Preparing for battery electric bus public transport: modelling tools and implementation decision making support, 2/7/25

Prof. Dr. Constantinos Antoniou

Part I. Literature (for further reading about distracted driving risk factors)

Sadrani, M., Tirachini, A., Antoniou, C., Electric bus planning with a detailed energy consumption model. In Revision, 2025.

Sadrani, M., Tirachini, A., Antoniou, C. (2025). Bus Scheduling with Heterogeneous Fleets: Formulation and Hybrid Metaheuristic Algorithms. Expert Systems with Applications 263, 125720.

Sadrani, M., Najafi, A., Mirqasemi, R., & Antoniou, C. (2023). Charging strategy selection for electric bus systems: A multi-criteria decision-making approach. Applied Energy, 347, 121415. https://doi.org/10.1016/j.apenergy.2023.121415

Sadrani, M., Mirqasemi, R., Tirachini, A., & Antoniou, C. (2024). Barriers to electrification of bus systems: A fuzzy multi-criteria analysis in developed and developing countries. Energy Conversion and Management, 314, 118700. https://doi.org/10.1016/j.enconman.2024.118700

Part II. Recent News

Vivian La (2025, January 17). *Boston schools will expand their electric bus fleet with $35 million grant* https://www.wbur.org/news/2025/01/17/boston-schools-electric-buses-epa-grant

Amy Lunday (2024, October 11). *Johns Hopkins' first electric buses will hit the road in 2025* https://hub.jhu.edu/2024/10/11/climate-action-and-sustainability-plan-electric-buses/

Megan Perrero (2025, February 18). *Editor's Notebook: Keeping the Momentum Going on the Zero-Emission Transition into 2025 and Beyond* https://www.masstransitmag.com/bus/vehicles/hybrid-hydrogen-electric-vehicles/article/55265320/editors-notebook-keeping-the-momentum-going-on-the-zero-emission-transition-into-2025-and-beyond

Part III.

Jinhua questions

Q: Maybe I'll start with the first one you presented, where you mentioned that energy consumption follows a kind of non-monotonic distribution. That's very interesting to find, right? But one thing I want to add is the comparison between diesel buses and electric buses in terms of energy consumption. In diesel buses, we don't care about the distribution; we care about the total consumption. But for electricity, the time-of-day distribution matters critically.

With the same total amount of electricity, depending on whether it is distributed during peak hours or non-peak hours, the impact on the grid—and therefore the cost to the agency—differs significantly. Right? So, tailoring the methodology to incorporate this type of varied energy cost over time into the process is important.

A: So, first of all, thanks for highlighting that. Obviously, the energy cost and the function we mentioned here apply to battery-electric buses under these conditions. It's not for diesel, which operates differently. That was also one of the challenges—developing energy consumption models for electric buses.

Now, this study only focuses on a corridor. One of the things we want to do is examine it at a broader level, where we incorporate these aspects into the dispatching process. That way, an operator can understand and integrate charging into the system, including dispatching and operations.

Q: I see. Thank you. The other thing I noticed—you mentioned one point where you said the optimal solution is about 35 buses per hour, right? For a U.S. audience, that's like, "Wow! We've never heard of this number," right? But in many places, like in Europe and Asia, we sometimes have headways as short as half a minute. That's actually the reality there.

So, on that note, I do want to ask—given that level of high density, how much burden does this add to the grid? From an infrastructure point of view, for example, in your experience with European or Asian cities, how do those cities handle such strong energy demand on the natural grid?

A: I cannot say that I'm an expert on this part. As you're talking about electric vehicles in general, we've had a lot of discussions about that—how the grid handles it, how the infrastructure supports it. Last week, we had an event where we discussed this, and there were representatives from some companies that develop high-voltage chargers for electric vehicles. They mentioned that they aren't allowed to install them in certain places because the grid doesn't provide the necessary support. So, this is obviously a big issue.

We've also discussed this with bus operators, where they say, "Okay, as you mentioned, having an entire fleet that is all-electric is a huge challenge." But imagine depots where all these buses need to be charged at the same time. Obviously, significant investment in infrastructure is required, right? And we know that in China, they take a very strong end-to-end approach to these things.

By the way, speaking of China, I was in Changsha, Hunan Province, in November for a conference. It was in a different context—road safety—but we had a discussion about how China is classified. Some Americans and Europeans said, "Oh, China is developed!" We were amazed at some of the advancements there that we don't even have in Europe or the U.S. But then, local professors said, "No, no, no, we are still developing." Some things may look modern, but the classification isn't always straightforward.

So, this also ties into a broader point—it's not easy to categorize countries in a specific way. Saying a country is "developed" or "developing" assumes many things, but a more fine-tuned analysis is needed for specific aspects.

Q: That's interesting. "Developing" and "developed" in the Western context are used to refer to the status of development as a noun. But in China, they interpret "developing" as a verb, describing the fact that they are changing quickly.

On that note, you mentioned that the barriers have different priorities between developing and developed countries. In developing countries, you particularly highlighted management as a key barrier, right? Can you elaborate on this? What types of management challenges have you encountered?

A: Yes. Again, I'm Greek, so theoretically, it's a developed country—but that's another discussion.

Currently, besides the fact that in many of these papers, my co-author and the co-supervisor of Mohammed was Alejandro Tirakini, I also have a PhD student from Chile, Cesan Nunez, who is actually working on mobility as a service from a management perspective. And precisely because of these issues, we have been discussing this a lot.

In some countries, you have difficulties in organization, in establishing regulations, in developing in an organized way, and in maintaining well-adhered schedules. There are also challenges related to non-corruption, ensuring employees arrive on time, proper training, etc. This is the kind of management issue we're talking about.

It seems that in many of these countries, managing public transport services is tricky. While technological and economic issues exist everywhere and are obviously important, on top of that, you have challenges that, in the developed world, are generally expected to function more smoothly due to better structure and governance. These are things that people in developed countries may not think about on a daily basis, but in certain parts of the world, they present real barriers.

I don't know if this helps as a response.

Q: Yeah, thank you. Maybe one question—if you look at a particular agency in the United States, it may have 5 electric buses, or it's still really at the pilot stage. And suppose, let's say, by 2040, many cities are aiming for 100% electrification. The reality and the ambition seem to have a huge gap.

In optimization, we often optimize for a specific time point. We say, "Okay, here's the optimal solution with this number of buses, this number of chargers, etc." But what I find is that many agencies need help in optimizing a trajectory. Meaning, this year I have five licenses—next year, can I get to 20? Can I get to 50? They need an optimized pathway forward, particularly considering the dependency between buses and chargers. Can they grow hand in hand in a proportional way?

Instead of just finding the optimal final solution, we should be identifying the optimal pathway forward. Is there a way academics can help in that regard?

A: I think there are several ways—both technical and explanatory—to address the difficulty you mentioned.

Again, I have another example from a Mediterranean country in Europe that, at some point, was trying to secure funding from the European Investment Bank for buses in general. To make it more appealing, they proposed that all 1,500 buses for which they requested funding should be electric. However, the European Investment Bank immediately rejected the proposal.

Why? Because, as you mentioned, you cannot switch your fleet overnight. To do so, you would need to build enough chargers for 1,500 electric buses right away. You would have to train maintenance personnel, drivers, and everyone else overnight. It's simply not feasible. The grid wouldn't be able to handle it, and so on.

Simple things like this need to be understood—don't get overly excited; recognize the challenges so that you can say, "Okay, I have a plan, and I understand how to get there." I think this is important—not just the detailed technical aspects, which, of course, are also necessary. But again, technology is often not the primary barrier. We've seen this repeatedly in many fields.

Q: I see. Thank you! That example is actually very interesting. I really like that case.

So maybe one last question from me before I pass it to John for audience questions. When we talk to U.S. agencies, I'm familiar with many of the Asian systems, like those in Shanghai and Singapore. Often, the response is, "Oh, Singapore is so different from us—we can't learn from them. That's too far removed from our reality."

With that in mind, do you have good examples from European cities where you think public transit electrification is being implemented successfully? Which cities would you name as the best models for us to study and learn from?

A: I'm going to avoid answering this question because I don't feel confident enough. I have some ideas about certain systems, but not enough to say definitively whether they are really good examples or not.

I mean, there are many cities where you casually see electric buses—like in Munich, where they are well integrated into the system, even in cold weather. It's a system that I believe works very well. Many cities are doing a good job, but I don't feel comfortable saying which ones are better or worse. Sorry about that.

Audience

Q: I'd like to take a step back to the charging segment that you presented. You made the point that, overall, overnight charging is a better solution than opportunity charging. But I'd like to double-click on that a little bit—what variables did you consider behind that conclusion?

For example, Jinhua mentioned that the time of day is a major factor in electricity pricing. Of course, we might see very different situations depending on the region—such as in New York State, where electricity may be more expensive during the day, versus California, where it may be less expensive. So, there are these regional differences to consider.

There's also the factor of the overall fleet. I guess my question is, if you had to explain this to a smart 14-year-old, how would they think about the decision between opportunity charging and overnight charging? Recognizing, of course, that overnight charging requires a different vehicle with a larger battery.

A: Right. So, first of all, again, great question—or I guess, a summary of a collage of multiple questions.

I think the important thing to consider here is that the way the criteria are selected, ranked, and evaluated comes from experts, not from us. We developed this methodology with multiple steps, and then we conducted a number of surveys with selected experts who provided this information. The process follows these steps:

1. First, we gather a long list of criteria from the literature.

2. Then, experts refine the list.

3. Next, experts rank the criteria and assign weights to each of them.

4. Finally, we run applications using the Best-Worst Method (BWM) and Fuzzy RAFSI methodologies.

From this process, we identified key criteria, which I mentioned earlier: economic, environmental, social, operational, and quality of service factors.

For example, if we take the social aspect—because technology and environmental aspects are more straightforward—the social criteria include:

• Job opportunities created by each option,

• Fire risk at various stages (on the vehicle, at the depot, and at the charging station),

• The impact of charging infrastructure on surrounding residential areas, and

• The effect on the city's landscape.

As you can see, this is a relatively broad approach. I hope this first part of my answer helps put things into context.

Now, for the smart 14-year-old—I'm trying to think, as that's just a bit younger than my youngest child. We have two charging technologies. The key question is:

• Do we want to charge a big battery overnight, then carry it around all day, ensuring we won't run out of energy?

• Or do we want a smaller battery to avoid carrying excess weight all day, leaving more space for passengers, while periodically stopping to recharge during bus stops using opportunity charging?

Now, I realize my bias may have come through regarding one option over the other. But the most interesting takeaway from this study is not just that overnight charging appears to slightly outperform opportunity charging, but rather, the sensitivity analysis—understanding how robust these results are and how confident we can be in our conclusions.

For example, we found that if the weight of charging time as a criterion increases by just 13%, the ranking of alternatives switches. And 13% isn't a huge change—it's within the range of variability we observed in our estimates. So in that case, we can't be super confident in saying that one method is clearly superior. Statistically, overnight charging seems better, but in some scenarios, the reverse could also be true.

I think I may have lost the 14-year-old by the end—no matter how smart he or she was—but hopefully, this explanation helps clarify the thought process.

Q: But maybe it's safe to say that for different cities, different geographies, and different agencies, some solutions will clearly be better than others. It could be that opportunity charging is actually a superior solution for a particular agency compared to overnight charging. Is that a fair assessment?

A: Absolutely. Ideally, if a specific city or NPO wants to do this, they can reapply the methodology for their own city, using experts familiar with their local context. They can tailor the parameters to reflect the city's landscape, population type, and other specific factors.

In our case, we chose to be location-agnostic and designed the study around a general, average situation. However, someone could take this methodology and apply it with local experts, guiding them to respond specifically for their area. Alternatively, they could use the existing weights and experiment by adjusting them—for example, increasing the weight of a particular criterion by 20% or 30%—to see how it impacts the outcome.

So, this could be another way to apply the methodology effectively.

Q: Excellent! Starting with the first segment of your talk on E-bus planning, Don McKenzie had a question: What is it that drives bus energy use per passenger down in the intermediate range of frequency? Average bus making fewer stops, nonlinear dependence of energy use on the load.

