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Semester Project

Pragmatic Mobility : How to design a more efficient vehicle ?

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Abstract

Urban environments face increasing challenges related to road traffic congestion, limited parking, and the environmental inefficiencies of personal cars. Meanwhile, current cycle-based alternatives such as e-bikes and velomobiles often fail to meet comfort, safety, or usability expectations, limiting their adoption. This project investigates the feasibility of a new vehicle category which bridges that gap: a compact, lightweight, and energy-efficient vehicle concept offering car-like comfort while retaining the legal and spatial advantages of a bicycle.

Using a first-principles approach, this paper model the energy demands of short-distance urban trips, accounting for both ideal and real-world driving patterns. Key parameters are identified such as mass, frontal area, and drivetrain efficiency that govern energy use. A novel vehicle design is proposed. It incorporates an active leaning mechanism, vertical parking capability, and tandem seating, aiming to balance aerodynamic performance, urban compatibility, and user experience.

The vehicle concept is evaluated against existing solutions in terms of efficiency, spatial footprint, and human factors. A comparative simulation study using PyBullet explores the steady-state dynamic stability of various configurations (3-wheel vs. 4-wheel, pivot vs. linear leaning mechanisms) under PID control of the proposed design. Results demonstrate that the proposed design offers superior trade-offs in the three metrics defined, albeit at the cost of increased mechanical complexity and the need for active stabilization requiring a complex controller.

This study provides both a physical and behavioral justification for a pragmatic urban mobility solution. It also outlines the path toward prototyping, with considerations for dynamic control and safety.

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1 Introduction

1.1 Problem Statement

Personal cars contribute significantly to green house gas emission and are inherently inefficient [17]. Cities around the world are struggling with both traffic jams and lack of car parking space. There is a need for an intermediate vehicle that combines the efficiency, road/parking use and affordability of a bike with the comfort and utility of a car, and would provide the majority of short-distance trips on the road.

1.2 Objectives of the Project

The objective of this project is to first analyze the constraints on urban vehicle design from an efficiency, urban and human standpoint. Secondly, to propose an improved trade-off between efficiency and usability through a vehicle design. The last goal is then to validate the design viability and behavior via modeling and simulation

1.3 Methodology Overview

A top-down approach has been used, which relies on a model defined from first principle and real world measurements. Then, the ergonomic, psychological and social constraints from the users are taken into consideration. To provide a perspective on several existing solutions, a list of literature references is included. Finally, the proposed vehicle's is defined, its dynamic behavior is studied, and a performance evaluation is conducted.

2 Foundations of Efficiency

A First-Principle analysis is informative of the energy demands of a vehicle. This section establishes a framework to understand how physical forces, design choices, and driving behavior jointly determine the energy efficiency of small personal vehicles. Starting from the classical longitudinal force balance, we derive expressions for steady-state cruising power and identify dominant energy losses. We then extend the model to incorporate real-world driving conditions such as idling, acceleration, braking and the embedded energy associated with mass and manufacturing. By disentangling these contributors, we identify which design decisions yield the most significant reductions in energy consumption, both during operation and over the vehicle's full lifecycle.

2.1 Longitudinal Dynamics: A First-Principles Approach

The longitudinal dynamics of a ground vehicle can be expressed by Newton's second law:

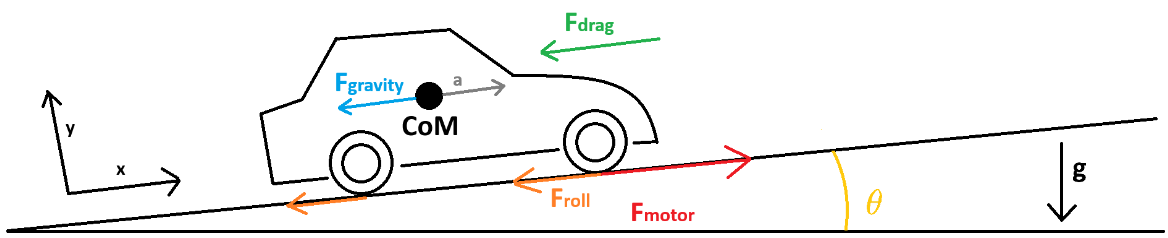


Figure 2.1: Longitudinal car dynamics

To model the energy requirements of a vehicle in motion, we begin with the classical longitudinal force balance:

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

This equation expresses Newton's second law applied to a vehicle moving along a slope, where m is the vehicle mass and a its acceleration. The right-hand side aggregates all relevant external forces acting on the vehicle in the direction of travel.

