (visited on 09/05/2023).

[15] F. Eran and I. Salomon. “The Political Economy of Transport Innovations”. In: *Transport Developments and Innovations in an Evolving World*. Ed. by Michel Beuthe et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 11–26. isbn: 978-3-540-24827-9. doi: 10.1007/978-3-540-24827-9_2. url: https://doi.org/10.1007/978-3-540-24827-9_2.

[16] Yutong Eurobus. *ICE 12 – PURE ELECTRICITY*. 2023. url: https://yutongeurobus.se/ice-12-pure-electricity/#tab-id-2 (visited on 09/06/2023).

[17] Eurostat. *Industrial producer prices down in the euro area and in the EU*. 2023. url: https://ec.europa.eu/eurostat/documents/2995521/16863268/4-05062023-AP-EN.pdf/d4c2a984-e6ef-37e1-5c0d-919e5f8f796b (visited on 10/11/2023).

[18] T. Fan et al. “Life cycle ownership cost and environmental externality of alternative fuel options for transit buses”. In: *Transportation Research Part D: Transport and Environment* 57 (2017). Cited by: 45, pp. 287–302. doi: 10.1016/j.trd.2017.09.023. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85033579805&doi=10.1016%2fj.trd.2017.09.023&partnerID=40&md5=aa970511646bbb80444bfc8fcfe7a067.

[19] H.-J. Gisler. “HESS passenger trailer; [HESS Personenanhänger]”. In: *VDI Berichte* 1617 (2001). Cited by: 0, pp. 211–228. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-4344569697&partnerID=40&md5=36ddb02717fdcfbf550410595ddb8f24.

[20] Andrés Camilo. H-M, P. Pereirinha, and A. Bouscayrol. “Regenerative Braking Strategy of a Formula SAE Electric Race Car Using Energetic Macroscopic Representation”. In: *World Electric Vehicle Journal* 11.2 (June 2020), p. 45. issn: 2032-6653. doi: 10.3390/wevj11020045. url: http://dx.doi.org/10.3390/wevj11020045.

[21] B. Tavoos Hassan and H. Farzaneh. “Quantifying the multiple environmental, health, and economic benefits from the electrification of the Delhi public transport bus fleet, estimating a district-wise near roadway avoided PM2.5 exposure”. In: *Journal of Environmental Management* 321 (2022). Cited by: 2. doi: 10.1016/j.jenvman.2022.116027. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85137294411&doi=10.1016%2fj.jenvman.2022.116027&partnerID=40&md5=38c356bb99967be956afe847c90469cd.

[22] X. He et al. “Energy consumption and well-to-wheels air pollutant emissions of battery electric buses under complex operating conditions and implications on fleet electrification”. In: *Journal of Cleaner Production* 171 (2018). Cited by: 48, pp. 714–722. doi: 10.1016/j.jclepro.2017.10.017. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85034570815&doi=10.1016%2fj.jclepro.2017.10.017&partnerID=40&md5=274e117dbe9d61cac9ba7ccd4131ae0a.

[23] V. Hug. *Copenhagen trial with 12 m B.Y.D K9 electric buses*. 2015. url: https://www.nordicenergy.org/wp-content/uploads/2018/02/3.-Test-of-large-charged-electric-buses-in-Copenhagen-Victor-Hug.pdf (visited on 09/06/2023).

[24] B. Hussein et al. “Evaluation of the techno-economic performance of battery electric buses: Case study of a bus line in paris”. In: *Research in Transportation Economics* 95 (2022). Cited by: 5. doi: 10.1016/j.retrec.2022.101207. url: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85130931580&doi=10.1016%2fj.retrec.2022.101207&partnerID=40&md5=c5893041bcaace5a7d23e6245f4847d6.

[25] Paris IEA. *Global EV Outlook 2023*. 2023. URL: https://www.iea.org/reports/global-ev-outlook-2023 (visited on 09/05/2023).

[26] J. Ji et al. “Trip energy consumption estimation for electric buses”. In: *Communications in Transportation Research* 2 (2022). Cited by: 21; All Open Access, Green Open Access. DOI: 10.1016/j.commtr.2022.100069. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85132502927&doi=10.1016%2fj.commtr.2022.100069&partnerID=40&md5=47c9d03e14a442f63ca401577c78607f.

[27] Y. Ko and Y. Ko. “A Development of Optimal Design and Operation Algorithm for Battery-Powered Electric City Tour Bus System”. In: *Energies* 16.3 (Jan. 2023), p. 1100. ISSN: 1996-1073. DOI: 10.3390/en16031100. URL: http://dx.doi.org/10.3390/en16031100.

[28] F. Konstantinos et al. “Riders’ perceptions towards transit bus electrification: Evidence from Salt Lake City, Utah”. In: *Transportation Research Part D: Transport and Environment* 117 (2023). Cited by: 1. DOI: 10.1016/j.trd.2023.103642. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85148321587&doi=10.1016%2fj.trd.2023.103642&partnerID=40&md5=8d1ed8377cc71650417c552061b890cf.

[29] K. Kottenhoff and C. Lindh. “The value and effects of introducing high standard train and bus concepts in Blekinge, Sweden”. In: *Transport Policy* 2.4 (Oct. 1995), pp. 235–241. URL: https://ideas.repec.org/a/eee/trapol/v2y1995i4p235-241.html.

[30] John H. T. L, C. Tran, and D. Ton-That. “A Paradox over Electric Vehicles, Mining of Lithium for Car Batteries”. In: *Energies* 15.21 (Oct. 2022), p. 7997. ISSN: 1996-1073. DOI: 10.3390/en15217997. URL: http://dx.doi.org/10.3390/en15217997.

[31] M. Manuel et al. “Heavy-Duty Battery Electric Buses’ Integration in Cities Based on Superfast Charging Technologies: Impact on the Urban Life”. In: *Sustainability* 14.8 (Apr. 2022), p. 4777. ISSN: 2071-1050. DOI: 10.3390/su14084777. URL: http://dx.doi.org/10.3390/su14084777.

[32] A. Nedelea. *Take A Closer Look At A Nio EV Battery Swapping Station In China*. 2022. URL: https://insideevs.com/news/570403/nio-battery-swap-station-china/ (visited on 09/06/2023).

[33] OV in Nederland Wiki. *Map of bus operators*. 2019. URL: https://wiki.ovinnederland.nl/wiki/Vervoerderskaart (visited on 09/05/2023).

[34] CBS Statistics Netherlands. *Population counter*. 2023. URL: https://www.cbs.nl/en-gb/visualisations/dashboard-population/population-counter (visited on 10/11/2023).

[35] Nikola. *Korean Solution to Electric Power Supply for Public Transport*. 2015. URL: https://kojects.com/2013/04/29/korean-solution-to-electric-power-supply-for-public-transport/ (visited on 10/11/2023).

[36] P. Planing. “On the origin of innovations—the opportunity vacuum as a conceptual model for the explanation of innovation”. In: *Journal of Innovation and Entrepreneurship* 6 (Mar. 2017), pp. 1–18. DOI: 10.1186/s13731-017-0063-2.

[37] RKlinkenberg. *QBZ Ebusco 2.1 4605*. 2022. URL: https://buspositions.nl/foto/67528 (visited on 09/15/2023).

[38] Kelvin S. et al. “The economics of public transport electrification: A case study from Victoria, Australia”. In: *Energy Economics* 120 (2023). Cited by: 1. DOI: 10.1016/j.eneco.2023.106599. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85150179979&doi=10.1016%2fj.eneco.2023.106599&partnerID=40&md5=a7a623a204166b29f1dc2b64f98bec42.