A: The issue is that you have more buses than you actually need. In this intermediate range, energy use per passenger drops because there are more buses serving roughly the same demand.

So, what happens is that the benefit we get from not having too much weight on each bus seems to outweigh the inefficiency of adding more buses. Essentially, there are more buses carrying fewer passengers per bus, which results in a drop in energy use per passenger.

At the beginning of the range, I think the increase in energy use is due to the rise in the number of buses being introduced into operation. So, we see a pattern of increase, then decrease, then increase again. I explained it in reverse because that was easier for me to conceptualize.

I'm not sure if this fully satisfies the person who asked the question, but I'd be happy to follow up if needed.

Q: I think that makes sense. There's a sweet spot where having fewer passengers per bus actually reduces energy consumption.

Let's move on. There was another question about the definition of the segment, which I believe is on the slide after this. You talked about different segments—could you clarify that?

A: So, a segment simply refers to dividing the route from beginning to end into sections so that we can calculate the slope more effectively.

Sorry for jumping back and forth—I know it can be a bit annoying. But we took this route in Santiago de Chile and split it into segments to standardize the slope and make it easier to calculate. Since the calculation isn't done continuously—though it theoretically could be—we break it into manageable parts.

The idea is that higher or lower energy consumption along different segments reflects the topography of the route.

Since we're talking about this—sorry, just to clarify—on the X-axis, we have the direction of the route, and here again, we have a histogram. On the X-axis, we also have energy consumption, allowing us to see the density and how it evolves.

So, what we're looking at is the percentage of energy consumption per segment.

Q: Yi Wei had a question: Does this study consider transfer time when passengers transition from a traditional bus to an electric bus in the proposed model for the planning process? In addition to riding time costs and waiting time costs, are you also looking at factors like transfer time and other aspects of the planning process?

A: The short answer is no.

To explain, this study focuses on a long bus line primarily used for commuting. It extends far from the city center, covering a large area, rather than being a short central line that is fully integrated and analyzed as part of the broader system. We isolated this route and used demand patterns from the existing line for our analysis.

As I mentioned in response to a previous question, one of our next goals is to expand this approach and examine how it operates within a larger network, incorporating additional parameters.

For now, we consider:

• Waiting time before boarding,

• Waiting time due to rejected or declined boarding, and

• Onboard time in terms of passenger waiting time.

Q: Another question from Kelly Connor was: Did you consider energy costs, time-of-day charging, and grid reliability in the decision-making framework for selecting the type of charging approach? I think we touched on that a little bit already.

A: no. In this case, we assume that charging occurs without explicitly modeling energy costs or time-of-day pricing. One of the reasons for this is that we focus on a single tour, which is much shorter than the 400-kilometer range that the bus has. Incorporating charging into city-wide planning and dispatching is a separate challenge that goes beyond the scope of this study. Regarding the multi-criteria decision-making analysis, I've already addressed what was covered and what was not.

Q: Okay. And there's a follow-up question here: How does cybersecurity play into the decision about charging strategies? I guess the concept is that if you have a network of opportunity charging stations, it may present a greater cybersecurity risk compared to a centralized depot with overnight charging infrastructure.

A: So, I quickly looked at the criteria, and cybersecurity did not come up in the process of identifying them. However, it's clear that a larger network of charging stations presents a greater surface for cyberattacks.

This factor was not considered in our analysis, nor was it found significant by the experts we consulted. However, it is certainly something that could be relevant and of interest in future studies.

Q: Adrian Down had a question about charging: Did you consider a hybrid model that combines both overnight and opportunity charging?

A: No, we did not consider that.

When you present respondents with more than two options, it becomes trickier to compare them. Off the top of my head, I'm not sure how we could incorporate a hybrid model directly into the analysis, though it's certainly an interesting idea.

Methodologically, we typically compare one option against the other in terms of criteria. The challenge is not just in the criteria themselves but also in how the options are defined.

Thinking out loud—one possible way to approach this could be as a post-processing step. We already have the criteria and their weights for the two main alternatives (overnight charging and opportunity charging). If we were to create a hybrid model, we could potentially construct weights for this intermediate solution—not necessarily by averaging but by adjusting each criterion individually to see where it would fall.

Of course, another approach would be to redo the exercise with three options, though I'm not sure off the top of my head how best to handle that. But it's definitely an interesting point to consider.

Q: Jeremy Fichter had a question: Does the model account for the cost of infrastructure needed to maintain reliable service at such short headways? For example, dedicated right-of-way, signal priority, active service management, etc.

So, this is really taking a big step back and asking, to some degree—does the model consider the advantages of a full BRT system versus a non-BRT system?

A: Let me answer indirectly by explaining exactly what the model captures—I think that can be helpful in addressing some of the questions.

The first part focuses on energy consumption dynamics. For this, we use a longitudinal vehicle dynamics model, along with additional models that capture vehicle-related factors. Specifically, we consider:

• The impact of vehicle speed,

• Total weight, which includes both vehicle weight and passenger load, and

• Regenerative braking, which is particularly important in routes with slopes, as it allows for energy recapture.

Additionally, we account for:

• Route gradient and its impact on energy consumption, which was a significant factor, and

• Auxiliary energy consumption, such as heating, ventilation, and air conditioning (HVAC). While heating isn't a major factor in Santiago de Chile, ventilation and air conditioning are relevant considerations.

In terms of passenger flow, we considered:

• Time-dependent variations in passenger flows,

• Stop-level interactions—for instance, the impact of passengers remaining at stops and increased boarding times,

• Passenger variations between stops, and

• Crowding impacts, including failure-to-board scenarios, which were explicitly modeled.

For the formulation of the problem, we incorporated this detailed tenancy model into the planning of battery electric buses and formulated it as an integer nonlinear problem. This allows us to optimize:

• Vehicle type selection,

• Service frequency, and

• Cost considerations, including both user costs and operator costs.

This framework enables average cost analysis, economies of scale assessments, and other evaluations.

I hope this answers what is explicitly captured in the model. The study was applied to a single corridor, a single route, to demonstrate the benefits—or rather, the differences—in performance.

To compare model performance, we evaluated the output of our model against a model that assumes average energy consumption. While such models are not bad—many models don't even consider energy consumption in this way—our results show a 13% to 17% difference, depending on demand levels.

We argue that, assuming this detailed model is more accurate (since we know detailed models can sometimes introduce larger errors), the observed difference suggests an improvement in model performance and the reliability of results.

Part IV. Summary of Memos.

Themes from Other Memos

1. Inspired by the clearly illustrated and laid out rankings of what operators consider problematic – economic, management or operational troubles. However, the complexity of MINLP and hybrid metaheuristics proved challenging to grasp, prompting a shift toward more accessible sources for deeper understanding.
2. Interested in the complexities of integrating technological advancements, economic feasibility, and policy considerations into real-world applications. However, it also raised an important question: How can transportation agencies implement these complex models

in practice, given their resource constraints and data limitations? Another crucial aspect was the trade-off between different charging strategies for electric buses. Strengthening institutional capacity and improving coordination among different stakeholders is just as important as investing in new transportation technologies.

3. Fascinated about how they applied their model to Santiago's unique urban layout and terrain. One of the key features of their optimization model was the detailed energy estimation framework. Integer Nonlinear Programming (INLP) to minimize passenger and vehicle costs was particularly interesting. Their fusion of a genetic algorithm with simulated annealing was an approach I'd never considered. At a broader level, I felt their overall findings on electric bus planning had several important real-world implications.

4. Reflection on the real-world applicability of these models in different contexts. The goal of the control is to optimize service frequency and vehicle type to minimize total costs, which include passenger, operator, and energy costs. A hybrid meta-heuristics was introduced to improve performance in large instances, which was demonstrated by comparing it with several other solution algorithms. This work also demonstrated how the proposed model outperforms traditional fixed-energy consumption approaches, offering more accurate and reliable results.

5. Optimizing electric bus routing within current electric grid constraints or expanding the grid to meet future needs presents a true challenge. "Economic barriers are the most challenging aspects to electrifying bus systems worldwide." He emphasized the development of a general optimization framework and stressed the need for expert opinions to be included in the model. Cities looking to electrify their bus fleet will have to make significant capital investments up front, and this capital will limit their deployment strategy.

6. Particularly interested in the discussion of charging strategies. The divergence between the US and Asia is an interesting comparison of whether charging capacity and methods can be fully converted to pure electric buses. The key challenge is the vast one-time fixed cost to transform the current bus fleet into the electric fleet and the lack of central power or significant government-oriented funding to support this one-time transformation. Furthermore, the cost of labor, durable batteries, and charging infrastructure in the US is much higher than in Asia. There are simply no incentives to lead this gigantic change.

7. The research considers variables such as passenger load, route gradients, and auxiliary energy needs, integrating them into a mathematical model for decision-making. Second thing I'm interested in is the comparative analysis of overnight charging versus opportunity charging for electric buses. This highlights the need for localized assessments rather than a one-size-fits-all solution. It was also noted that cities and transit authorities can apply this framework to their specific conditions, adjusting criteria weights accordingly.

8. Future research should explore hybrid charging strategies, dynamic grid impact analysis, and long-term electrification pathways for transit agencies. Investigating vehicle-to-grid (V2G) integration, cybersecurity risks in charging infrastructure, and economic incentives for BEB adoption could further enhance deployment. Additionally, case studies in high-density cities can provide insights into best practices for large-scale

electrification. These areas will help shape more efficient, cost-effective, and sustainable electric bus networks worldwide.

My Reflection

This week's talk provided a valuable insight of approaching the electric vehicle routing problem (E-VRP), no matter for passengers or freights. The model proposed considered four aspects: Energy consumption dynamics, passenger flow behavior, operation research and transport economics.

In the current state of E-VRP research, articles tend to assume linear energy consumption function to simplify the VRP model. However, the power needed for electric vehicles along paths is highly non-linear, which is influenced by different aspects, such as vehicle type, weight, heating, and most intuitive road slope. It is insightful to incorporate the non-linear energy consumption function into the model to make the model more practical and real-life feasible. Additionally, the charging function is also non-linear, which can be formulated as piecewise linear. This has already been widely used in E-VRP studies.

Metaheuristics or metaheuristics are good approaches to enhance adaptivity in this problem. Per professor Antoniou's introduction, the research he has done developed hybrid algorithms combining metaheuristics such as Generic Algorithm (GA) and simulation, to better understand different scenarios for mixed fleets or types of buses. This also provides a potential approach to the E-VRP for freights, which also includes multiple fleet types and scenarios.

What's interesting to me is the strategy selection and decision-making approach. As new technology emerging, there could be different charging options. How to understand or predict human's decision-making probability, in order to better implement charging facilities, is a critical question when facing a facility location problem. Professor also discussed the differences between developed and developing countries. The survey of ranking barriers gives us insights of same or different emphasize in the electrification of bus systems.

In summary, this is a fantastic seminar, discussing various aspects in electrification and scheduling electric vehicles. I am inspired by the approaches and methods professor Antoniou presented.

Part V. Other Information

Other questions: How to combine the regenerative braking into the energy consumption estimation formula, meaning both considering uphill and downhill power requirement? Do you also consider battery swapping?

Other literature: Zhou, Y., Meng, Q., Ong, G. P., & Wang, H. (2024). Electric bus charging scheduling on a bus network. Transportation Research Part C: Emerging Technologies, 161, 104553.