Substituting each component force into the equation, we obtain the fully expanded expression:

$$m \cdot a = F_{\text{motor}} - \frac{1}{2}\rho\, C_d\, A\, v^2 - C_{rr}\, m\, g + m\, g\, \sin\theta$$

This relation captures the competing effects of propulsion, aerodynamic drag, rolling resistance, and gravitation through road slope. Each parameter affects directly energy consumption.

Definition of Parameters:

m : vehicle mass [kg]
a : longitudinal acceleration [m/s^2]
F_{motor} : force produced by the motor or absorbed by braking [N]
ρ : air density [kg/m^3]
C_d : aerodynamic drag coefficient [–]
A : frontal area of the vehicle [m^2]
v : vehicle speed [m/s]
C_{rr} : rolling resistance coefficient [–]
g : gravitational acceleration [m/s^2]
θ : road slope angle [rad]

Note that the gravitational term becomes negative when descending ($\theta < 0$) and positive when climbing. While the average gravitational contribution over a round trip cancels out, energy losses due to braking and powertrain inefficiencies remain.

Based of the previous equation, we can define the efficiency as

$$\eta(v) = \left(\frac{1}{2} \rho \, C_d \, A \, v^2 + C_{rr} \, m \, g \right) \quad [\text{N}] \tag{2.1}$$

Equation (2.1) reveals key design levers: mass m, frontal area A, drag coefficient C_d, and rolling resistance C_{rr}. This simplified model excludes transients like acceleration, braking, wind gusts, and idling, as well as the embodied energy of the vehicle and powertrain losses, which are addressed next.

2.2 Driving Patterns: Beyond the Idealized Model

Real-world driving involves multiple phases, each with distinct energy characteristics: cruising, accelerating, braking, and idling. Empirical studies (e.g., [14]) provide typical phase distributions over urban trips:

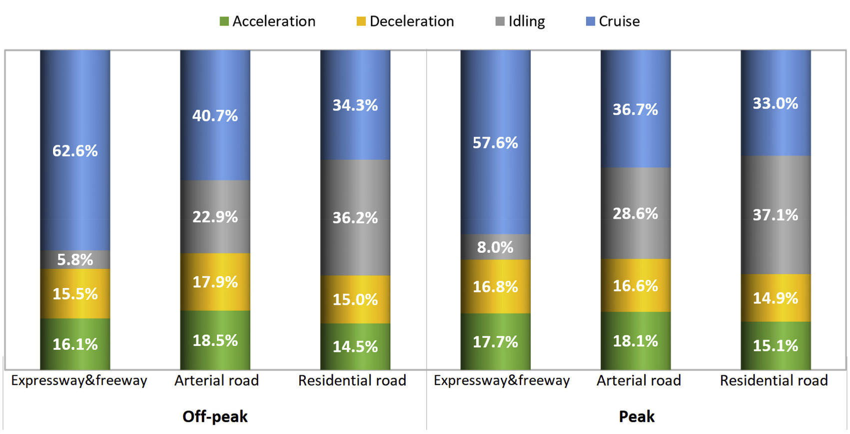


Figure 2.2: Proportion of driving phases during urban operation (Source: [14])

Most trips in Europe are short, with 80% under 10 km and 22 minutes [11], reinforcing the relevance of frequent transient phases and vehicle warm-up times, especially for Internal Combustion Engine Car (ICE). Trips powered by human effort become a plausible benchmark for energy use over such durations.