[39] Sustainable-BUS. *100 Yutong electric buses delivered in Kazakhstan’s capital Nur-Sultan*. 2020. URL: https://www.sustainable-bus.com/electric-bus/100-yutong-electric-buses-delivered-in-kazakhstans-capital-city-nur-sultan/ (visited on 09/05/2023).

[40] J. Wassink. *Bye bye Superbus*. 2020. URL: https://www.delta.tudelft.nl/article/bye-bye-superbus# (visited on 09/15/2023).

[41] Wikipedia. *Minivan*. 2023. URL: https://en.wikipedia.org/wiki/Minivan (visited on 09/06/2023).

[42] D. Xie et al. "Collaborative optimization of electric bus line scheduling with multiple charging modes". In: *Transportation Research Part D: Transport and Environment* 114 (2023). Cited by: 0. DOI: `10.1016/j.trd.2022.103551`. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85144085969&doi=10.1016%2fj.trd.2022.103551&partnerID=40&md5=9aa10eb93ae12fc46ea32bd07fd2cbc2`.

[43] Z. Yu et al. "Robust optimization for integrated planning of electric-bus charger deployment and charging scheduling". In: *Transportation Research Part D: Transport and Environment* 110 (2022). Cited by: 13. DOI: `10.1016/j.trd.2022.103410`. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85135898703&doi=10.1016%2fj.trd.2022.103410&partnerID=40&md5=07fb87a2cca10da31b384397d19d1147`.

[44] Gao. Z et al. "Battery capacity and recharging needs for electric buses in city transit service". In: *Energy* 122 (2017), pp. 588–600. ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2017.01.101`. URL: `https://www.sciencedirect.com/science/article/pii/S0360544217301081`.

[45] W. Zhang, H. Zhao, and M. Xu. "Optimal operating strategy of short turning lines for the battery electric bus system". In: *Communications in Transportation Research* 1 (2021). Cited by: 30; All Open Access, Gold Open Access, Green Open Access. DOI: `10.1016/j.commtr.2021.100023`. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85132283026&doi=10.1016%2fj.commtr.2021.100023&partnerID=40&md5=0b28ddf4335ef2c384c602dd9f7fc9ff`.

[46] W. Zhang et al. "Research on short-term load forecasting methods of electric buses charging station". In: *Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control* 41 (Feb. 2013), pp. 61–66.

[47] Y. Zhou et al. "Bi-Objective Optimization for Battery Electric Bus Deployment Considering Cost and Environmental Equity". In: *IEEE Transactions on Intelligent Transportation Systems* 22.4 (2021). Cited by: 18; All Open Access, Green Open Access, pp. 2487–2497. DOI: `10.1109/TITS.2020.3043687`. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85099081114&doi=10.1109%2fTITS.2020.3043687&partnerID=40&md5=a4ede11493eb8f6b6a453f0a56e9003f`.

A

List of interviews and meetings

The following table lists the people that the author have had a meeting with.

Time	Location	Name	Entity	Topic
Jul-23	Online	Peirong Zhu	Xiamen King Long United Automotive Industry Co., Ltd	Characteristics and pricing of BEB parts
Aug-23	Online	Tianyi Li	University of Stuttgart	Pricing of different BEB vehicles

B

Comparison between real and research timetables

Regional line towards city-in this research							Regional line towards suburban-in this research						
Hour/Min							Hour/Min						
5	50						5						
6	00	10	20	30	40	50	6						
7	00	10	20	30	40		7	00	30				
8	00	30					8	00	30				
9	00	30					9	00	30				
10	00	30					10	00	30				
11	00	30					11	00	30				
12	00	30					12	00	30				
13	00	30					13	00	30				
14	00	30					14	00	30				
15	00	30					15	00	30				
16	00	30					16	00	30	40	50		
17	00	30					17	00	10	20	30	40	50
18	00	30					18	00	10	30	40		
19	00						19	00	30				
20	00						20	00					
21	00						21	00					
22	00						22	00					
23							23						
0							0						

Regional line towards city-in reality						Regional line towards suburban-in reality				
Hour/Min						Hour/Min				
5	44					5	44			
6	14	34	44	54		6	16	46		
7	04	14	24	34	54	7	16	46		
8	14	34	54			8	16	46		
9	16	46				9	16	46		
10	16	46				10	16	46		
11	16	46				11	16	46		
12	16	46				12	16	46		
13	16	46				13	16	46		
14	16	46				14	16	46		
15	16	46				15	16	38	53	
16	16	46				16	08	23	41	56
17	16	46				17	11	26	41	56
18	16	46				18	11	26	38	53
19	31					19	31			
20	31					20	31			
21	31					21	31			
22	31					22	31			
23	31					23	31			
0	31					0	31			

City line in this research						
Hour/Min						
5						
6	00	30				
7	00	20	30	40	50	
8	00	10	20	30	40	50
9	00	10	30	50		
10	10	30	50			
11	10	30	50			
12	10	30	50			
13	10	30	50			
14	10	30	50			
15	10	20	30	40	50	
16	00	10	20	30	40	50
17	00	10	20	30	40	50
18	10	30	50			
19	10	30				
20	00	30				
21	00	30				
22	00	30				
23	00					
0						

City line in reality						
Hour/Min						
5	52					
6	09	24	33	44	54	
7	04	14	24	34	44	54
8	04	14	24	34	44	54
9	04	19	34	49		
10	04	19	34	49		
11	04	19	34	49		
12	04	19	34	49		
13	04	19	34	49		
14	04	19	34	49		
15	04	20	37	48	58	
16	08	18	28	38	48	58
17	08	18	29	39	49	59
18	09	19	28	38	58	
19	14	34	54			
20	14	44				
21	14	44				
22	14	44				
23	14	44				
0	14					

C

Timetables in MBEBS application discovery

Daily loops of buses are mostly the same and unchanged part of the combined timetable comparing with non-combined ones. For daily loops, only that in Formation I is displayed as an example.

Daily loops

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
1	S8	2	S8	3	S8	4	S8	5	H2	6	H1	7	H2	8	H1
6:00	38001	6:30	38002	7:00	38003	7:30	38004	6:00	12145	6:00	12045	6:30	12046	6:30	12146
7:00	38101	7:30	38102	8:00	38103	8:30	38104	7:00	12001	7:00	12101	7:30	12102	7:30	12002
8:00	38005	8:30	38006	9:00	38007	9:30	38008	7:50	12103	7:50	12003	8:10	12004	8:10	12104
9:00	38105	9:30	38106	10:00	38107	10:30	38108	8:30	12005	8:30	12105	8:50	12106	8:50	12006
10:00	38009	10:30	38010	11:00	38011	11:30	38012	9:10	12107	9:10	12007	9:30	12008	9:30	12108
11:00	38109	11:30	38110	12:00	38111	12:30	38112	9:50	12009	9:50	12109	10:10	12110	10:10	12010
12:00	38013	12:30	38014	13:00	38015	13:30	38016	10:30	12111	10:30	12011	10:50	12012	10:50	12112
13:00	38113	13:30	38114	14:00	38115	14:30	38116	11:10	12013	11:10	12113	11:30	12114	11:30	12014
14:00	38017	14:30	38018	15:00	38019	15:30	38020	11:50	12115	11:50	12015	12:10	12016	12:10	12116
15:00	38117	15:30	38118	16:00	38119	16:30	38120	12:30	12017	12:30	12117	12:50	12118	12:50	12018
16:00	38021	16:30	38022	17:00	38023	17:30	38024	13:10	12119	13:10	12019	13:30	12020	13:30	12120
17:00	38121	17:30	38122	18:00	38123	18:30	38124	13:50	12021	13:50	12121	14:10	12122	14:10	12022
18:00	38025	18:30	38026	19:00	38027	20:00	38028	14:30	12123	14:30	12023	14:50	12024	14:50	12124
19:00	38130	19:30	38125	20:00	38126	21:00	38127	15:10	12025	15:10	12125	15:30	12126	15:30	12026
				21:00	38029	22:00	38030	15:50	12127	15:50	12027	16:10	12028	16:20	12128
				22:00	38128	23:00	38129	16:30	12029	16:30	12129	16:50	12130	16:50	12030
								17:20	12131	17:20	12031	17:40	12032	17:40	12132
								17:50	12033	17:50	12133	18:10	12134	18:10	12034
								18:30	12135	18:30	12035	18:50	12036	18:50	12136
								19:10	12037	19:10	12137	19:30	12138	19:30	12038
								20:00	12139	20:00	12039	20:30	12040	20:30	12140
								21:00	12041	21:00	12141	21:30	12142	21:30	12042
								22:00	12143	22:00	12043	22:30	12044	22:30	12144
								23:00	12045	23:00	12145				
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

