École Polytechnique Fédérale de Lausanne

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Semester Project

A First-Principles Approach to Practical and Sustainable Personal Mobility

Biorobotics Laboratory

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Table of Contents

Project Assignment

The goal of this project is to explore alternative design for personal mobility solution. This work will pay attention to the dynamic behavior of such system on the road and the energy usage compared to existing personal mobility solution.

Abstract

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1 Introduction

1.1 Problem Statement

Personal vehicles contribute significantly to green house gas emission and are inherently inefficient.[7] Public transportation systems are essential for sustainable mobility, yet they often face challenges in achieving widespread adoption, particularly in less densely populated areas. In rural regions, lower population density leads to reduced ridership for fixed transit routes and a smaller tax base to fund public transportation systems, limiting its potential as a viable alternative to personal vehicles.[1]

This project seeks to address these issues using a first-principles approach to developing practical and sustainable personal mobility solutions that minimize energy loss, reduce emissions, and better integrate with existing infrastructure.

1.2 Objectives of the Project

This project aims to explore the design space of personal mobility solution. Define a metric for efficiency and the constraint to make the system desirable while significantly more efficient. Finally, study in details the road behavior of the emerging solutions.

1.3 Methodology Overview

To tackle this problem, we will follow a top-down approach using a model defined from first principle. Then, we will incorporate the ergonomics and psychological and social constraint from the users. The proposed vehicle dynamic behavior will then be studied, followed by a performance, economic and legal analysis.

2 Background and Context

2.1 First Principles Analysis of Energy Loss in an average car

The force acting longitudinally on a vehicle can be modeled by the following :

[TODO : figure with axis and gravity] []

$$m \cdot a = F_{\text{motor}} - F_{\text{drag}} - F_{\text{roll}} + F_{\text{gravity}}$$

where:

- **Aerodynamic Drag:**

  $$F_{\text{drag}} = \frac{1}{2}\rho\, C_d\, A\, v^2,$$

  with ρ being the air density, C_d the drag coefficient, A the frontal area, and v the vehicle speed.

- **Rolling Resistance:**

  $$F_{\text{roll}} = C_{rr}\, m\, g,$$

  where C_{rr} is the rolling resistance coefficient, m the vehicle mass, and g the gravitational acceleration.

- **Gravitational Component:**

  $$F_{\text{gravity}} = m\, g\, \sin\theta,$$

  representing the component of gravity along the road when the vehicle is on an slope with angle θ. this term become positive when we go downhill, the slope's angle θ is defined as negative downhill and positive uphill. for a round trip, the gravity term should cancel out. But not the losses from storing and restoring the energy through the power train.

- **Force from motor Acceleration/Braking**

  $$F_{\text{motor}}$$

  this term model the force by the motor/brake

Energy can be defined as a force endured over a distance. Similarly, power can be defined as a force endured at a given speed. Energy efficiency in this context can be defined by the amount of energy required to move by a given distance. Funny enough, this can also be brought back to a force. We will not address "the what" being moved for now, even tho it usually makes sense to also take into account "the what" in the form of cargo/ passenger in the efficiency to compare fairly a train and a car.

Vehicle Energy efficiency, measured as energy [kilo Watt Hour] per 100 [kilometer] as a function of speed (the others parameters usually remain nearly constant while travelling)

$$\eta(v) = \frac{1}{36} \cdot \left(\frac{1}{2}\rho\, C_d\, A\, v^2 + C_{rr}\, m\, g\right) \quad [\text{kWh/100km}]. \tag{2.1}$$

This gives an idea of what we can tune to minimize the amount of energy per unit of distance. Naturally, this model simplifies the reality by ignoring the energy wasted due to the acceleration/braking/idling cycle due to, e.g., a red light or the increased drag from wind. It also ignores the embodied energy in the vehicle and the power train efficiency.