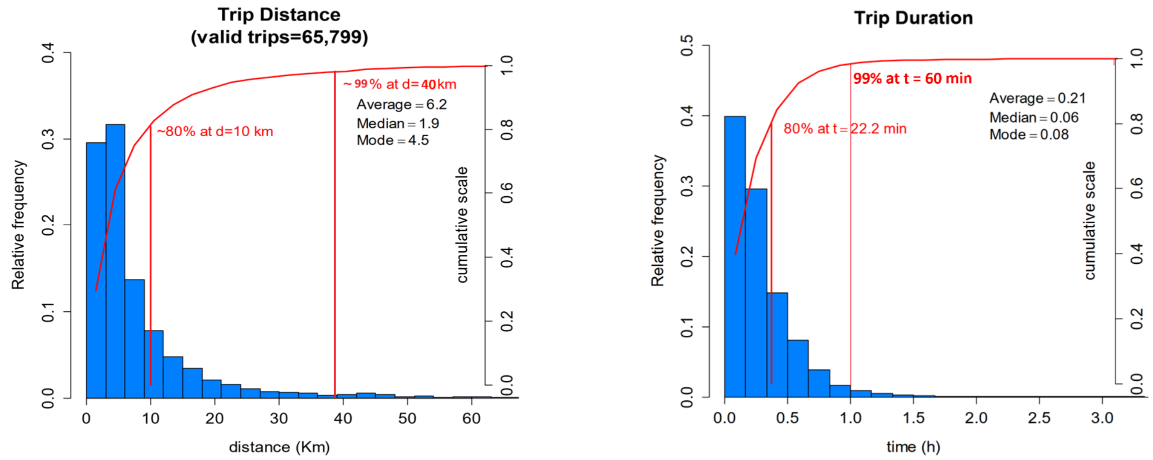


Figure 2.3: Trip length and duration distributions in Europe (Source: [11])

We define distinct phase efficiencies:

- **Idling Efficiency:** Energy consumed per unit time when stationary. Typically:
  - ICE: 12 kW
  - EV: $\leq$ 0.5 kW
- **Braking/Deceleration Efficiency:** Energy recovered during braking.
  - ICE: 0%
  - EV (regen): 50–70% [3]
- **Acceleration Efficiency:** Energy transferred from tank/battery to kinetic motion.
  - ICE: 13%
  - EV: up to 80% [13]

These phase-specific efficiencies reinforce the importance of designing for all driving modes, especially in urban environments characterized by frequent starts and stops.

2.3 Embodied Energy and Material Impact: Why Mass Matters

Although this work does not perform a full lifecycle analysis, it is important to acknowledge that manufacturing represents a non-negligible share of a vehicle's total emissions, especially for EVs with energy-intensive battery production. As the electric grid become more efficient, manufacturing emissions become the limiting factor.

A low-mass, long-lived vehicle, built from materials with low embodied energy, offers a clear advantage in this regard.

2.4 Parameters Affecting Efficiency

From Eq. (2.1), we identify key parameters influencing operational energy efficiency:

- Reduce **mass** m to minimize both rolling resistance and gravitational load.
- Minimize **frontal area** A and optimize **drag coefficient** C_d.
- Lower the **rolling resistance coefficient** C_{rr} via tire selection and surface optimization.
- Maximize **powertrain efficiency** to reduce losses during acceleration and regenerative braking.
- Improve **idling efficiency**, especially critical for short, stop-start urban trips.

2.5 Aerodynamic Optimization Through Form Factor

Compact, narrow vehicle designs naturally limit frontal area A. Reclined seating and tandem configurations can further reduce the product C_dA, though this introduces challenges related to comfort and accessibility.