Peak loops of all formations with combined network can be found in the following part.

C.1. Formation I Regional-City 1+1

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S8	10	S8	11	S8	12	S8	13	S8	14	S8	15	S8	16	S8	17	H1
↓↓↓ Regional network departures ↓↓↓																	
7:10	38802	7:40	38804	6:20	38807	7:20	38803	5:50	38805	6:10	38806	6:40	38808	6:50	38801		
↓↓↓ City network departures ↓↓↓																	
						17:10	12811		DH	7:20	12801	7:40	12802	8:00	12803	7:20	12901
							DH	7:40	12902	8:00	12903	8:20	12904	8:40	12905	17:30	12812
								8:20	12804	8:40	12805	9:00	12806	15:20	12814		
								9:00	12906	15:20	12914	15:40	12915	16:00	12907		
								15:40	12815	16:00	12807	16:20	12808	16:40	12809		
								16:10	12908	16:40	12909	17:00	12910	17:10	12911		
								17:00	12810								
								17:30	12912								
↓↓↓ Regional network departures ↓↓↓																	
16:40	38905	16:50	38902	17:10	38907	18:40	38901	18:10	38906	17:20	38903	17:40	38904	17:50	38908		
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

C.2. Formation II Regional-City 1+1

The city line has high frequency all across the day.

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S8	10	S8	11	S8	12	S8	13	S8	14	S8	15	S8	16	S8	17	H1
↓↓↓ Regional network departures ↓↓↓																	
5:50	38805	6:20	38807	6:40	38808	6:10	38806	6:50	38801	7:10	38802	7:20	38803	7:40	38804		
↓↓↓ City network departures ↓↓↓																	
7:20	12801	7:40	12802	8:00	12803		DH									7:20	12901
8:00	12903	8:20	12904	8:40	12905	7:40	12902									17:40	12832
8:40	12805	9:00	12806	9:20	12807	8:20	12804										
9:20	12907	9:40	12908	10:00	12909	9:00	12906										
10:00	12809	10:20	12810	10:40	12811	9:40	12808										
10:40	12911	11:00	12912	11:20	12913	10:20	12910										
11:20	12813	11:40	12814	12:00	12815	11:00	12812										
12:00	12915	12:20	12916	12:40	12917	11:40	12914										
12:40	12817	13:00	12818	13:20	12819	12:20	12816										
13:20	12919	13:40	12920	14:00	12921	13:00	12918										
14:00	12821	14:20	12822	14:40	12823	13:40	12820										
14:40	12923	15:00	12924	15:20	12925	14:20	12922										
15:20	12825	15:40	12826	16:00	12827	15:00	12824										
16:00	12927	16:20	12928	16:40	12929	15:40	12926										
16:40	12829	17:00	12830	17:20	12831	16:20	12828										
17:10	12931	17:30	12932		DH	17:00	12930										
↓↓↓ Regional network departures ↓↓↓																	
17:50	38908	18:10	38906	18:40	38901	17:40	38904	16:40	38905	16:50	38902	17:10	38907	17:20	38903		
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

C.3. Formation III Regional-City 1+1

The city line does not operate at morning and evening stages.

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S8	10	S8	11	S8	12	S8	13	S8	14	S8	15	S8	16	S8
↓↓↓ Regional network departures ↓↓↓															
5:50	38805	6:10	38806	6:20	38807	6:40	38808	6:50	38801	7:10	38802	7:20	38803	7:40	38804
↓↓↓ City network departures ↓↓↓															
6:50	12046	7:10	12001	7:30	12002	7:50	12003								
7:30	12102	7:50	12103	8:10	12104	8:30	12105								
8:10	12004	8:30	12005	8:50	12006	9:10	12007								
8:50	12106	9:10	12107	9:30	12108	9:50	12109								
9:30	12008	9:50	12009	10:10	12010	10:30	12011								
10:10	12110	10:30	12111	10:50	12112	11:10	12113								
10:50	12012	11:10	12013	11:30	12014	11:50	12015								
11:30	12114	11:50	12115	12:10	12116	12:30	12117								
12:10	12016	12:30	12017	12:50	12018	13:10	12019								
12:50	12118	13:10	12119	13:30	12120	13:50	12121								
13:30	12020	13:50	12021	14:10	12022	14:30	12023								
14:10	12122	14:30	12123	14:50	12124	15:10	12125								
14:50	12024	15:10	12025	15:30	12026	15:50	12027								
15:30	12126	15:50	12127	16:10	12128	16:30	12129								
16:10	12028	16:30	12029	16:50	12030										
16:50	12130	17:10	12131	17:30	12132										
↓↓↓ Regional network departures ↓↓↓															
17:50	38908	18:10	38906	18:40	38901	17:40	38904	16:40	38905	16:50	38902	17:10	38907	17:20	38903
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

C.4. Formation IV-1 Regional-City 1+2

Two city lines and one regional line.

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S8	10	S8	11	S8	12	S8	13	S8	14	S8	15	S8	16	S8	17	H1
↓↓↓ Regional network departures ↓↓↓																	
5:50	38805	6:10	38806	6:40	38808	6:50	38801	6:50	38801	7:10	38802	7:20	38803	7:40	38804	7:20	12901
↓↓↓ City network departures ↓↓↓																	
	DH	7:20	12801	7:40	12802	8:00	12803	7:50	12003	8:10	12004	8:30	12005		DH	7:20	12901
7:40	12902	8:00	12903	8:20	12904	8:40	12905	8:30	12105	8:50	12106	9:10	12107	9:30	12108	17:40	12832
8:20	12804	8:40	12805	9:00	12806	15:20	12814	9:10	12007	9:30	12008	9:50	12009	10:10	12010		
9:00	12906	15:20	12914	15:40	12915	16:00	12907	9:50	12109	10:10	12110	10:30	12111	10:50	12112		
15:40	12815	16:00	12807	16:20	12808	16:40	12909	10:30	12011	10:50	12012	11:10	12013	11:30	12014		
16:10	12908	16:40	12809	17:00	12810	17:20	12811	11:10	12113	11:30	12114	11:50	12115	12:10	12116		
17:00	12910	17:10	12911	17:30	12912		DH	11:50	12015	12:10	12016	12:30	12017	12:50	12018		
								12:30	12117	12:50	12118	13:10	12119	13:30	12120		
								13:10	12019	13:30	12020	13:50	12021	14:10	12022		
								13:50	12121	14:10	12122	14:30	12123	14:50	12124		
								14:30	12023	14:50	12024	15:10	12025	15:30	12026		
								15:10	12125	15:30	12126	15:50	12127	16:20	12128		
								15:50	12027								
								16:30	12129								
↓↓↓ Regional network departures ↓↓↓																	
17:40	38904	17:50	38908	18:10	38906	18:40	38901	17:20	38903	16:40	38905	16:50	38902	17:10	38907		
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

C.5. Formation IV-2 Regional-City 2+1

One city line and two regional lines.