2.2 Driving regime and trips statistics

To model more accurately the efficiency of a vehicle, we must factor the different driving condition and their relative weight over an average trip. A vehicle can be modelled with four distinct driving mode : Cruising, accelerating, braking and idling. There is a fair amount of research studying theses driving modes and their relative proportion. Even tho the exact proportion of each phase will be subject to variation, we can nonetheless see that no phase can be neglected, and thus we need to have a vehicle that is efficient in each case.

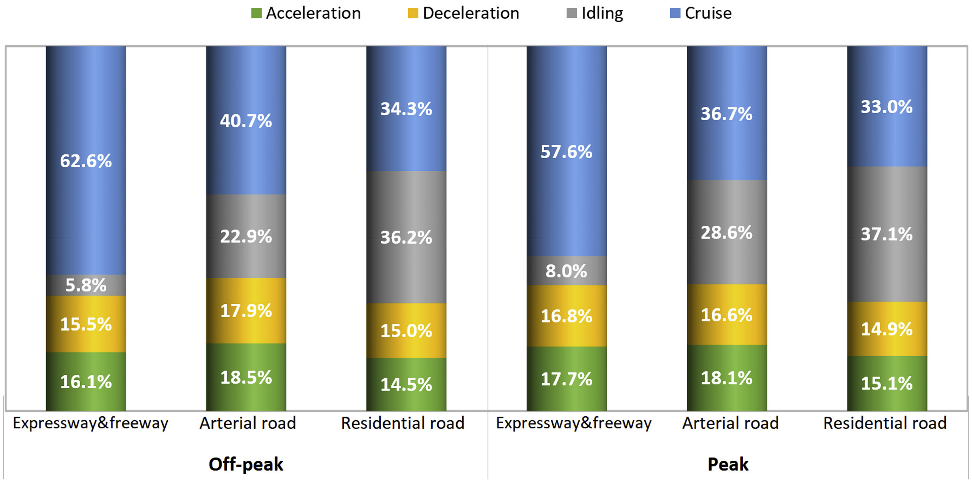

Figure 2.1: Figure from Ma, Real-World driving cycle[6] showing the relative proportion of driving mode

We can also notice that the majority of trips are fairly short, with 80% being less than 10 [km] for an average duration of 22 [minutes] which must be taken into account if there is a warm-up time required as it's the case for internal combustion engine. The trips being fairly short, it's reasonable to assume that the driver could sustain an effort during this time frame if the power at play is comparable to what a human being can output.

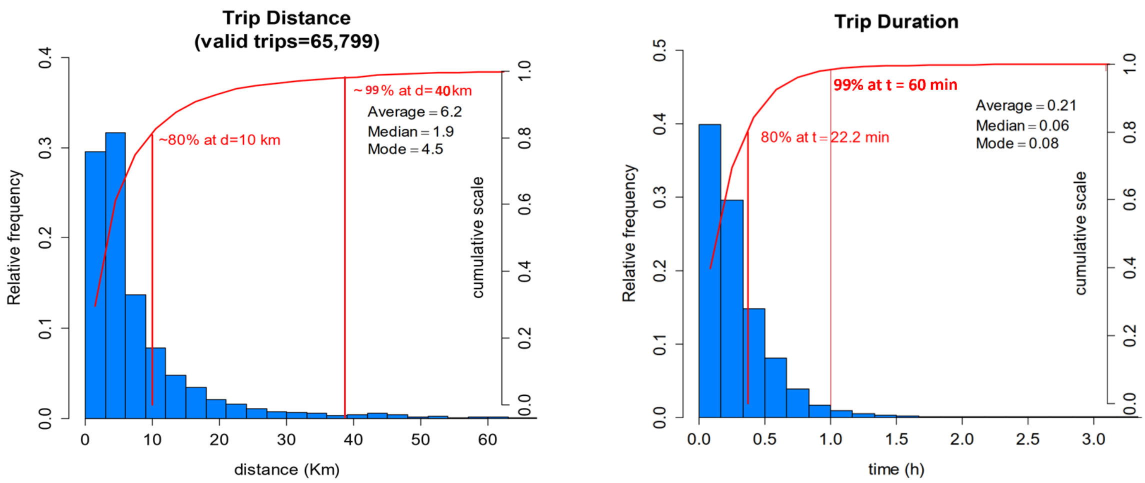

Figure 2.2: Comparison of trip length and trip duration frequency distributions. (from Donati 2015[5])

we can define an idling efficiency (even tho the vehicle is not moving and thus only wasting energy, some will waste more energy per unit of time than others) we can define a deceleration efficiency, measuring how much energy we can recover while braking (0% for a typical ICE vehicle up to XX% for an electric vehicle with regenerative braking)

we can define an acceleration efficiency by looking at how much energy is wasted from the tank/battery to the wheel/kinetic energy.