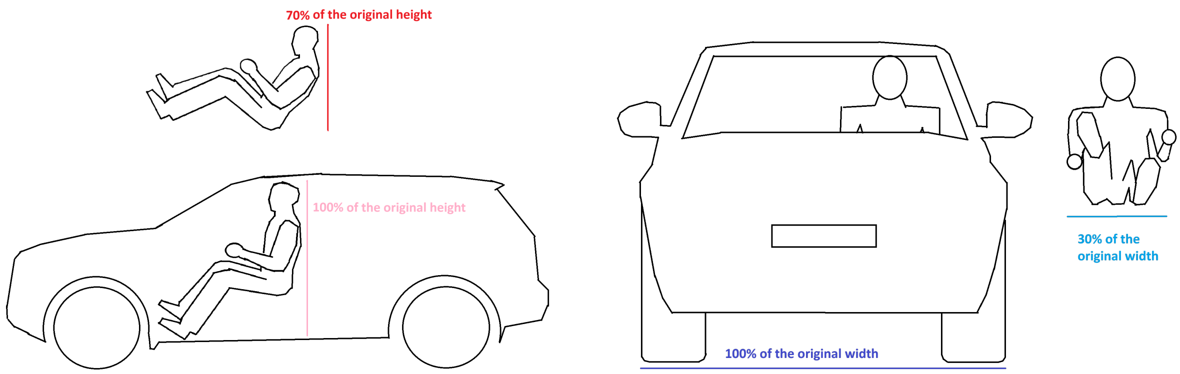


Figure 2.4: Effect of seat recline and tandem seating on frontal area

Digital augmentation (cameras, screens) could replace traditional visibility elements to further reduce A, but may induce motion sickness due to visual-vestibular mismatches. A partially reclined posture with direct external visibility is a pragmatic compromise.

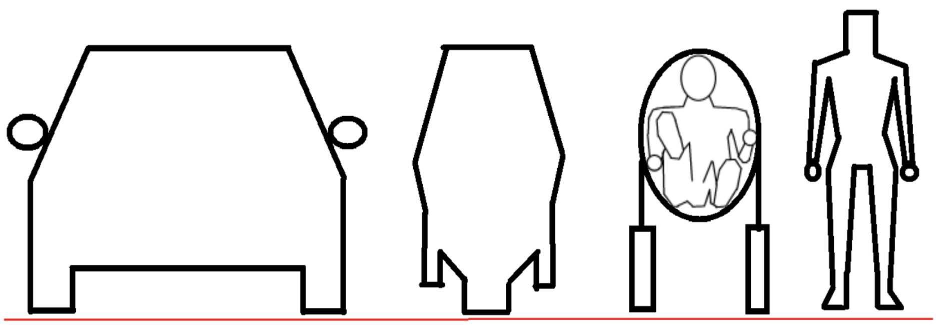


Figure 2.5: Frontal area comparison of car, leaning vehicle, proposed concept, and a standing person

Our proposed design incorporates a height-adjustable wheel system, enabling both dynamic tilt control and variable ingress/egress configurations combining aerodynamic form with accessibility.

3 Design Constraints from Urban Road Usage

This chapter builds a bridge between pure efficiency modeling and real-world usability. It introduces constraints imposed by urban infrastructure and traffic behavior. We first explore the spatial pressures that incentivize narrow and light vehicles. Then, we derive performance requirements (e.g., power-to-weight, acceleration, braking) needed to fluidly integrate with existing traffic. Finally, we introduce a proposed design in light of theses criterion.

3.1 Urban Space: Width, Distance, and Parking Constraints

The geometric footprint of a vehicle has a disproportionate impact in dense cities. A wide vehicle not only occupies more road space but also demands larger safety margins from other road users, longer parking slots, and wider lanes. Reducing width allows for better road sharing, denser parking, and higher capacity utilization of limited urban infrastructure. Minimizing frontal width also directly contributes to aerodynamic efficiency.

Beyond static width, the effective road space a vehicle occupies also depends on its longitudinal spacing, which is governed by the driver's reaction time and travel speed. At a cruising speed v and a reaction time τ, the effective longitudinal space required per vehicle (headway) is approximately:

$$s_{\text{eff}} = v \cdot \tau + l$$

where l is the vehicle length. For example, at 50 km/h (13.9 m/s) and a conservative reaction time of 1.5 s, the spacing is:

$$s_{\text{eff}} = 13.9 \cdot 1.5 + 4.5 \approx 25.35\,\text{m}$$

This means that an average vehicle occupies over 25 times 1.7 m square meters of road space at 50 kmh, even before accounting for lateral gaps. By reducing the width of the vehicle to 70 cm, we can reduce that space to only 40% of the original surface of road required.