Preparing for battery electric bus public transport:

modelling tools and implementation decision making support

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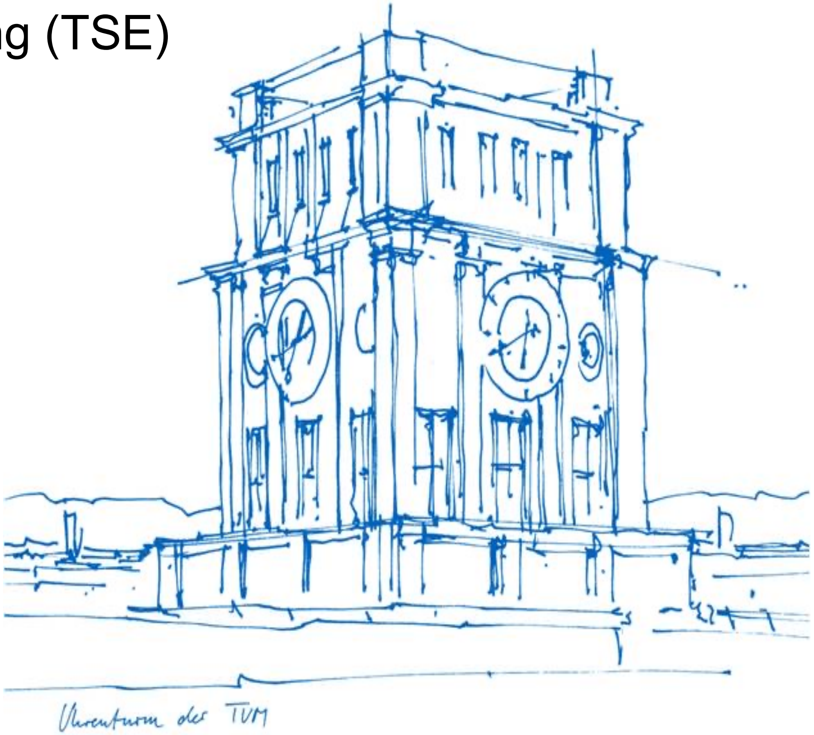

MIT Mobility Forum
February 07, 2025

Background - Constantinos (Costas) Antoniou

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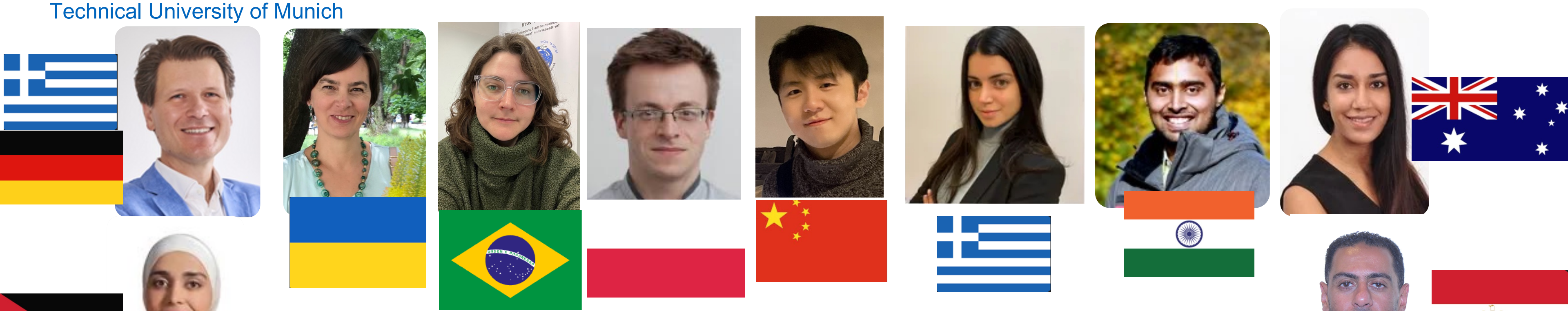

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Five continents
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Outline

1. Electric bus planning model
2. Mixed-fleet bus planning model
3. Charging strategy selection
4. Barriers to electric bus adoption

Electric bus planning with a detailed energy consumption model

Relevant manuscript:

Sadrani, M., Tirachini, A., Antoniou, C., Electric bus planning with a detailed energy consumption model. In Revision, 2025.

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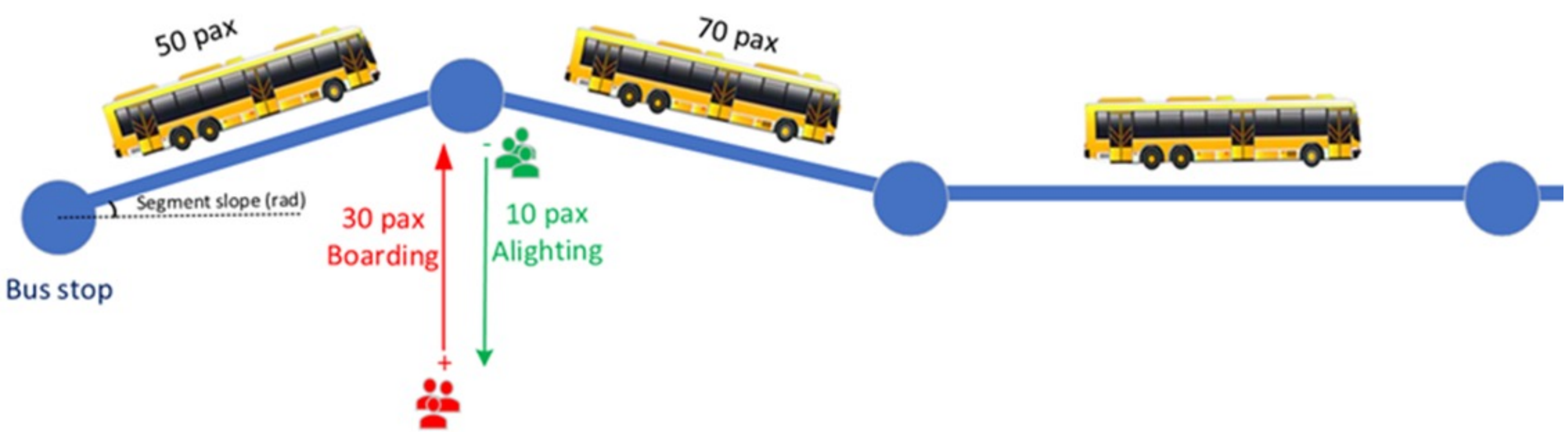
Electric bus planning model

- Developing an optimization model for electric bus planning equipped with a **detailed energy estimation framework**
- Modeling vehicle dynamics and road conditions affecting the energy demand of electric buses, such as variations in **passenger load**, **vehicle speed**, and **road slope**



Energy consumption of battery electric buses

- Several factors can affect the energy demand of BEBs (vehicle-related and route-related variables):
  - ✓ Vehicle weight (unloaded/empty)
  - ✓ **Passenger load**
  - ✓ **Vehicle speed**
  - ✓ **Auxiliary devices** (e.g., air conditioning, ventilation, heating, in-vehicle displays, and headlights)

  - ✓ **Road slope**
  - ✓ Weather

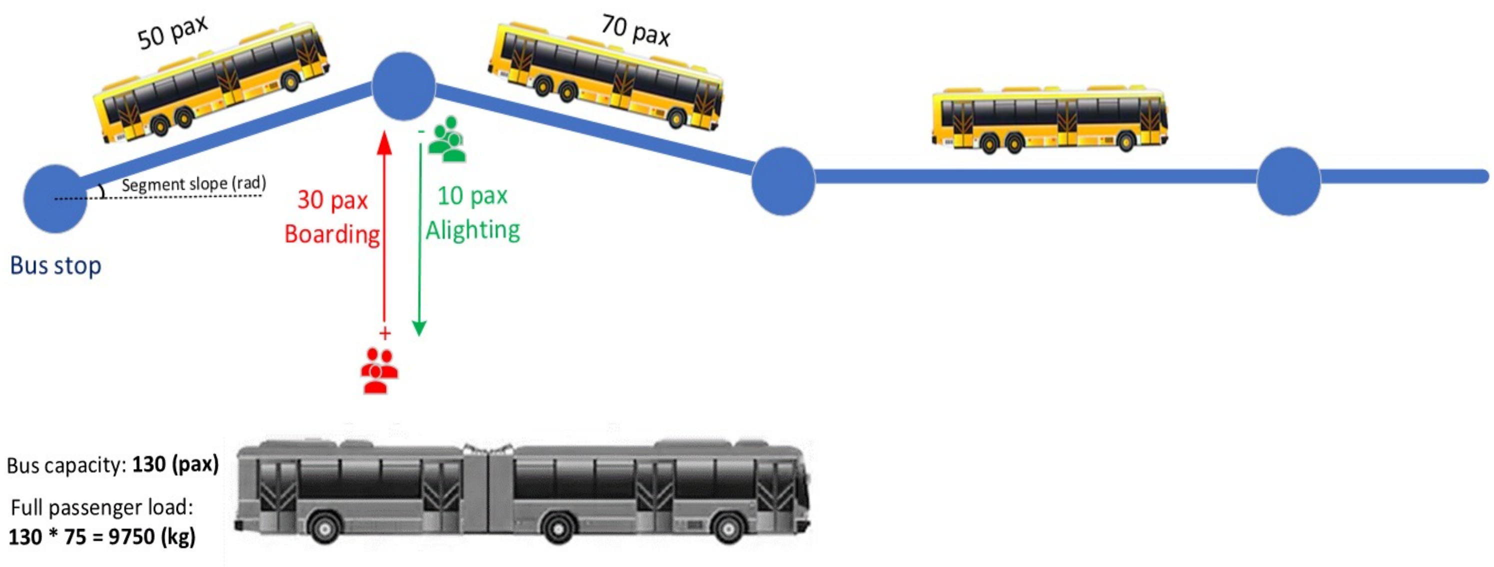
Model formulation for electric bus planning

Energy consumption dynamics	Passenger flow behavior	Operations research	Transport economics
1 Longitudinal vehicle dynamics model	1 Time-dependent OD flows	1 Integrating a detailed energy model into the planning of BEBs	1 Users' and operators' cost elements
2 Vehicle-related factors: Vehicle speed and total weight (vehicle weight + passenger load) Regenerative braking system	2 Stop-level interactions	2 BEB planning problem as a novel INLP formulation to optimize vehicle type selection and service frequencies	2 Average cost analysis and economies of scale
3 Route-related factors: Route gradients	3 Variations in passenger load		
4 Auxiliary energy to power non-propulsion systems, such as heating, ventilating, and air conditioning (HVAC) services	4 Crowding impacts (failing to board)		

We combine contributions from energy consumption dynamics, transport economics, passenger flow behavior, and operations research to optimize public transport supply with EB fleets.

Urban bus operations

- The passenger load inside buses can vary at each trip segment
- The total weight of a BEB = Empty Bus Weight + Passenger Load



- Using a simplified fixed energy consumption rate for planning (e.g., 1.00 kWh/km) is not precise

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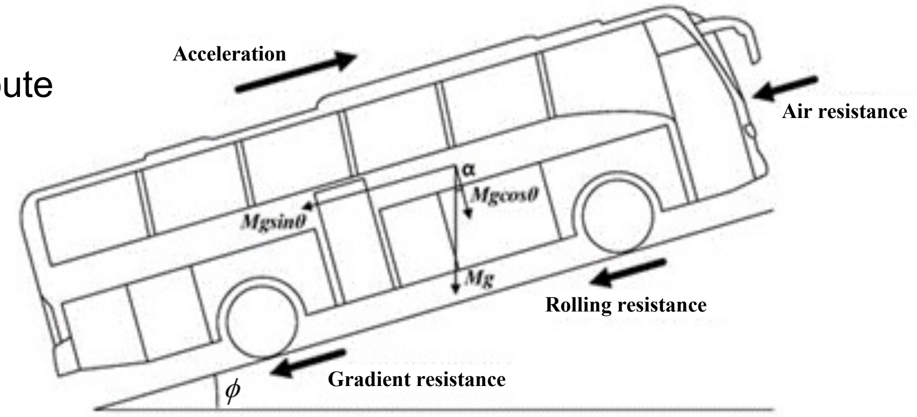
Energy estimation based on longitudinal vehicle dynamics

Total energy = Auxiliary power + Tractive power

- Auxiliary power (auxiliary facilities, such as air conditioning and heating)
- Tractive power (resistance forces based on Newton's second law)

Tractive power changes, depending on driving and route conditions

$$F_t = \underbrace{0.5 p A C_d v^2}_{\text{Aerodynamic drag force}} + \underbrace{M g C_r \cos\phi}_{\text{Rolling resistance}} + \underbrace{M g \sin\phi}_{\text{Grade force}} + \underbrace{\delta M a}_{\text{Inertia force}}$$



We consider variations in **passenger load**, **vehicle speed**, and **road slope**

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Model formulation for electric bus planning