Vehicle 9-16

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S1	10	S1	11	S1	12	S1	13	S1	14	S1	15	S1	16	S1
↓↓↓ Regional network departures ↓↓↓															
5:50	31805	6:10	31806	6:20	31807	6:40	31808	6:50	31801	7:10	31802	7:20	38803	7:40	38804
↓↓↓ City network departures ↓↓↓															
				7:30	13002	7:50	13003								
				8:10	13104	8:30	13105								
				8:50	13006	9:10	13007								
				9:30	13108	9:50	13109								
				10:10	13010	10:30	13011								
				10:50	13112	11:10	13113								
				11:30	13014	11:50	13015								
				12:10	13116	12:30	13117								
				12:50	13018	13:10	13019								
				13:30	13120	13:50	13121								
				14:10	13022	14:30	13023								
				14:50	13124	15:10	13125								
				15:30	13026	15:50	13027								
				16:10	13128	16:30	13129								
				16:50	13030	17:10	13031								
↓↓↓ Regional network departures ↓↓↓															
18:10	38906	18:40	38901	17:40	38904	17:50	38908	17:10	31907	17:20	31903	16:50	38902	17:20	38903
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

Vehicle 17-24

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S1	10	S1	11	S1	12	S1	13	S1	14	S1	15	S1	16	S1
↓↓↓ Regional network departures ↓↓↓															
5:50	38805	6:10	38806	6:20	38807	6:40	38808	6:50	38801	7:10	38802	7:20	38803	7:40	38804
↓↓↓ City network departures ↓↓↓															
				7:30	13102	7:50	13103								
				8:10	13004	8:30	13005								
				8:50	13106	9:10	13107								
				9:30	13008	9:50	13009								
				10:10	13110	10:30	13111								
				10:50	13012	11:10	13013								
				11:30	13114	11:50	13115								
				12:10	13016	12:30	13017								
				12:50	13118	13:10	13119								
				13:30	13020	13:50	13021								
				14:10	13122	14:30	13123								
				14:50	13024	15:10	13025								
				15:30	13126	15:50	13127								
				16:10	13028	16:30	13029								
				16:50	13130	17:10	13131								
↓↓↓ Regional network departures ↓↓↓															
18:10	31906	18:40	31901	17:40	31904	17:50	31908	16:40	38905	17:10	38907	16:40	31905	16:50	31902
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

C.6. Formation V Regional-City 2+2

A mini network consists of two city line and two regional lines.

Vehicle 9-16

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S1	10	S1	11	S1	12	S1	13	S1	14	S1	15	S1	16	S1
↓↓↓ Regional network departures ↓↓↓															
5:50	31805	6:10	31806	6:20	31807	6:40	31808	6:50	31801	7:10	31802	7:20	38803	7:40	38804
↓↓↓ City network departures ↓↓↓															
7:20	12901	7:40	12902	7:30	13002	7:50	13003								
8:00	12803	8:20	12804	8:10	13104	8:30	13105								
8:40	12905	9:00	12906	8:50	13006	9:10	13007								
15:20	12814	15:40	12815	9:30	13108	9:50	13109								
16:00	12907	16:10	12908	10:10	13010	10:30	13011								
16:40	12809	17:00	12810	10:50	13112	11:10	13113								
17:10	12911	17:30	12912	11:30	13014	11:50	13015								
				12:10	13116	12:30	13117								
				12:50	13018	13:10	13019								
				13:30	13120	13:50	13121								
				14:10	13022	14:30	13023								
				14:50	13124	15:10	13125								
				15:30	13026	15:50	13027								
				16:10	13128	16:30	13129								
				16:50	13030	17:10	13031								
↓↓↓ Regional network departures ↓↓↓															
18:10	38906	18:40	38901	17:40	38904	17:50	38908	17:10	31907	17:20	31903	16:50	38902	17:20	38903
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

Vehicle 17-24

Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot	Bus	Depot
9	S1	10	S1	11	S1	12	S1	13	S1	14	S1	15	S1	16	S1
↓↓↓ Regional network departures ↓↓↓															
5:50	38805	6:10	38806	6:20	38807	6:40	38808	6:50	38801	7:10	38802	7:20	38803	7:40	38804
↓↓↓ City network departures ↓↓↓															
7:20	12801	7:40	12802	7:30	13102	7:50	13103								
8:00	12903	8:20	12904	8:10	13004	8:30	13005								
8:40	12805	9:00	12806	8:50	13106	9:10	13107								
15:20	12914	15:40	12915	9:30	13008	9:50	13009								
16:00	12807	16:20	12808	10:10	13110	10:30	13111								
16:40	12909	17:00	12910	10:50	13012	11:10	13013								
17:20	12811	17:40	12812	11:30	13114	11:50	13115								
				12:10	13016	12:30	13017								
				12:50	13118	13:10	13119								
				13:30	13020	13:50	13021								
				14:10	13122	14:30	13123								
				14:50	13024	15:10	13025								
				15:30	13126	15:50	13127								
				16:10	13028	16:30	13029								
				16:50	13130	17:10	13131								
↓↓↓ Regional network departures ↓↓↓															
18:10	31906	18:40	31901	17:40	31904	17:50	31908	16:40	38905	17:10	38907	16:40	31905	16:50	31902
Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride	Time	Ride

D

Referenced real vehicle data

Besides these listed data, the author had visited commercial vehicle exhibitions including Beijing International Expo on Commercial Vehicles & Components in China and IAA Transportation in Hanover. Besides, the continuous collection process by travelling and taking photos for buses and visiting to bus manufacturers' websites from time to time makes up a very important part of real vehicle data collection. They are hard to count and the quantity goes far beyond the following table.