Parking further amplifies this inefficiency. A typical car requires a footprint of at least $2.0 \times 5.0 = 10\,\text{m}^2$, not including maneuvering space. This imposes a high space burden in cities already constrained by building density and infrastructure.
In contrast, our proposed vehicle, being light enough to be lifted to a vertical position, could feasibly occupy as little as: $\boxed{0.65 \times 1.0 = 0.65\,\text{m}^2}$

This represents a more than 15-fold reduction in static parking footprint compared to conventional vehicles.

3.2 Speed, Power and Traffic Fluidity

To integrate fluidly and safely into urban traffic, a vehicle must have sufficient power to:

- Climb steep inclines (e.g., up to 15% gradient).
- Accelerate at a pace comparable to surrounding traffic (typically 0.1–0.3 g).
- Reach legal urban speed limits (up to 50-60 km/h).

We define the power-to-weight ratio (PWR) as:

$$\text{PWR} = \frac{P}{m} \quad [\text{W/kg}]$$

where P is the mechanical power available at the wheels, and m is the total mass of the system (vehicle + payload + passenger).

Hill Climbing Requirement

The minimum power to climb a slope of angle θ at constant velocity v is:

$$P_{\text{slope}} = mg\sin(\theta)\,v$$

For a 250 kg system on a 15% slope ($\theta \approx 8.6°$) at 50 km/h:

$$P = 250\,\text{kg} \cdot 9.81\,\text{m/s}^2 \cdot 0.15 \cdot \frac{50}{3.6} \approx \mathbf{5.3\,kW}$$

This corresponds to a required PWR of:

$$\text{PWR}_{\text{min}} = \frac{5\,300}{250} \approx \mathbf{21\,W/kg}$$

It is worth noting that this value is based on a *worst-case* scenario: climbing a sustained 15% gradient at 50 km/h at maximum weight. In practice, the vehicle will likely will be lighter. And it will either implement a lower climbing speed or accept a short-duration higher power draw, as real gradients are often less severe or shorter in length.

Nevertheless, even accounting for these factors, the required power density remains in the same order of magnitude. A value between 10-30 W/kg is a reasonable target for lightweight urban vehicles aiming to maintain functional parity with traditional car in urban settings.

Acceleration with Traction and Power Limits

Electric drivetrains offer the advantage of delivering near-instant peak torque and high short-duration power relative to their steady-state consumption. Empirically, a lightweight electric vehicle may draw 2-3 times more power during short bursts. For acceleration, we will thus use 3 times the steady state power density required.

We model vehicle acceleration using two regimes:

1. **Traction-limited phase:** The vehicle accelerates at a constant rate up to the maximum grip-limited threshold (e.g., 1 g).
2. **Power-limited phase:** Beyond a certain speed, acceleration is constrained by available mechanical power and follows:
$$a(v) = \frac{P}{m\,v}$$

As the speed increase, the impact is non negligeable. A suitable metric for evaluating responsiveness in traffic is the **speed threshold beyond which the vehicle can no longer sustain a given acceleration**. This is computed using:

$$v = \frac{P}{m\,a} \quad \Rightarrow \quad v_{\text{limit}}[\text{km/h}] = \frac{3.6 \cdot P}{m \cdot a}$$

Based on the following data from figure 3.1

GOFAR			BRAKING EVENTS FREQUENCY %
BRAKING EVENTS BY SEVERITY	Light braking	0 g to -0.05 g	45.739%
		-0.05 g to -0.1 g	28.067%
	Average braking	-0.1 g to -0.15 g	11.551%
		-0.15 g to -0.2 g	7.135%
		-0.2 g to -0.3 g	6.185%
	Heavy braking	-0.3 g to -0.4 g	1.121%
		-0.4 g to -0.5 g	0.159%
	Near misses	-0.5 g to -0.6 g	0.031%
		-0.6 g to -0.7 g	0.007%
		-0.7 g to -0.8 g	0.004%
		Over 0.8 g	0.001%
	Based on 10 million trips on GOFAR.co		