2.3 Parameters affecting Efficiency

From the previous equations (2.1), we see that to improve the efficiency we must minimize the mass m and frontal area A of the vehicle followed by a reduction of C_d and C_{rr}. Furthermore, the power train efficiency is quite important as braking and acceleration cycle are frequent and thus energy is lost every time energy is converted back and forth. Finally, we must also maximize the idling efficiency, as the vehicle will spend a significant amount of time stopped.

2.4 Importance of embodied Energy and material impact

while this work will not go too deep into the manufacturing impact of the vehicle, it's important to note that a significant amount of resources is used and that electric vehicle tend to be more energy and resources intensive than ICE vehicle during its manufacturing, but ICE vehicle compensate by a higher energy and emissions during its life. To reduce the impact of the manufacturing, the vehicle should last as long as possible and minimize the mass of energy intensive material.

Vehicle Type	**Lifecycle Emissions (tonnes CO2e)**	**Emissions in Prod. (tonnes CO2e)**
Standard gasoline vehicle	24	5.6
Hybrid vehicle	21	6.5
Plug-in hybrid vehicle	19	6.7
Battery electric vehicle (500 [g/kWh] CO2e)	19	8.8
Battery electric vehicle (100 [g/kWh] CO2e)	10.8	8.8

Table 2.1: Vehicle Whole Life Carbon Emissions Analysis, Based upon a 2015 vehicle in use for 150'000 [Km] using 10% ethanol blend. Data from [3], the energy intensity correspond to the world and Europe average respectively, some country doing way better and other worse [2]

2.5 Comparison with existing vehicle

look at velomobile, twizi, smart, tesla, suv, small car, bike get number on kwh/100km, embodied energy, typical speed, mass, frontal area, C_d, C_{rr}

3 Design Considerations

3.1 Reducing Frontal Area and improving the coefficient of drag

A typical passenger car offer five seats, while the average occupancy rate for private car remains well below two persons per car [4].

To reduce the frontal area, we consider a smaller vehicle with one or two seat. Passengers would be one behind the other. This offers the benefit of both reducing the width of the vehicle while also allowing to create a more elongated envelope that improve the coefficient of drag. Furthermore, we can also reduce the effective used height of the vehicle by tilting the seats, allowing to further reduce the frontal area.

show graphically the frontal area of a car and the passenger inside. Front and side view. (graph SUV side + front and proposed seating side + front

show the proposed solution to reduce the space occupied with the tilted chair. show the lying position / human tuboid.

talk about ergonomic and the user FoV, limitation on height reduction (or deport viewing with set of problem like motion sickness)

Talk about ergonomics, how to get in and out

3.2 Reducing mass and embodied energy

why are car heavy ? what is energy intensive in a car ?

3.3 Addressing Visibility and Safety Concerns in Traffic

why trike and velomobile are not more mainstream (economics and driving lower than anybody else, more ?)

3.4 User comfort requirement

(thermal, noise, water ingress, seating position) study about what people need in car. we are we sensitive about when travelling / commuting

joystick -¿ poignet + bas que le coude

nuque -¿ 4-20° -¿ max 15° depuis le 4° -¿ total 30°

talk about ergonomy and the user FoV, limitation on height reduction (or deport viewing with set of problem like motion sickness)

https://www.epfl.ch/labs/chili/fr/chili/

3.5 Narrow Track and Low Vehicle Geometry (literature review)

Acknowledge existing solution

4 Innovative Design Concept

4.1 Elevating the Vehicle Without Increasing Frontal Area

from previous chapter, want to lower frontal area while keeping user eyes high from the ground

how can we do so on a kinematic standpoint and what synergies can we gain from coupling the steering to the leaning ?