Type	Characteristics	Value	Unit	Source
BYD K9A	Consuming rate	1.41-1.77	kWh/km	
BYD K9A	Mass	12.600-18.000	kg	RDW
BYD K9UB	Mass	13.650-19.000	kg	RDW
Ebusco 2.2	Mass	12.750-19.000	kg	RDW
MAN A78	Seats	43	#	RDW
MAN Lion's Intercity	Mass	11.360	kg	RDW
MB eCitaro	Price	600.000	€	Interview
MB Integro	Mass	12.420	kg	RDW
MB Integro	Seats	50	#	RDW
Newflyer XE40	Consuming rate	0.9-1.4	kWh/km	
Van Hool A12E	Price	550.000	€	Other sources
VDL LLE99E	Seats	29	#	RDW
VDL SLE120Hyb	Seats	39	#	RDW
VDL SLF120E	Mass	13.935-18.745	kg	RDW
VDL SLF120E	Price	550.000	€	Interview
VDL SLF120E	Seats	31	#	RDW
Volvo 7900E	Mass	12.940-19.000	kg	RDW
Yutong C12E	Mass	13.300	kg	

E

CBA Results

E.1. Full CBA table example

CBA		A	A	A	A	R1	R1	R1	R1	
Year	Month	Purchasing	Infrastructure	Operation	Energy	Purchasing	Infrastructure	Operation	Energy	Discount rate
2022	Jan	65440000	334000	0	626499.5895	50300000	2060000	120960	603769.3578	1
	Feb	0	0	0	625873.0899	0	0	120839.04	603165.5885	0.999
	Mar	0	0	0	625247.2168	0	0	120718.201	602562.4229	0.998001
	Apr	0	0	0	624621.9696	0	0	120597.4828	601959.8605	0.997003
	May	0	0	0	623997.3476	0	0	120476.8853	601357.9006	0.996006
	Jun	0	0	0	623373.3503	0	0	120356.4084	600756.5427	0.99501
	Jul	0	0	0	622749.9769	0	0	120236.052	600155.7861	0.994015
	Aug	0	0	0	622127.227	0	0	120115.8159	599555.6304	0.993021
	Sep	0	0	0	621505.0997	0	0	119995.7001	598956.0747	0.992028
	Oct	0	0	0	620883.5946	0	0	119875.7044	598357.1187	0.991036
	Nov	0	0	0	620262.711	0	0	119755.8287	597758.7615	0.990045
	Dec	0	0	0	619642.4483	0	0	119636.0729	597161.0028	0.989055
2023	Jan	0	0	0	619022.8059	0	0	119516.4368	596563.8418	0.988066
	Feb	0	0	0	618403.7831	0	0	119396.9204	595967.2779	0.987078
	Mar	0	0	0	617785.3793	0	0	119277.5235	595371.3107	0.986091
...	...	...	...	...	...	...	...	...	...	...
2033	Oct	0	0	0	544069.8134	0	0	105045.0563	524330.2427	0.868428
	Nov	0	0	0	543525.7436	0	0	104940.0112	523805.9125	0.86756
	Dec	0	0	0	542982.2178	0	0	104835.0712	523282.1066	0.866692
Total		65440000	334000	0	84060353.88	50300000	2060000	16229763.87	81010533.33	
				A Total	149834353.9			R1 Total	149600297.2	

E.2. CBA results by scenario

Regular scenarios 1-6

1	Low ridership	Low price level			
	A	B	R1	R2	R3
Difference in investments		-6232000	-3835070.838	1316929.162	-10924000
Difference in energy costs		-541075.69	-911926.3546	-1059669.37	-738767.586
NPV		6773075.69	4746997.192	-257259.7922	11662767.59
BCR		-0.0868222	-0.237786052	0.804651761	-0.067627937
2	Midi ridership	Low price level			
Difference in investments		-6232000	-3835070.838	1316929.162	-10924000
Difference in energy costs		-539618.48	-913263.2623	-1063596.983	-738154.1896
NPV		6771618.48	4748334.1	-253332.179	11662154.19
BCR		-0.0865883	-0.238134653	0.807634164	-0.067571786
3	High ridership	Low price level			
Difference in investments		-6232000	-3835070.838	1316929.162	-10924000
Difference in energy costs		-538038.79	-914946.1627	-1067753.01	-737387.1278
NPV		6770038.79	4750017	-249176.1521	11661387.13
BCR		-0.0863349	-0.238573471	0.810790011	-0.067501568
4	Low ridership	Midi price level			
Difference in investments		-8082000	-2229118.063	3152881.937	-12774000
Difference in energy costs		-901792.82	-1519877.258	-1766115.617	-1231279.31
NPV		8983792.82	3748995.321	-1386766.32	14005279.31
BCR		-0.1115804	-0.681828963	0.560159134	-0.096389487
5	Midi ridership	Midi price level			
Difference in investments		-8082000	-2229118.063	3152881.937	-12774000
Difference in energy costs		-899364.13	-1522105.437	-1772661.639	-1230256.983
NPV		8981364.13	3751223.5	-1380220.298	14004256.98
BCR		-0.1112799	-0.682828542	0.562235337	-0.096309455
6	High ridership	Midi price level			
Difference in investments		-8082000	-2229118.063	3152881.937	-12774000
Difference in energy costs		-896731.32	-1524910.271	-1779588.35	-1228978.546
NPV		8978731.32	3754028.334	-1373293.587	14002978.55
BCR		-0.1109541	-0.684086813	0.564432283	-0.096209374

Regular scenarios 7-12

7	Low ridership	High price level			
Difference in investments		-9932000	-623165.2879	4988834.712	-14624000
Difference in energy costs		-1442868.5	-2431803.612	-2825784.987	-1970046.896
NPV		11374868.5	3054968.9	-2163049.725	16594046.9
BCR		-0.1452747	-3.902341256	0.56642185	-0.134713272
8	Midi ridership	High price level			
Difference in investments		-9932000	-623165.2879	4988834.712	-14624000
Difference in energy costs		-1438982.6	-2435368.699	-2836258.622	-1968411.172
NPV		11370982.6	3058533.987	-2152576.09	16592411.17
BCR		-0.1448835	-3.908062189	0.568521265	-0.13460142
9	High ridership	High price level			
Difference in investments		-9932000	-623165.2879	4988834.712	-14624000
Difference in energy costs		-1434770.1	-2439856.434	-2847341.361	-1966365.674
NPV		11366770.1	3063021.722	-2141493.351	16590365.67
BCR		-0.1444593	-3.915263705	0.570742774	-0.134461548
10	Low ridership	Supreme price level			
Difference in investments		-10862000	2815763.874	9807763.874	-16474000
Difference in energy costs		-1803585.6	-3039754.515	-3532231.234	-2462558.62
NPV		12665585.6	223990.6411	-6275532.641	18936558.62
BCR		-0.1660454	1.079548801	0.360146439	-0.149481524
11	Midi ridership	Supreme price level			
Difference in investments		-10862000	2815763.874	9807763.874	-16474000
Difference in energy costs		-1798728.3	-3044210.874	-3545323.278	-2460513.965
NPV		12660728.3	228446.9999	-6262440.597	18934513.97
BCR		-0.1655983	1.081131448	0.361481304	-0.14935741
12	High ridership	Supreme price level			
Difference in investments		-10862000	2815763.874	9807763.874	-16474000
Difference in energy costs		-1793462.6	-3049820.542	-3559176.701	-2457957.093
NPV		12655462.6	234056.668	-6248587.174	18931957.09
BCR		-0.1651135	1.083123685	0.3628938	-0.149202203

Extreme scenarios

Scenario name	Ridership	Price level	Exception				
Reliable modules	High	Low	Very low operation cost	Operation cost=0.5			
	A	B	R1	R2	R3		
Difference in investments		-6232000	-7892511.8	-2740511.8	-10924000		
Difference in energy costs		-538038.79	-914946.16	-1067753	-737387.1278		
NPV		6770038.79	8807457.97	3808264.82	11661387.13		
BCR		-0.0863349	-0.1159259	-0.3896181	-0.067501568		
Energy crisis	High	Low	Super high energy price	Energy price avg=0.8			
Difference in investments		-6232000	-3835070.8	1316929.16	-10924000		
Difference in energy costs		-2869540.2	-4879712.9	-5694682.7	-3932731.348		
NPV		9101540.22	8714783.71	4377753.56	14856731.35		
BCR		-0.4604525	-1.2723918	4.32421339	-0.360008362		
Lithium Scarcity	Midi	Low	Super high vehicle price	Prices as shown on the right		Type	Price
Difference in investments		-10172000	-10075071	-2623070.8	-17164000	City	530000
Difference in energy costs		-539618.48	-913263.26	-1063597	-738154.1896	Regional	620000
NPV		10711618.5	10988334.1	3686667.82	17902154.19	Utility	680000
BCR		-0.0530494	-0.0906458	-0.4054778	-0.043005954	MBEBS	690000