- Integer Non-Linear Programming (INLP)

Optimization Model

Objective Function

Minimizing Total Costs (Passenger Costs + Operator Costs)

Passenger Costs = In-vehicle riding time costs
+ Initial waiting time costs
+ Extra waiting time costs due to failing to board

Operator Costs = Capital costs
+ Human driving costs
+ Energy costs

Constraints

Vehicle movement

Size-sensitive characterization

Charging and battery

Passenger flows

Decision Variables

- Service frequency selection [integer variables]
- Vehicle type selection [binary variables]

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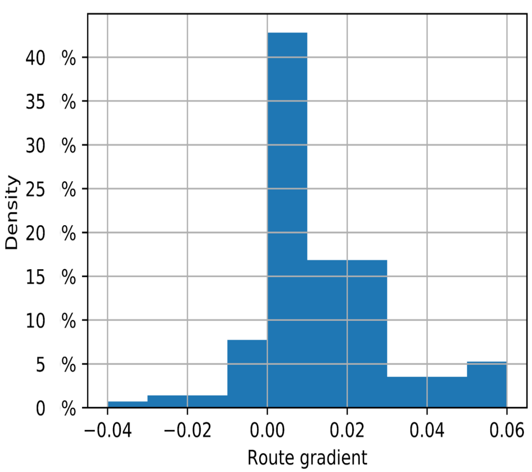
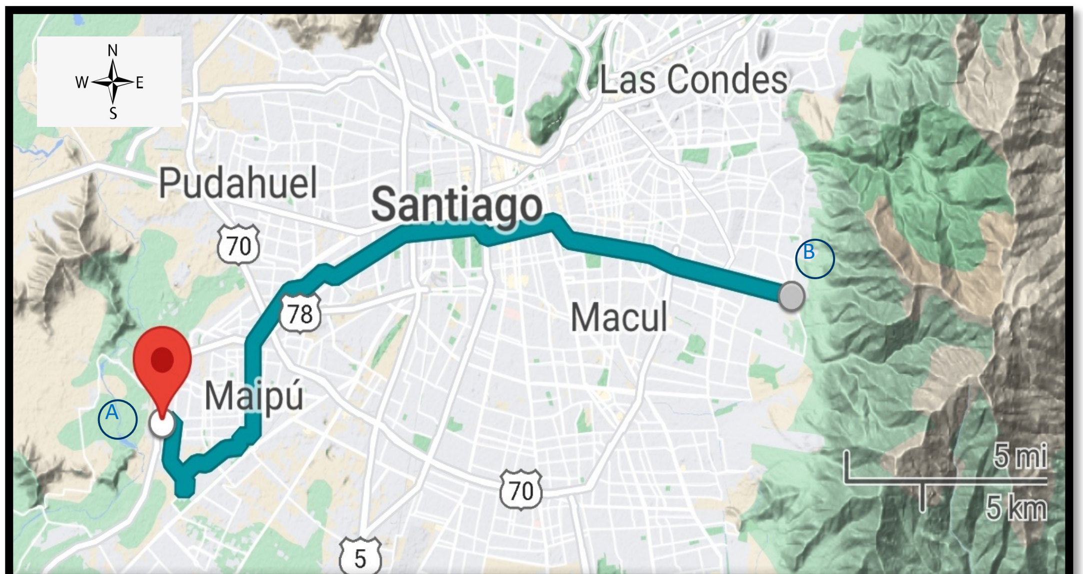
Numerical experiments: Santiago case study

- Bi-directional BRT route connecting the east and west of the city
- 84 bus stops in each direction
- Mostly positive slope when moving from west to east
- Simulate a 3-h period (7:00 to 10:00 AM)

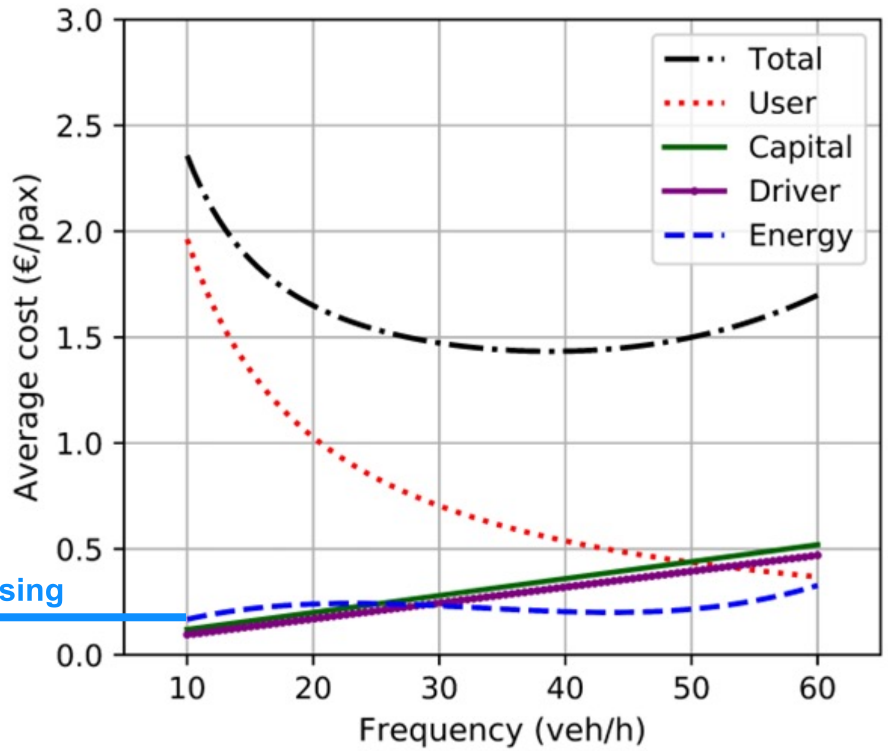


Road slope for West-to-East (W-E) direction



Test corridor, bus route 506 in Santiago

Numerical results



Increasing-Decreasing-Increasing

- Energy consumption cost function is **<u>not monotonic</u>** as a function of service frequency.
- Only a variable energy estimation model (sensitive to load and slope effects) can identify this effect.

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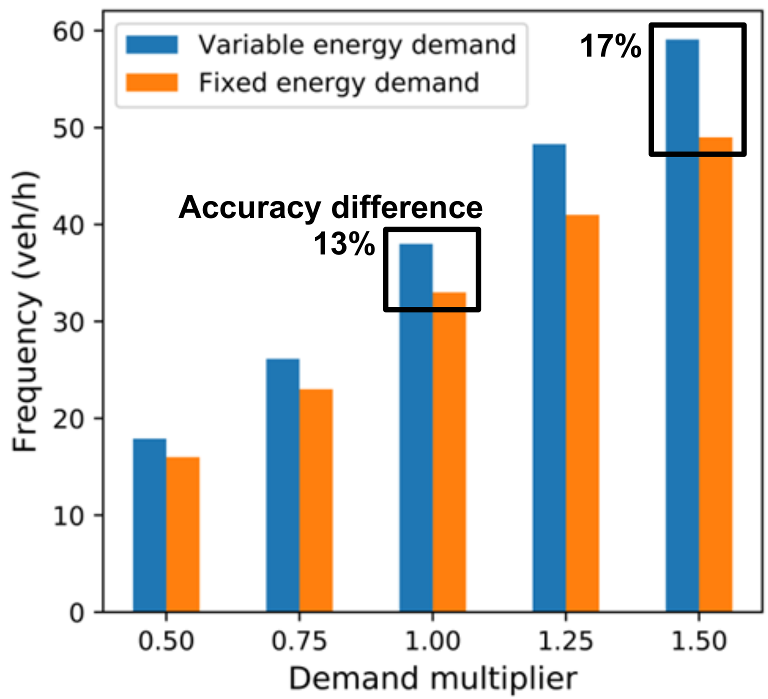
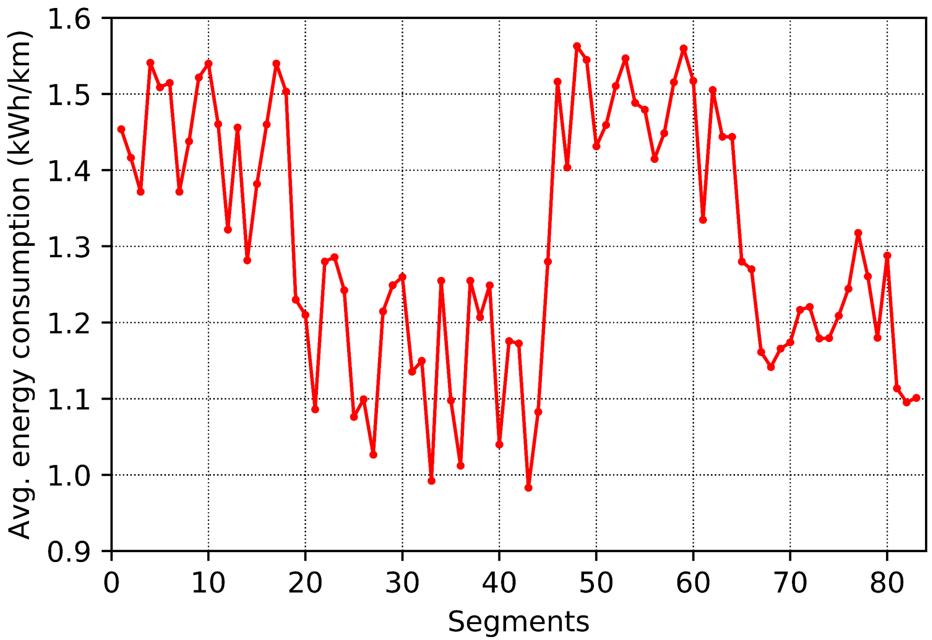
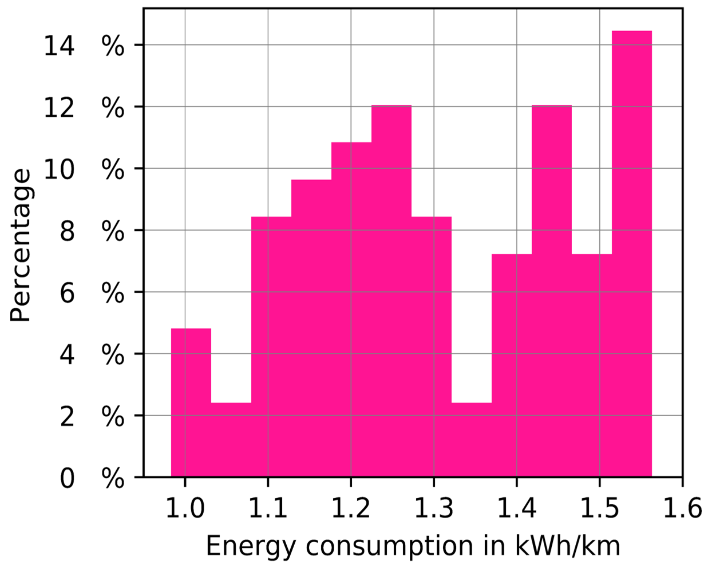
Sensitivity to demand level



- Using a fixed energy consumption rate instead of a variable energy estimation model can significantly reduce the accuracy of planning outcomes.
- Solutions are more sensitive to the energy estimation method at larger demand levels.

Variations in energy demand pattern





- The average energy demand over this route is **1.34 kWh/km**
- 34% higher than the simplified fixed value (**1.00 kWh/km**), lacking local slope and driving information

Bus Scheduling with Heterogeneous Fleets: Formulation and Hybrid Metaheuristic Algorithms

Relevant manuscript:

Sadrani, M., Tirachini, A., Antoniou, C. (2025). Bus Scheduling with Heterogeneous Fleets: Formulation and Hybrid Metaheuristic Algorithms. Expert Systems with Applications 263, 125720.