*** steering approach
-¿ skid steer
-¿ ackerman
-¿ swerve wheel + crab steering
-¿ 2 wheel lean to steer (trail + no trail ?)
-¿ other
*** geometry and kinematic
-¿ vertical actuator
-¿ arm along vehciule
-¿ arm sideways vehicule
-¿ others ?

4.2 mass reduction

can we afford high performance material ? do they make sense ? what material can we use to keep mass and carbon imprint low

4.3 Benefits for Vertical Parking and Accessibility

talk about the advantage of the selected design, how it could park vertically and what good it would do.

talk about the stability while boarding and exiting, how the vehciule can help to make it a ”normal chair” posture then reclining

4.4 Literature review of existing concept

4.5 Integration with Public Infrastructure (e.g., Trains)

5 Dynamic Analysis

-¿ test with simple bycycle, show behavior, try to see the counter steer thing ?

-¿ how does it behave on straight road (with bump and or not flat) ?

-¿ how does it behave during cornering (road with bump and not flat)

-¿ relationship spring to negate effect of weight and weight change ?

5.1 Prevention of Tipping During Turns

5.2 Stability on the Road: Key Parameters and Insights

5.3 Comparison of Steering and Leaning Systems

5.4 Energy efficiency

TODO IF TIME : we can if we have time use the markov process and integrate of the efficiency over many trips to have an average trip efficiency and have some weight.

also get some number on the acceleration braking amount and quantity (how much and how many) (use markov model (1 seconde per state and compare with gofar data for braking)

5.5 Travel time

It's also interesting to look at the speed profile on road to define how fast the vehicle need to go (as required by real world data) and the tradeoff between trip time and speed if we have to cap the max speed.

get a number on the impact of the vehicle performance on trip duration.

6 System integration

6.1 Trade-offs Between Design Choices

6.2 power, speed gravity, acceleration, braking

from chapter 2, how much accelerating do we need ?
how much regenerative braking ?
what power for the motor ?
what battery size ?
impact on range, climbing hill, user acceptance

6.3 System review

how do we compare against other solutions ?
key performance indicator ?

7 Prototype Development

if we hypothetically wanted to build one, what would it take ?

7.1 Legal requirements

7.2 Material Selection and Cost Analysis

7.3 Preliminary Design Specifications

7.4 Feasibility of Building the Prototype

8 Economic and Practical Viability

8.1 Energy Efficiency Comparison with Conventional Cars

8.2 Cost-Benefit Analysis of the Proposed System

8.3 Scalability and Market Potential

9 Conclusion and Future Work

9.1 Summary of Findings

9.2 Challenges and Limitations

9.3 Suggestions for Future Research

a prototype should be built to verify the theoretical model.

Safety in case of collisions should be integrated

if such vehicle was deployed, how would traffic look like inside the city ? would it help with congestion ? impact of trip time if we remonter la file au feux ? safety impact ?

Multi-Modal Transport Efficiency with Train Onboarding, what would happen if we took the train with our "bike++" to coverage long distance ?

10 Appendix

References

[1] Barriers to Transportation Programs in Rural Areas – RHIhub Toolkit.

[2] Power sector carbon intensity worldwide by country 2023.

[3] zemo2025lifecycle.

[4] CEU. MOVE., Univ. Eiffel., TRT., Panteia., GDCC., and STRATEC. *Study on new mobility patterns in European cities: final report. Task A, EU wide passenger mobility survey.* Publications Office, LU, 2022.

[5] Alberto Donati, Panagiota Dilara, Christian Thiel, Alessio Spadaro, Dimitrios Gkatzoflias, and Ioannis Drossinos. Individual mobility: From conventional to electric cars, 2015. ISBN: 9789279518959 9789279518942 ISSN: 1018-5593, 1831-9424.

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