E.3. Sensitivity analysis data

Bandwidths

Energy price +50%	A	B	R1	R2	R3	-50%	A	B	R1	R2	R3
Difference investments		-8082000	-2229118	3152882	-12774000	Difference investments		-8082000	-2229118	3152882	-12774000
Difference energy costs		-1349046	-2283158	-2658992	-1845385	Difference energy costs		-449682	-761053	-886331	-615128
NPV		9431046	4512276	-493889	14619385	NPV		8531682	2990171	-2266551	13389128
BCR		-0.16692	-1.02424	0.843353	-0.14446	BCR		-0.05564	-0.34141	0.281118	-0.04815

Operation cost +50%	A	B	R1	R2	R3	-50%	A	B	R1	R2	R3
Difference investments		-8082000	1828323	7210323	-12774000	Difference investments		-8082000	-6286559	-904559	-12774000
Difference energy costs		-899364	-1522105	-1772662	-1230257	Difference energy costs		-899364	-1522105	-1772662	-1230257
NPV		8981364	-306217	-5437661	14004257	NPV		8981364	7808664	2677221	14004257
BCR		-0.11128	0.832515	0.245851	-0.09631	BCR		-0.11128	-0.24212	-1.9597	-0.09631

Positive changes

Original	+0%				
	A	B	R1	R2	R3
Difference in investments		-8082000	-2229118	3152882	-12774000
Difference in energy costs		-899364	-1522105	-1772662	-1230257
NPV		8981364	3751223	-1380220	14004257
BCR		-0.11128	-0.68283	0.562235	-0.0963095
Energy price	+50%				
Difference in investments		-8082000	-2229118	3152882	-12774000
Difference in energy costs		-1349046	-2283158	-2658992	-1845385.5
NPV		9431046	4512276	-493889	14619385.5
BCR		-0.16692	-1.02424	0.843353	-0.1444642
Operation cost	+50%				
Difference in investments		-8082000	1828323	7210323	-12774000
Difference in energy costs		-899364	-1522105	-1772662	-1230257
NPV		8981364	-306217	-5437661	14004257
BCR		-0.11128	0.832515	0.245851	-0.0963095
Vehicle price	+30%				
Difference in investments		-10512000	-5850118	1118882	-16584000
Difference in energy costs		-899364	-1522105	-1772662	-1230257
NPV		11411364	7372223	653779.7	17814257
BCR		-0.08556	-0.26018	1.584315	-0.0741834
Number of MBEBS	+30%				
Difference in investments		-1582000	4465882	9847882	-6274000
Difference in energy costs		-899364	-1522105	-1772662	-1230257
NPV		2481364	-2943777	-8075220	7504256.98
BCR		-0.5685	0.34083	0.180004	-0.1960881

The Adjustable Electric Bus

A Study to the Concept and its Social-Economical Performance

1st Shiyu Qin
Delft Technology University
Faculty of Civil Engineering and Geosciences
Delft, the Netherlands

3rd Arjan van Binsbergen
Delft Technology University
Faculty of Civil Engineering and Geosciences
Delft, the Netherlands

2nd Niels van Oort
Delft Technology University
Faculty of Civil Engineering and Geosciences
Delft, the Netherlands

4th Jan Anne Annema
Delft Technology University
Faculty of Technology, Policy & Management
Delft, the Netherlands

***Abstract*—This research proposes a new concept of electric bus with adjustable interior modules. By installing different modules, it can adjust both its internal layout and battery capacity spontaneously to make itself resemble an electric city bus or an electric regional bus when it is needed. It makes use of difference between peak times of regional lines and city lines so that it provides the same service as one city bus and one regional bus can do. This research firstly verified the timetable feasibility of this adjustable electric bus. It turns out that one vehicle is able to operate both city and regional bus network with observable resilience, reduction of minimum vehicle number and saving of electricity consumption. However adjustable BEB is limited by its high purchasing and operation cost, making it not highly profitable in a whole concession period. Accordingly, this research suggests low-entry utility electric bus is the more reliable and cost-efficient choice to carry out combined network operation.**

***Index Terms*—electric bus, adjustable, interior, timetabling, cost-benefit analysis, modular**

I. INTRODUCTION

In recent years battery electric buses (BEB) are taking over bus networks from buses with internal combustion engines [1]. Considering the high purchasing cost of BEB [5], increasing the efficiency of applying BEB becomes important. Meanwhile, the volume and weight of batteries are causing limitations to driving range and capacity of BEBs. BEBs with city bus layout cannot hold too much battery in order to save electricity and provide enough capacity; BEBs with ample batteries and high driving performance can only have high-floor layout capable for regional service.

Therefore, the concept of an adjustable BEB come to the table. In this research the target adjustable BEB is named 'Multi-modal BEB System' in short MBEBS. MBEBS make use of developed 12-meters integral chassis structures of current BEBs on which motor was integrated into the rear axle and controlling were scattered in the corners. Limited number of batteries, pantograph charger and air conditioner were put on the roof. The middle part and rear overhang of the chassis are designed with 8 spaces for different units called interior modules to enter. These modules, homogeneous on sizes, have 5 different types according to function, floor height, seats and battery capacity. They can be installed from both left and right sides of the chassis.

By installing indicated number and types of modules, a MBEBS can have two modes aiming for city or regional bus transport. At exclusive swapping stations located in big city hub stations where regional and city lines meet, modules are quickly exchanged by withdrawing or inserting movements so that MBEBS transfers between a regional- and a city BEB. By operating in different modes at different time, MBEBS would be able to combine regional and city bus transport. One MBEBS can do the job of one regional BEB plus one city BEB. It may save both vehicle investments and electricity consumption brought by extra battery weight [3] for bus networks.

II. METHOD

Demo buses with adjustable layout have been developed for testing passengers' experiences [2], but for current BEB the concept was hardly found in existing literature. This research discovers the concept from two aspects: firstly on its operation feasibility and then on its cost-benefit performance.

A. Small-scale networks modelling

This research starts from dispatching for simple networks including few lines with basic timetables in two situations: with and without MBEBS. Behaviour of MBEBS and differences it brings are recorded during dispatching process. Recorded behaviours of buses include minimum number of vehicles, daytime dwells, deadheading trips, transfers and charging operations. When new lines are added into simple network, its complexity grows. With higher complexity the behaviour of MBEBS observed from dispatching process becomes more realistic. Useful general intermediate conclusions of of applying MBEBS are concluded in this phase for larger scaled network analysis in the following phases.