Expert Systems With Applications 263 (2025) 125720

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Bus scheduling with heterogeneous fleets: Formulation and hybrid metaheuristic algorithms

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[c] Department of Civil Engineering, Universidad de Chile, Santiago, Chile

Mixed-fleet bus planning

- Developing MINLP models for formulating mixed-fleet bus operations to optimize fleet size and dispatching programs

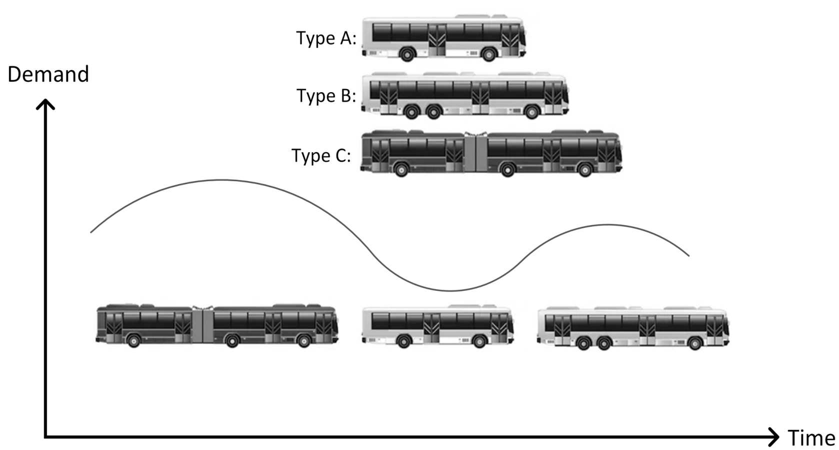
Objective Function

Minimizing Total Costs
(User Costs + Operating Costs)

Decision Variables

- **Fleet size**
- **Dispatching time**
- **Dispatching sequence**

- In a mixed operating environment, operation of buses of different types is possible to serve passenger demand
- Complex problem due to fleet heterogeneity, introducing an <u>NP-Hard combinatorial optimization problem</u>



This is a combinatorial problem, e.g., with a mixed fleet of {A, A, A, A, A, A, B, B, B, B, B, C, C, C, C}, $\frac{15!}{6!\times 5!\times 4!} = 630{,}630$ ways can be suggested only for dispatching sequence.

Mixed-fleet bus planning

- Need for more efficient algorithms to address solution complexity
- Developing two new hybrid metaheuristics to manage solution complexity:

- Genetic algorithm (GA)
- Grey wolf optimizer (GWO)
- GAMS solvers

→ Established Algorithms

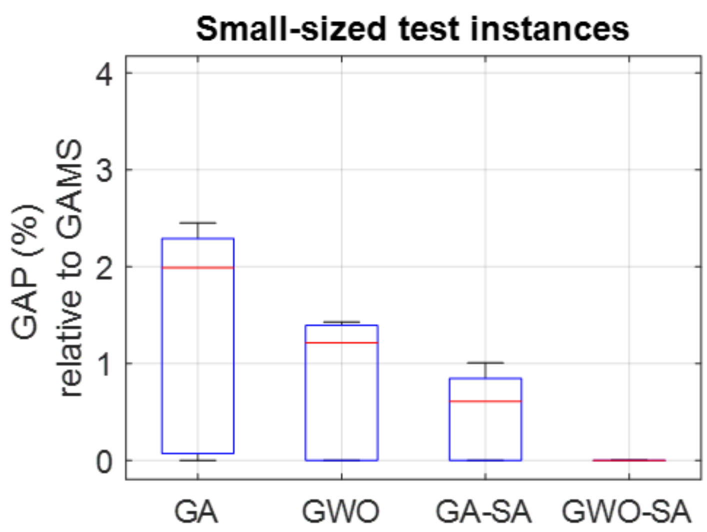
- **Hybrid of genetic algorithm and simulated annealing (GA-SA)**
- **Hybrid of grey wolf optimizer and simulated annealing (GWO-SA)**

→ **New Developed Algorithms Hybrid Metaheuristics**

- Our numerical experiments demonstrate that the developed hybrid metaheuristics outperform the established algorithms

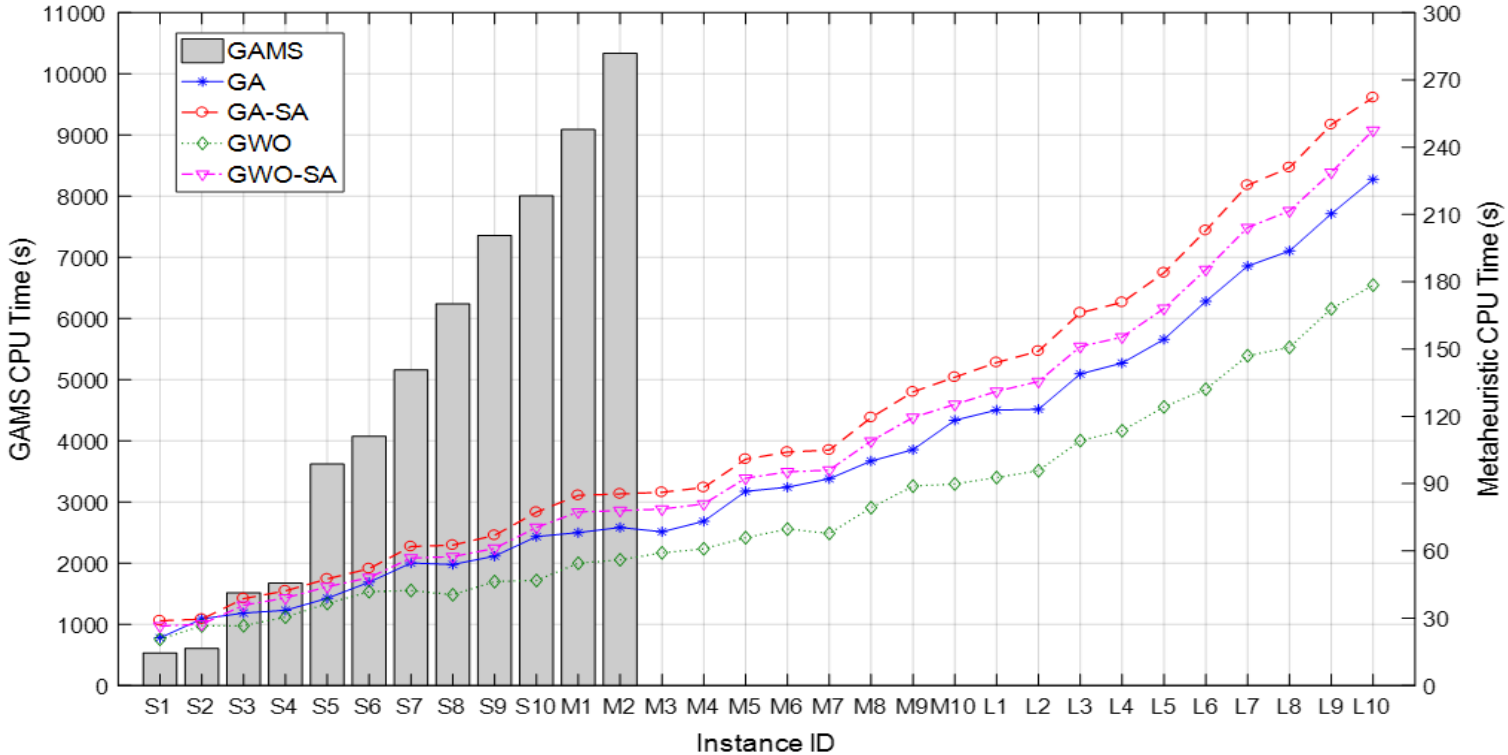
▪ Performance of metaheuristics

Comparison of solution gaps: Relative to the optimal solutions from GAMS



- The developed hybrid metaheuristics (GA-SA and GWO-SA) outperform the simpler algorithms (GA and GWO).

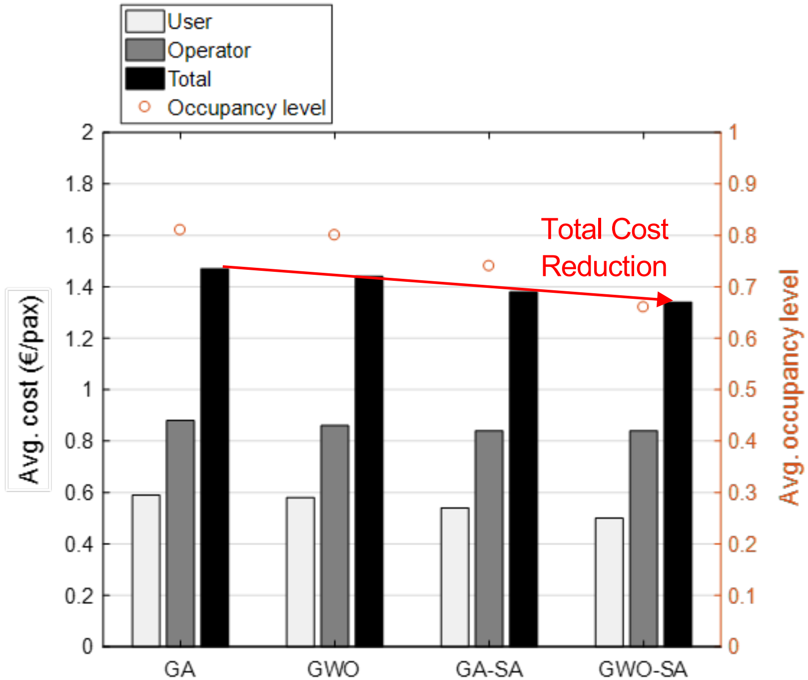
▪ CPU times of algorithms



Comparison of the solution methods in terms of CPU times

- The GAMS CPU times are notably high (even for small-scale problems), while the proposed metaheuristics deliver high-quality solutions in significantly shorter CPU times.

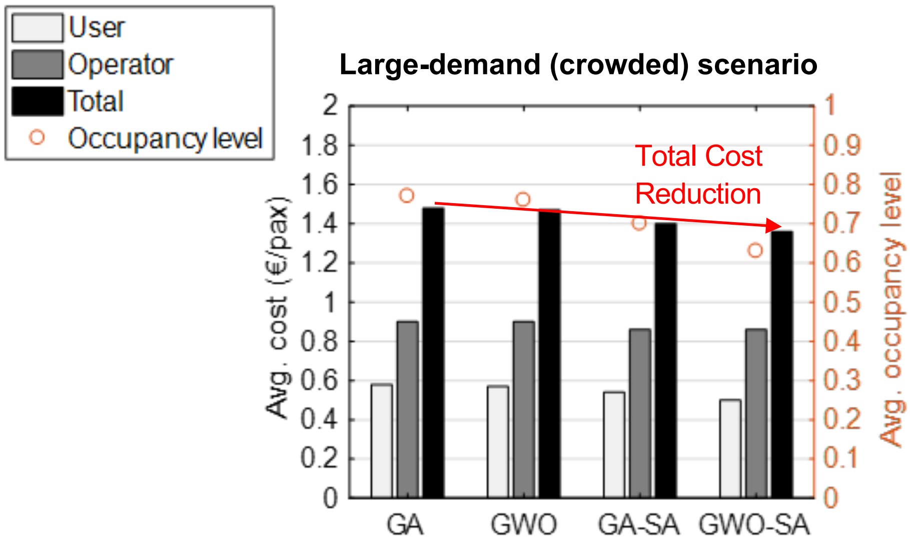
▪ Real-world application

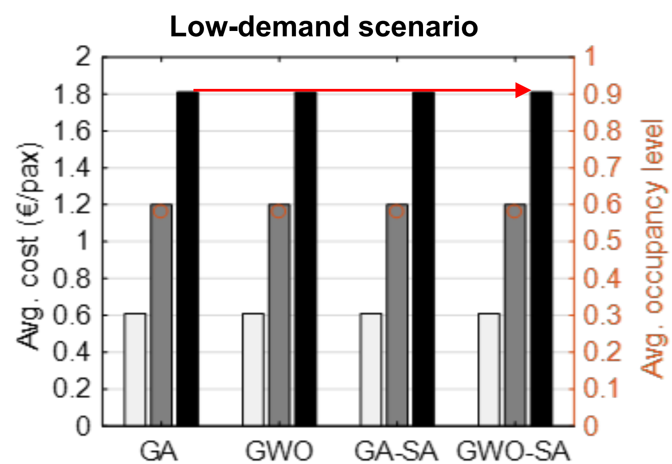


Comparing algorithms solutions regarding cost and occupancy levels

- GA-SA and GWO-SA solutions reduce total costs and improve trip comfort (lower crowding levels).
- This highlights the importance of generating precise dispatching plans through advanced algorithms.