B. Archetype network modelling

An archetype network with multiple lines, stations, different demand across time reflecting typical existing regional and

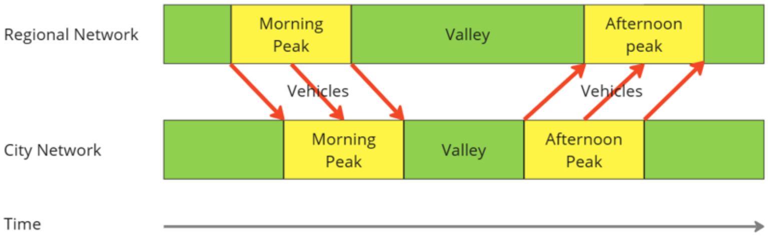


Fig. 1. Flow of vehicles between city and regional bus network

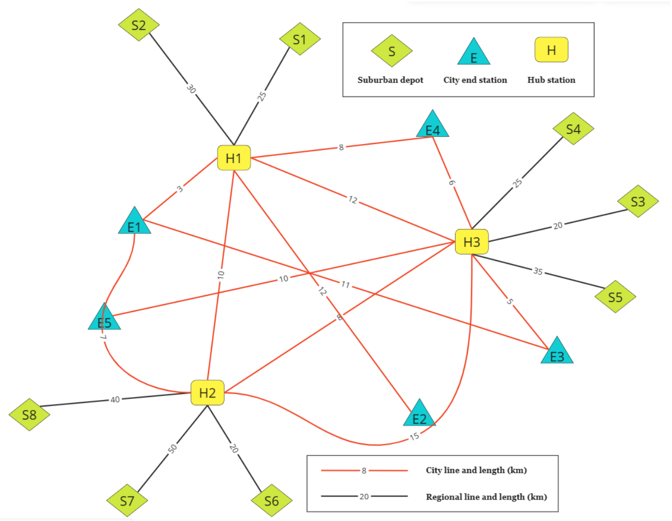


Fig. 2. Structure of the archetype network

city bus networks has been created as showed in figure 2. Research and reference cases pieced up by different types of BEBs were assumed according to typical organization of bus networks in reality. Characteristics (components, structure, capacity, driving range, weight, consuming rate, prices) of MBEBS and other BEBs which are thought to be rivals of the former are defined by viewing private data collection and interviews with bus manufacturers. For the MBEBS, some of its characteristics were concluded based on assumptions of interior modules. Using general intermediate conclusions to applying MBEBS from previous stage, number of vehicles, infrastructures and their operations are calculated for each cases according to network settings [6]. Type and number of vehicles on each lines are therefore clarified so that operation cost was measured. Furthermore, passenger load and total driven kilometers in a complete weekday were calculated to handle electricity consumption of different cases.

C. *Cost-Benefit Analysis*

Vehicle investments, infrastructures, electricity costs and exclusive operation costs of MBEBS are selected as monetary criteria to evaluate its cost-benefit performance. Pricing factors are also defined by viewing private data collection and interviews with bus manufacturers. Based on the numerical results and pricing factors, all cases are studied by a cost-benefit analysis (CBA) under an assumed 12-year bus concession period using one of the reference cases as basis. Scenarios with different ridership and level of prices are set up considering possible change of prices. Therefore numerical results are transferred to monetary values and cost-benefit performance of MBEBS in different scenarios are evaluated. Sensitivity analysis is then carried out by changing different factors in an amount in order to find out important factors influencing cost-benefit performance of MBEBS.

III. RESULTS

A. *Intermediate conclusions of simple network modelling*

The simple networks that are verified include two, three and four city and regional lines. It is shown that combining regional and city lines with MBEBS helps the reduction of minimum number of vehicles. It shows that as the combined network becomes more complex, the regional lines and its MBEBS can be simply recognized as free to combine to a hub station without any waste especially when demand of city peak vehicles is higher than MBEBS supply from regional lines. A symmetric allocation of MBEBS is more favourable for reducing deadheading trips and unused vehicles. These results shows feasibility of combining networks and applying MBEBS. Also, these results make modelling MBEBS for the archetype network easier. Through an additional sensitivity analysis, combining networks are proved to be robust to extended delay during transfer between modes. Up to 20 minutes delay during transfer only results 5% demand of extra buses.

B. *Numerical results of archetype network modelling*

The archetype network created for this research includes 3 hub stations, 8 regional lines and 12 city lines. Vehicles involved in this network for different cases are: city BEB, regional BEB, MBEBS and Utility BEB. Utility BEB is a kind of existing low-entry BEB with long driving range, higher floor in the rear and more seats appropriate for both city and regional services and also favourable to the idea of combining networks. It is seen as a rival of MBEBS.

Using these vehicles and according to current operation structures of city and regional network, five cases are proposed. The first and second cases (A & B) are for reference. Case A reflects a typical separated city and regional operation while

TABLE I
VEHICLE USAGE BY CASES

Vehicles	A	B	R1	R2	R3
City BEB	83		46		46
Regional BEB	42				
Utility BEB		88			42
MBEBS			42	88	
Total	125	88	88	88	88
Combined network		x	x	x	x

case B represents an improved whole-regional monopoly situation with Utility BEBs. The rest three (R1-R3) are research cases to MBEBS and Utility BEB as the rival: Case R1 for MBEBS-based combination, case R2 for MBEBS-monopoly combination and case R3 for Utility BEB-based combination. By vehicle allocation under combined networks, 42 peak vehicles are supplied by 8 regional lines gathering at 3 different hub stations. They are completely absorbed by city lines with some extra city BEB as supplement and redundant vehicles. Therefore, number of vehicles needed in each cases were estimated as table I shows. It can be seen that combining networks have significantly reduced number of vehicles comparing with cases without combination.

Using profiles of lines [4] and characteristics of vehicles, crowdness and the electricity consumption in each cases over one working day was calculated. On the perspective of numerical electricity consumption, cases with MBEBS has lower electricity consumption on both city and regional network. Difference of passengers' experience (city line crowdness and seats on regional line) between cases are relatively small.

C. CBA results

In this research, Vehicle investments, infrastructure and operation cost are unified as costs. electricity costs would be the only benefit. The CBA grasps difference of these values between each cases and reference case A. Minus difference in investments means a case spends less than reference case A. Positive difference in electricity costs means it brings more benefits than reference case A. The CBA result in table II is based on an intermediate investment price, electricity price and ridership level.

It can be seen that most research cases and reference case B are having positive NPV (net present value after the 12-years period) while case R3 partially using Utility BEBs for combining networks is the best among all. Result of passenger experience are displayed by a qualitative analysis: for city lines, all cases are performing worse than basis case A while case B with completely Utility BEBs is the worst; For regional lines, all cases are performing well.

D. Scenario & sensitivity analysis

Twelve different scenarios were created with 4 price levels and 3 ridership levels. The result of comparing scenarios shows negligible effect of ridership and strong influence of investment and electricity price levels. As price level rises, inferiority of MBEBS enlarges. In some cases, MBEBS even gets higher costs comparing with reference case A. In another 3 extreme scenarios out of 12 regular ones with some extreme settings in favour of MBEBS, NPVs of MBEBS cases are still falling behind Utility BEB cases despite decreased differences as figure 3 shows.

Result of sensitivity analysis to factors for total investments (costs), benefits and NPV based on an intermediate price level is as figure 4 shows. For electricity price and operation cost, they were given both increase and reduction to show and compare the bandwidth of changes. It was observed that change of electricity price has relatively smaller effects to NPV comparing with operation costs under the same percentage of change.

Changing of vehicle single prices has positive effects to investments of each research cases with a magnitude less than 150%. Changing number of vehicles exerts stronger negative influences to investments of all research cases than changing vehicle single prices. Sensitivity of MBEBS operation cost has an intermediate negative influence to to total investments of MBEBS cases.

Sensitivity of these factors to NPV are similar as their sensitivity to investments. This result again reflects the low effect of electricity costs. Increasing electricity price and single vehicle prices do have positive effect to all research cases but MBEBS operation cost have much stronger negative influences.