▪ Sensitivity to demand





- Utilizing more advanced (hybrid) algorithms makes a difference in terms of service quality and optimal fleet size in crowded scenarios, whereas the choice of solution algorithm becomes less significant as demand decreases.

Charging strategy selection for electric bus systems: A multi-criteria decision-making approach

Relevant article:
Sadrani, M., Najafi, A., Mirqasemi, R., & Antoniou, C. (2023). Charging strategy selection for electric bus systems: A multi-criteria decision-making approach. Applied Energy, 347, 121415. https://doi.org/10.1016/j.apenergy.2023.121415

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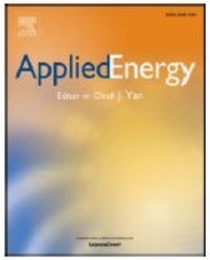

Check for updates

Charging strategy selection for electric bus systems: A multi-criteria decision-making approach

Mohammad Sadrani [a], Amirhossein Najafi [b], Razieh Mirqasemi [b], Constantinos Antoniou [a,*]

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Decision making framework for bus system electrification

- Developing a multi-criteria decision-making model for **selecting the best charging strategies**

Charging strategy selection

Multi-criteria decision-making framework

Fuzzy Best Worst Method for ranking alternatives including:

Opportunity charging

Overnight charging

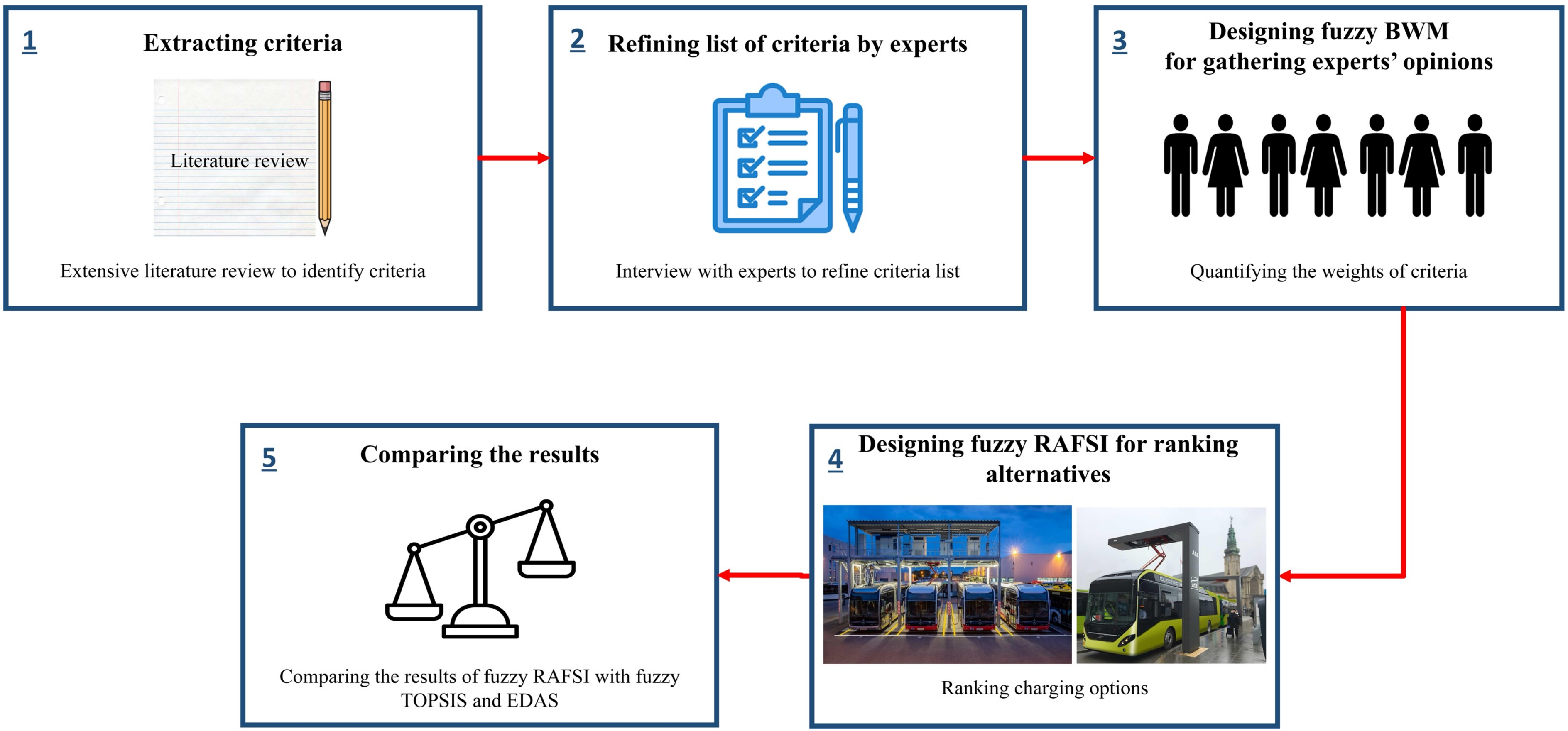
Advantages and disadvantages of different charging options

Overnight (slow) charging

Opportunity (fast) charging

- **Battery costs:** Opportunity charging systems require smaller on-board batteries, reducing battery costs.
- **Planning efforts:** Opportunity charging systems require more intricate planning with multiple charging stations along bus routes.
- **Charging infrastructure costs:** Opportunity charging systems require higher infrastructure costs, related to the installation of high-powered (fast) chargers and the procurement of land in multiple locations throughout the city.
- **Battery weight impacts:** Overnight charging systems require heavier battery packs, increasing the energy consumption of EBs.
- **Electricity tariff:** Overnight charging systems can take advantage of cheaper off-peak electricity tariffs at night.
- **Service delays:** Overnight charging systems allow EBs to be charged while off-duty, reducing the risk of operational delays caused by charging idle times during daily operations.

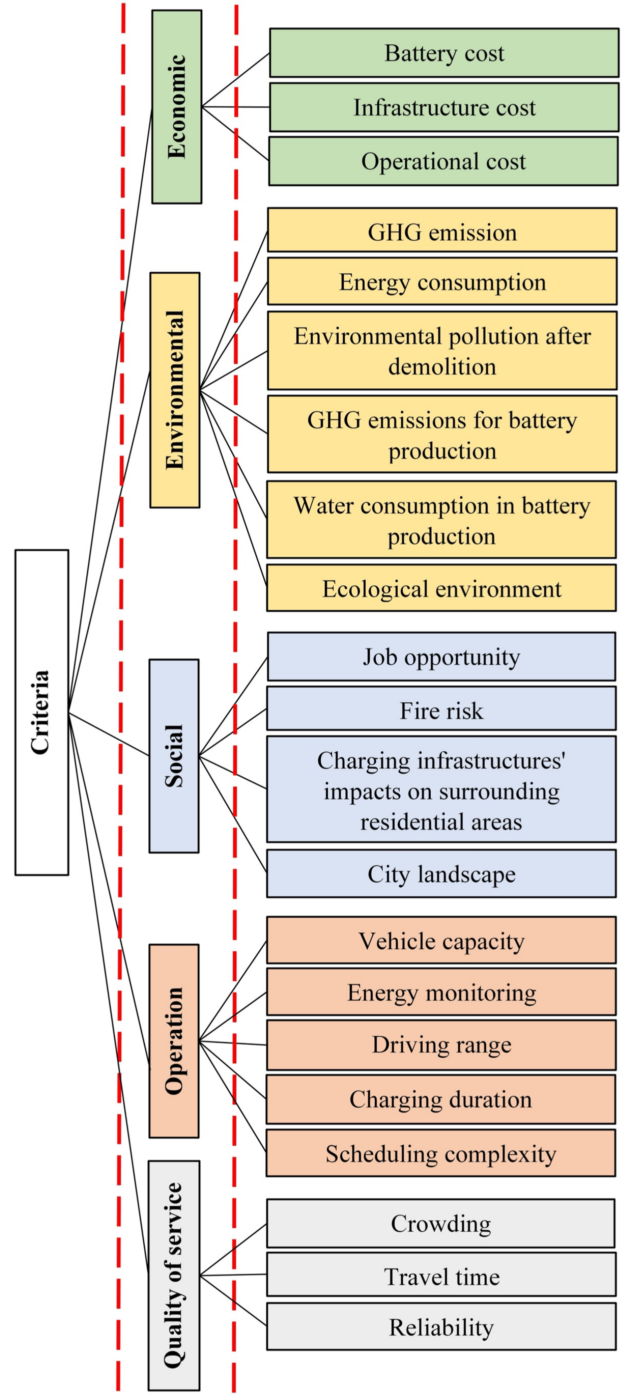
Decision making framework for electric bus charging strategy selection



BWM: Best-worst method
RAFSI: Ranking of Alternatives through Functional mapping of criterion subintervals into a Single Interval

Criteria identification

Important criteria affecting policymakers’ decisions in selecting charging strategies



Fuzzy Best Worst Method (FBWM)

Step 1: Build a set of criteria.

Step 2: Choose the best criterion and the worst criterion, **representing the most important and the least important criteria, respectively.**

Step 3: Compare the preference of the best criterion over all the other criteria **(Best-to-Others),** and the preference of all the criteria over the worst criterion **(Others-to-Worst)**.

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \ldots, \tilde{a}_{Bn})$$

$$\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \ldots, \tilde{a}_{nW})$$

Step 4: Calculate the optimal weights of the criteria by solving an optimization model.

$$min\ max_j \left\{ \left| \frac{\widetilde{W}_B}{\widetilde{W}_j} - \tilde{a}_{Bj} \right|, \left| \frac{\widetilde{W}_j}{\widetilde{W}_W} - \tilde{a}_{jW} \right| \right\}$$

$$s.t. \begin{cases} \sum_{j=1}^{n} R(\widetilde{W}_j) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1, 2, \ldots, n \end{cases}$$

Example of fuzzy preferences for main criteria (fuzzy survey)

Criteria	Best criterion	Worst criterion
	Economic	Social
Economic	Equally important	Absolutely important
Environmental	Very important	Weakly important
Social	Absolutely important	Equally important
Operation	Weakly important	Fairly important
Quality of service	Fairly important	Very important

Best-to-Others

Others-to-Worst

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A survey of ranking methods for options (e.g., FRAFSI)

Example for economic criteria

Category	Number	Criteria	Short description	Overnight charging	Opportunity charging
Economic criteria	1	Battery cost	This relates to the Battery pack price.	Good	Poor
	2	Charging equipment cost	This relates to the costs of purchesing and installing of the chargers, including charging equipments and charging stations.	Poor	Good
	3	Land acquisition cost	This relates to the cost of purchasing the required land for charging stations.	Very Poor	Good
	4	Labor cost	This relates to the required drivers and staffs salary who work on the charging stations, taking into account the wages on the night shift.	Fair	Fair
	5	Electricity tariff	This relates to electricity tariff cost during charging process.	Good	Fair
	6	Battery replacement cost	This relates to different aging phenomena resulting from battery charging frequency and power rates, and the need to replace them after the specified working hours or duration.	Poor	Poor
	7	Maintenance cost	This relates to costs of regular checks, repairing, or replacing components for vehicles and charging equipments.	Fair	Fair

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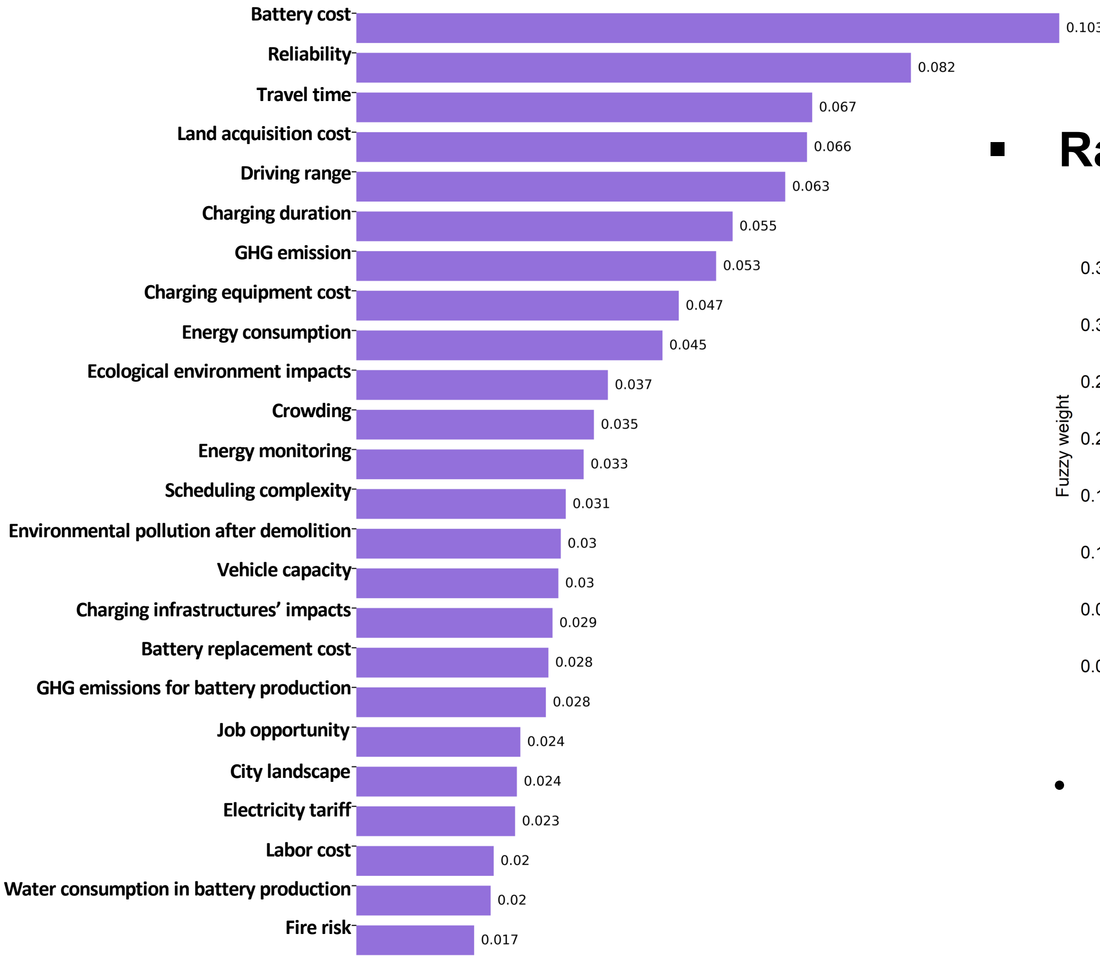
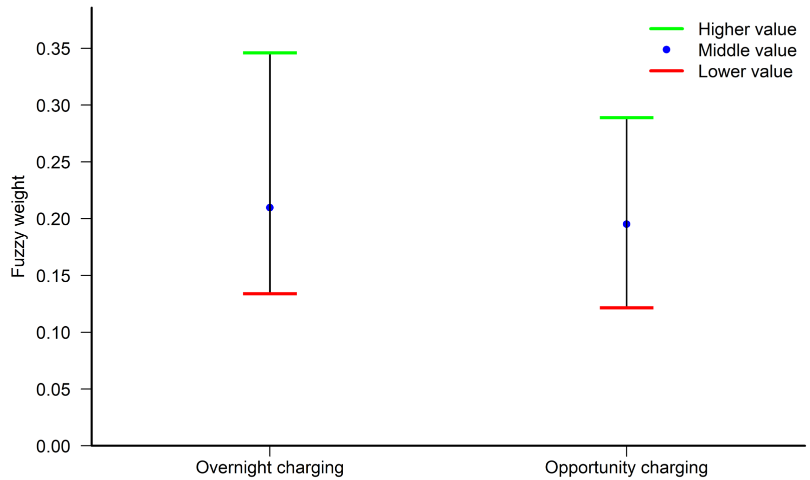
Results of decision-making model for charging strategy selection

▪ Weights of criteria from FBWM



- Battery cost is the most important factor, followed by reliability, travel time, land acquisition cost, and driving range.

▪ Ranking of alternatives from FRAFSI



- The results indicate a preference for overnight charging over opportunity charging.

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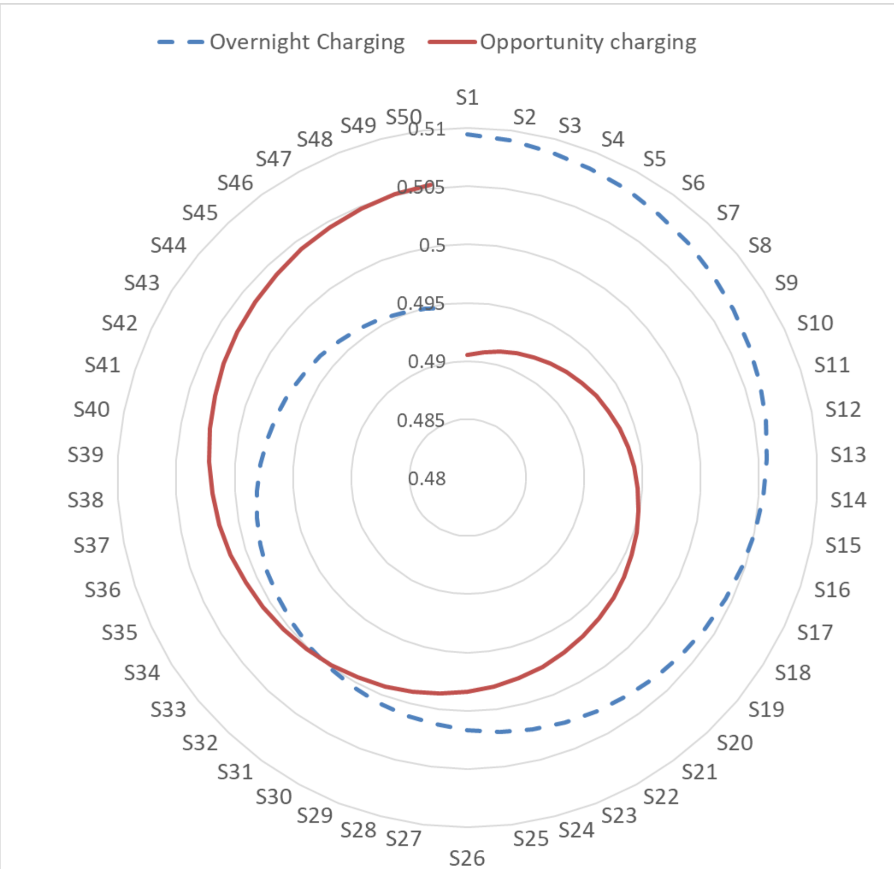
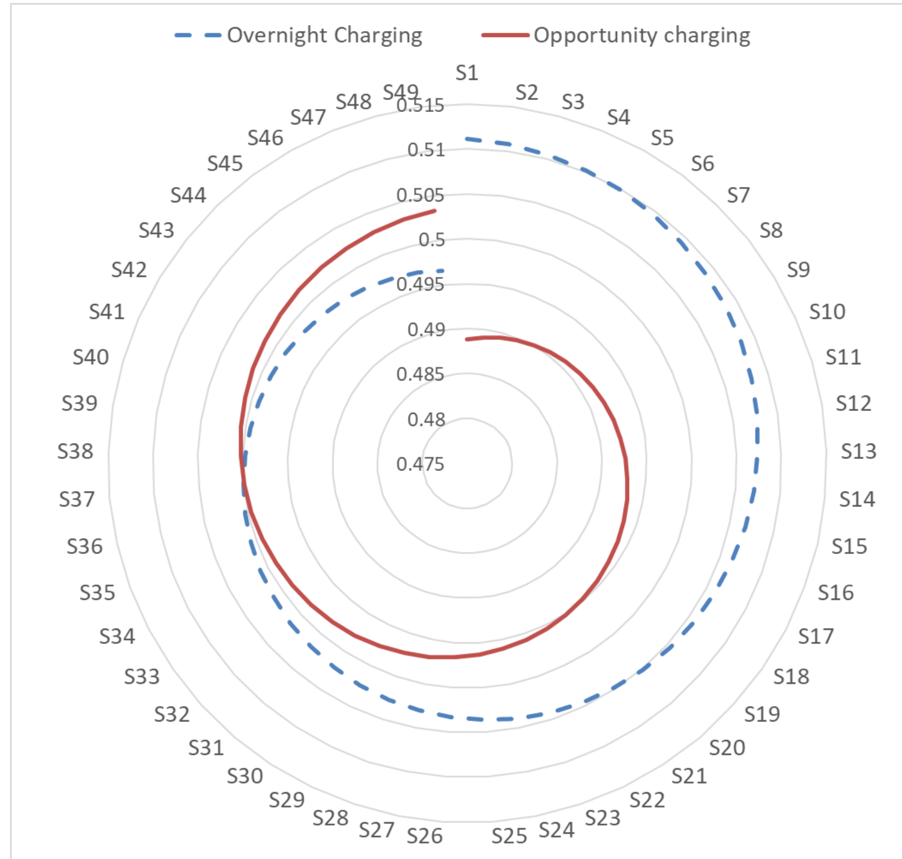
Sensitivity analysis

Sensitivity analysis on charging time weight



Sensitivity analysis on battery cost weight



- A 13% increase in the weight of charging time leads to a shift in ranking of alternatives, with preference for opportunity charging in scenario 31.
- A 24% increase in the weight of battery cost leads to a shift in ranking of alternatives, as seen in scenario 37.

Barriers to electrification of bus systems: A fuzzy multi-criteria analysis in developed and developing countries

Relevant Article:
Sadrani, M., Mirqasemi, R., Tirachini, A., & Antoniou, C. (2024). Barriers to electrification of bus systems: A fuzzy multi-criteria analysis in developed and developing countries. Energy Conversion and Management, 314, 118700.
https://doi.org/10.1016/j.enconman.2024.118700

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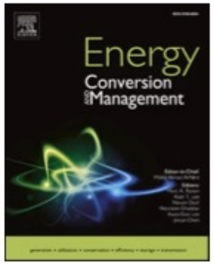

Barriers to electrification of bus systems: A fuzzy multi-criteria analysis in developed and developing countries

Mohammad Sadrani [a,*], Razieh Mirqasemi [b], Alejandro Tirachini [c,d], Constantinos Antoniou [a]

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Decision making framework for bus system electrification

- Developing a multi-criteria decision-making model for **ranking barriers to bus system electrification**