IV. CONCLUSIONS

Research findings

It has been proved that combining city and regional network with single type of vehicle is feasible on timetabling level. The bigger the networks will be combined is, the more flexible the combinations can be and the more vehicles can be applied effectively in both networks. These combinations were also proved to be robust to delays. In most research scenarios, all research caseshave reached a positive NPV, proving the idea of combining network is able to reduce total investment to such a big network significantly.

However, from the CBA it was found that MBEBS or the adjustable BEB is not the best vehicle to carry out such combining timetables due to its high investments and operation cost. Considering Utility BEB as a mature technology, it is a stable and economic choice for combining network. The adjustable BEB might just remain as a concept in forseeable years.

In conclusion, the adjustable BEB do save electricity cost, but this innovative concept has higher operation cost and vehicle investments compared to conventional Utility BEBs. Meanwhile, its high sensitivity to its own characteristics makes it easily becomes more expensive than using Utility BEBs. Infrastructure investment of the adjustable BEB is actually not very important comparing with electricity and operation costs which accumulates across days, months and

TABLE II
CBA RESULT INTERMEDIATE PRICING LEVEL AND RIDERSHIP

	A	B	R1	R2	R3	Unit
Crowdness on city lines	0	- - -	-	-	–	
Standing on regional lines	0	0	0	0	0	pax-km
Difference in investments (cost)	0	-808,2	-222,9	315,3	-1277,4	x1.000€
Difference in electricity costs (benefit)	0	90	152,2	177,3	123	x1.000€
NPV		898,1	375,1	-138	1400,4	x1.000€

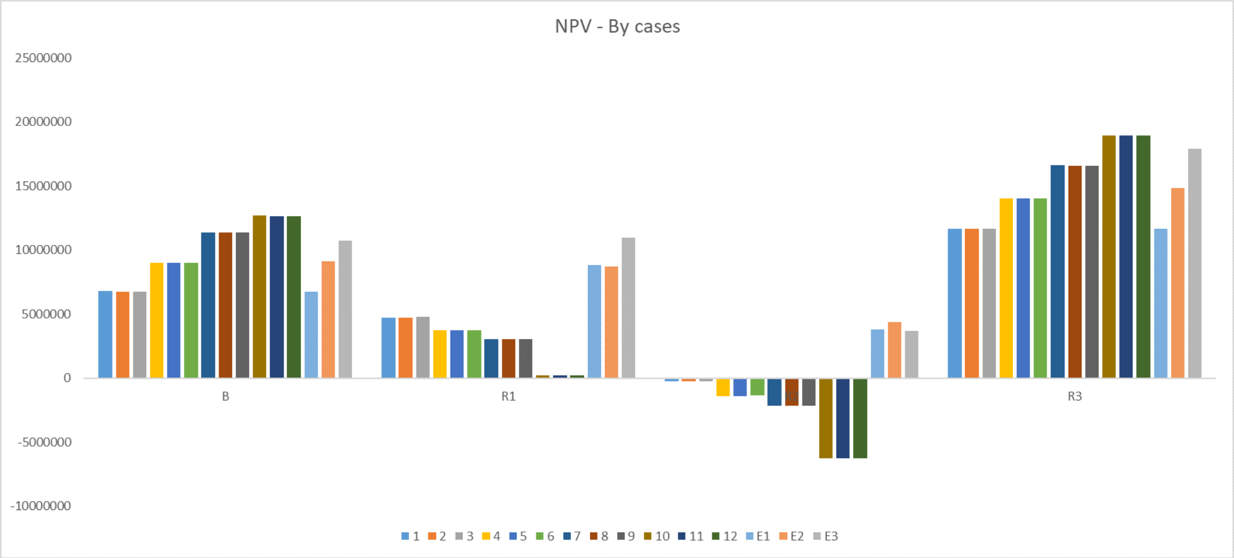


Fig. 3. NPV by cases in each scenario

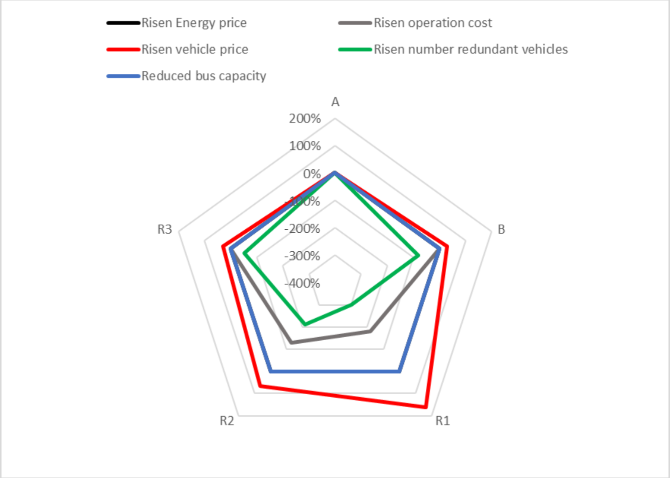


Fig. 4. Total investment change by cases of changing each factor (electricity cost is seen as investment)

years.

Recommendations

Some recommendations are given to MBEBS-related entities including bus manufacturer, concession manager and bus operators. Manufacturers of BEBs can consider to make small-scaled MEBES models and try its technological availability. Full-scale prototypes can be developed and applied for short period in cooperation with research institutes, bus operators and vehicle managing departments. The government in responsible for bus concession and services is suggested to merge city and regional networks especially in large cities to allow combination of networks. Accordingly, operators of city and regional networks can adjust timetable according to real distribution of lines, depots and demands to combine as much lines as possible.

Low-entry Utility BEBs would be a conservative and cost-efficient choice to do that. The whole electrified combined network would probably consist of appropriate share of city, regional and utility BEBs. For other bus operators like subcontractors and rental companies, MBEBS might be useful in response to various demand from different scenarios.

To further understand the adjustable BEB and combined networks, researchers can choose to focus on dispatching algorithm considering adjustable BEBs in a combined network.

For the adjustable BEB itself, it can make use of recycled or worse-performance material, especially for batteries which help adjustable BEBs become cheaper and more environmental friendly. Topic of adjustable with different sizes, other types of interior modules and module as electricity storage are also worthy to be looked into.

REFERENCES

[1] Paris IEA. Global EV Outlook 2023. 2023. url: https://www.iea.org/reports/global- ev-outlook-2023 (visited on 09/05/2023).

[2] B.M. Brooks. “An investigation into aspects of bus design and passenger requirements”. In: Ergonomics 22.2 (1979). Cited by: 9, pp. 175–188. doi: 10.1080/00140137908924602.

[3] B. Duangsrikaew et al. “Battery Sizing for Electric Vehicles Based on Real Driving Patterns in Thailand”. In: World Electric Vehicle Journal 10.2 (June 2019), p. 43. issn: 2032-6653. doi: 10.3390/wevj10020043.

[4] J. Ji et al. “Trip energy consumption estimation for electric buses”. In: Communications in Transportation Research 2 (2022). Cited by: 21; All Open Access, Green Open Access. doi: 10 . 1016 / j . commtr . 2022 . 100069.

[5] K. Say et al. “The economics of public transport electrification: A case study from Victoria, Australia”. In: energy Economics 120 (2023). Cited by: 1. doi: 10.1016/j.eneco.2023.106599.

[6] A. Ceder. Public Transit Planning and Operation: Modeling, Practice and Behavior, Second Edition (2nded.) CRC Press, 2015. doi: https://doi.org/10.1201/b18689.