Ranking electric bus adoption barriers

Multi-criteria decision-making framework

Fuzzy Best Worst Method for ranking barriers

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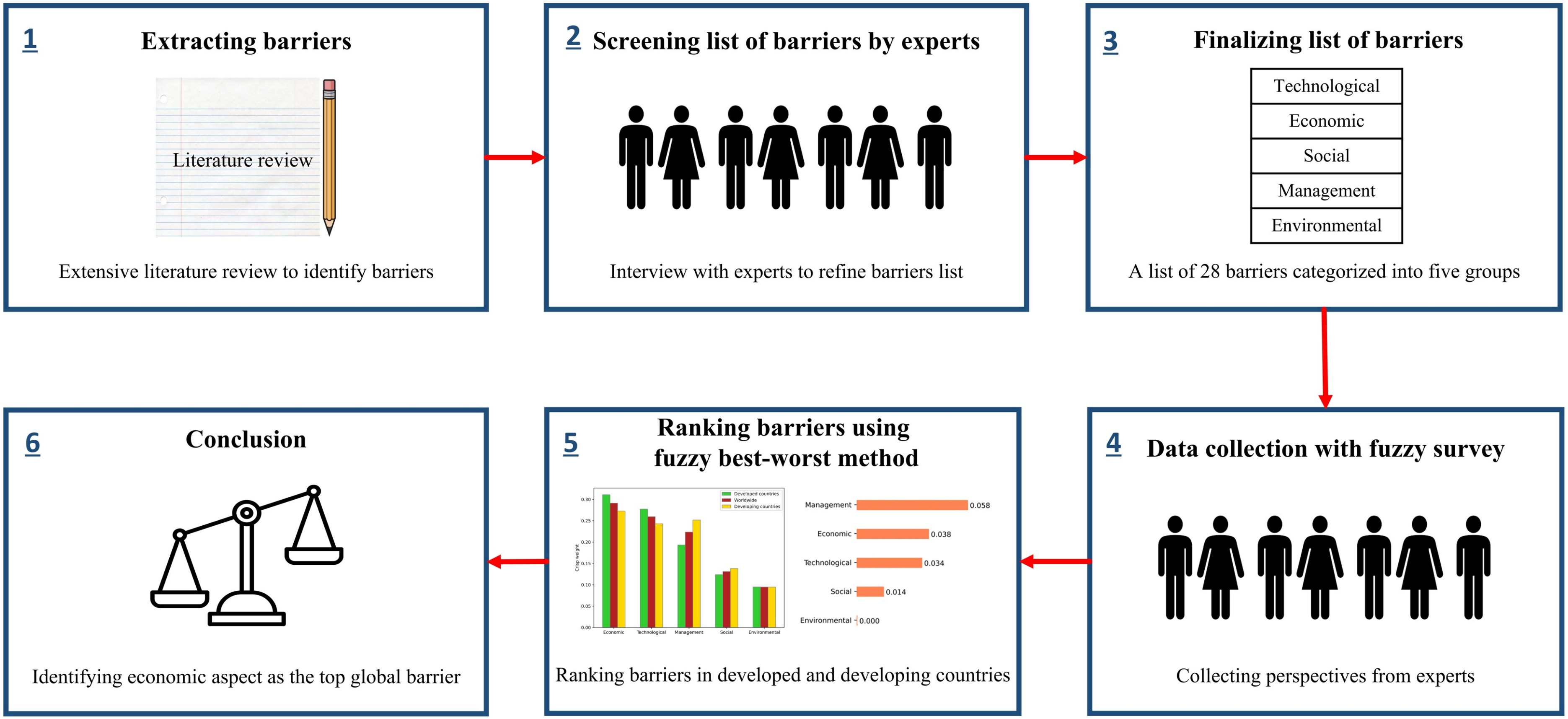
Decision making framework for ranking barriers to electrifying bus systems



A survey is applied to 48 experts from 31 countries

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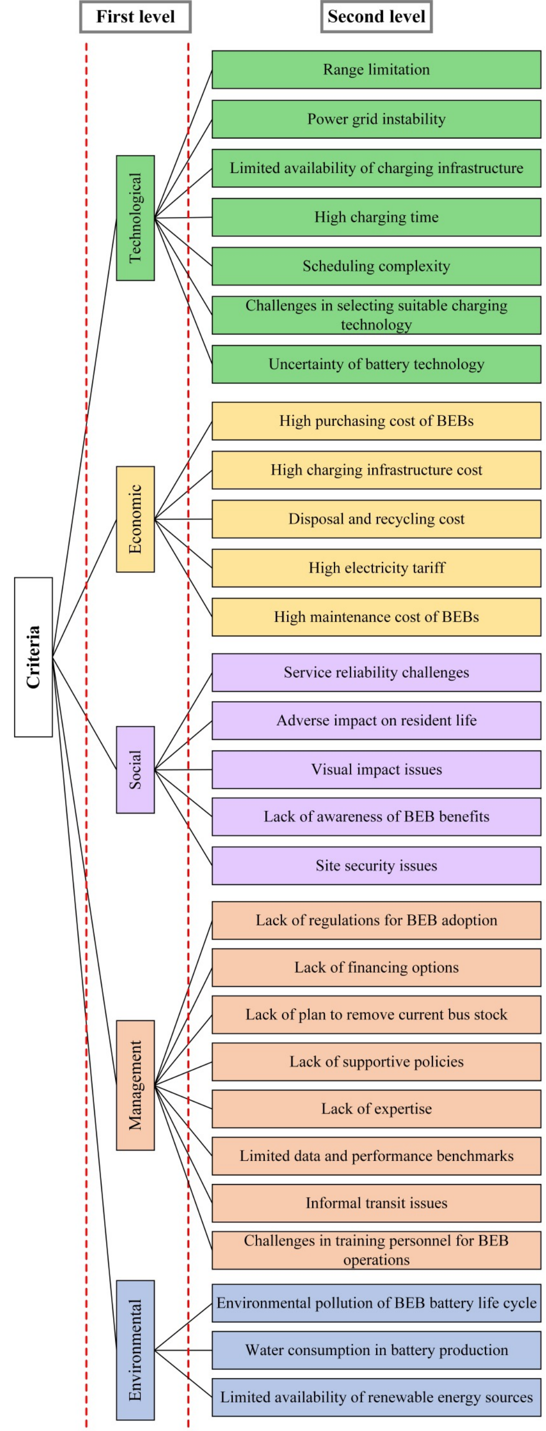
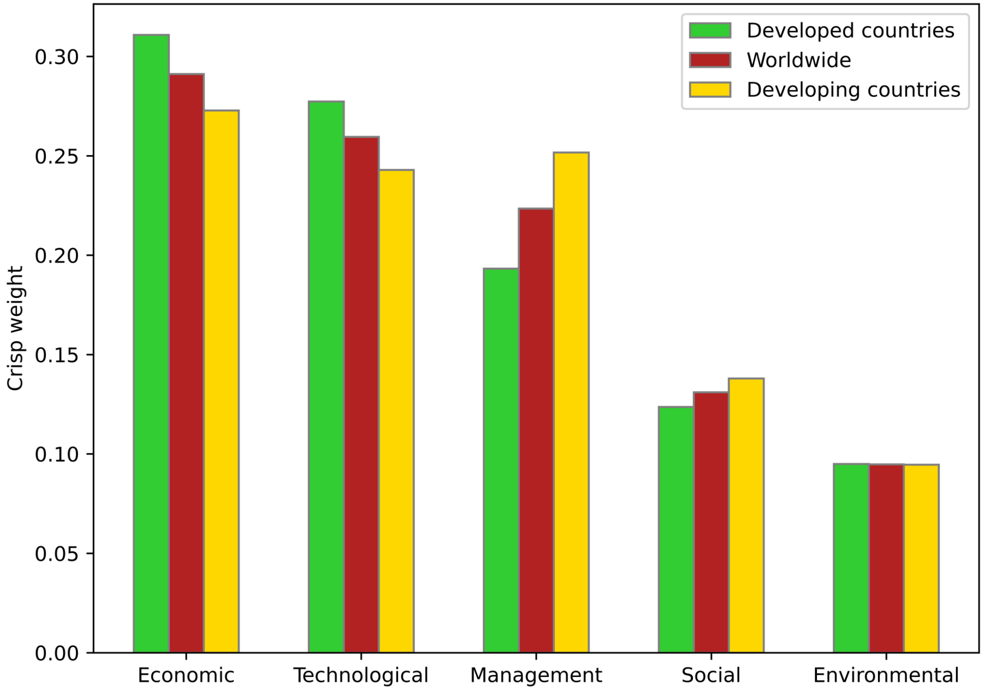
Barriers to electrifying bus systems

Evidence-based set of barriers through a comprehensive literature review and expert interviews



Ranking of barriers in developed and developing countries



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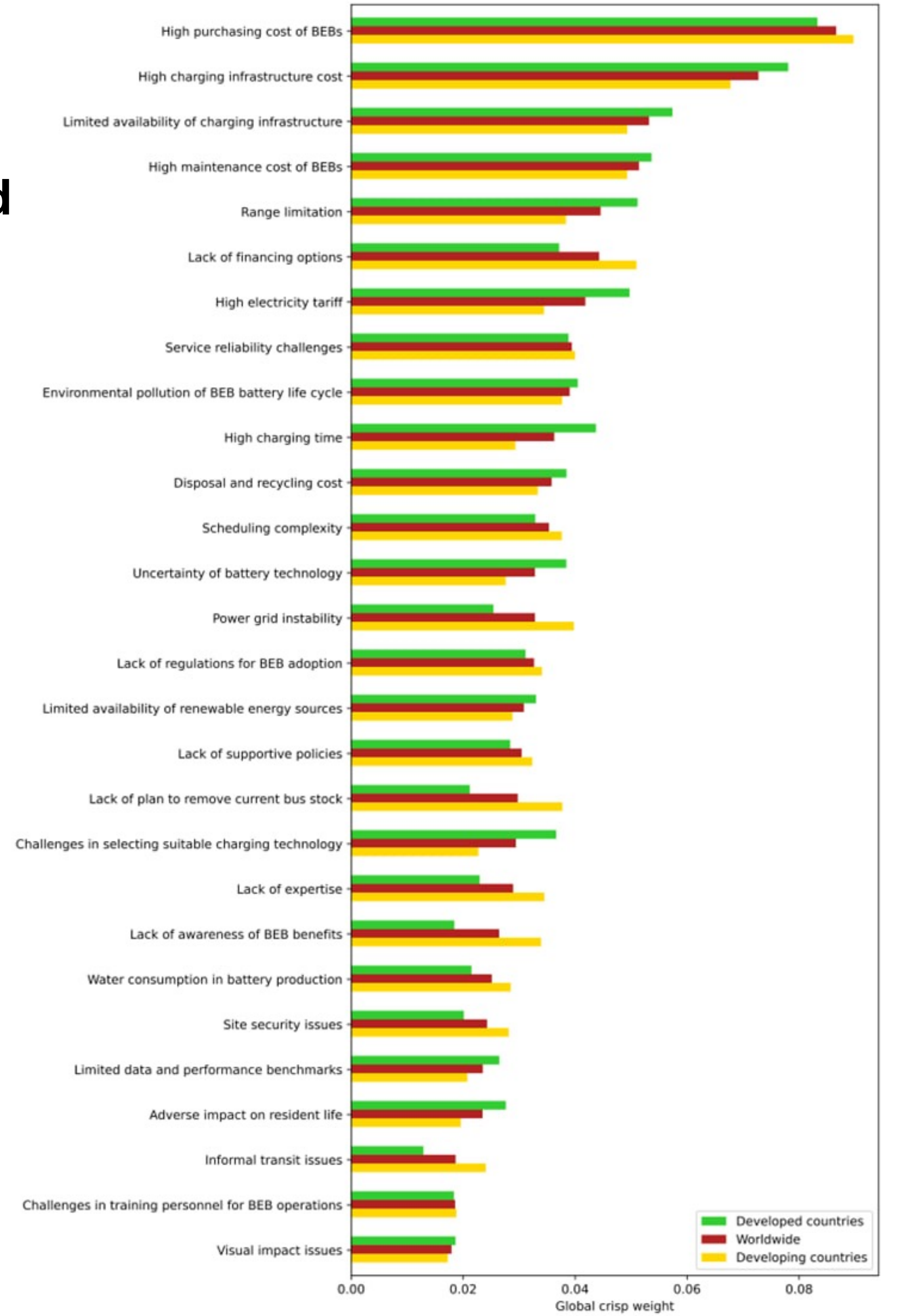
Ranking of barriers in developed and developing countries

- The top two barriers globally are the purchasing costs of BEBs and charging infrastructure costs.
- Lack of financing options, lack of plans to remove diesel bus stock, lack of expertise, and informal transit are specific barriers with larger weights in developing countries.
- Range limitation, high electricity tariffs, uncertainty in battery technology are specific barriers with larger weights in developed countries.



Almost there!

Main conclusions

- Fixed energy consumption rates reduce accuracy in electric bus planning compared to detailed energy estimation models.
- The energy consumption cost function is non-monotonic.
- Optimizing dispatching in mixed-fleet operations aligns supply with time-dependent demand.
- Advanced hybrid metaheuristics improve service quality and fleet size management in crowded scenarios.
- Battery cost is the most important factor in charging strategy selection.
- There is a preference for overnight charging over opportunity charging.
- Economic barriers are the most challenging aspects to electrifying bus systems worldwide.
- Management barriers are more relevant in developing countries.

Thank you for your attention!

Prof. Dr. Constantinos Antoniou

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