Figure 3.1: Real-World data about intensity and frequency of braking event from gofar.co[2]

We can deduce the following, assuming that we tend to break harder or at least equally than we accelerate

- **Comfortable acceleration:** Typically in the range of 0.2–0.3 g ($\approx$ 2–3 $\mathrm{m/s^2}$), especially in urban settings .
- **Comfortable braking:** Most braking events stay below 0.3 g ($\approx$ 3 $\mathrm{m/s^2}$), while emergency braking can exceed 0.7–0.9 g briefly.

Vehicle	**Mass** [kg]	**Power** [kW]	**PWR** [W/kg]	**0.3 g** [km/h]	**0.5 g** [km/h]	**1.0 g** [km/h]
Tesla Model 3 (RWD)	1'745	211	121	148	89	44
Renault Zoe	1'502	100	67	81	49	24
Average compact car	1'300	66	51	62	37	19
Citroën 2CV	600	16	26.7	32.6	19.6	9.8
E-bike (pedal assist)	100	0.25	2.5	3.1	1.8	0.9

Table 3.1: Power-to-weight ratios and maximum speeds at which vehicles can sustain constant acceleration levels. Beyond these speeds, acceleration becomes power-limited.

From this, we can infer that the power density required to be smooth in traffic should be between 25-40 W/kg peak to accomodate for acceleration as bellow would start to feel sluggish while higher will yield no benefit. One must keep in mind that the peak power density can be 2-3 times higher than the nominal power density for electric drive train and if we required 21 W/kg to be able to climb road we easily exceed 50 W/kg for acceleration.

Note on regenerative braking and battery design: While regenerative braking offers an opportunity to recover kinetic energy and improve overall efficiency, it is important to consider that it's often constrained by battery charge acceptance limits.

Standard lithium-ion battery packs can typically handle discharge rates up to 5 C, but only accept charge rates of about 1 C without degradation or overheating. This mismatch means that while high power can be drawn for acceleration, not all braking energy can be recovered at the same rate.

Furthermore, battery cell selection involves a trade-off: prioritizing power density (measured in W/kg) often comes at the expense of energy density (measured in Wh/kg). For regenerative braking to be effective, battery design must balance the need for peak power absorption with energy storage requirements.

Justifying Speed Limits

Given a required peak power density of 25-40 W/kg and a steady state power density of 21 W/kg, we can show that we can accomodate any speed found in an urban environment.

These power levels allow the vehicle to largely exceed typical city speed limits before aerodynamic drag becomes a limiting factor. For example, even with a modest power-to-weight ratio of just 10 W/kg, a 250 kg vehicle with optimized aerodynamics ($C_d = 0.15$, $A = 0.7\,\mathrm{m^2}$) and standard bike rolling resistance ($C_{rr} = 0.004$) can reach a steady-state cruising speed of:

$$P_{\text{resist}}(v) = (\frac{1}{2}\rho C_d A v^2 + C_{rr} m g)v$$

$$v = \sqrt[3]{\frac{P}{\frac{1}{2}\rho C_d A + \frac{C_{rr} m g}{v^2}}} \quad \text{solved numerically} \quad \Rightarrow \boxed{116.6\,\mathrm{km/h}}$$

This confirms that aerodynamic resistance is not a significant barrier below 80 km/h for well-designed lightweight vehicles, and thus that power for acceleration remains available at these speeds. From a safety standpoint, it is reasonable to cap the vehicle's maximum speed to 60-80 km/h to reduce the severity of potential crashes. This then minimizes the need for heavy structural reinforcements such as crumple zones. This design choice directly contributes to lower vehicle mass, further improving efficiency.

One way to implement this is to limit the average power over a given time to match the average power from the user. On average, a person walking can generate 100-150 W. Assuming that we compensate the losses and cancel out the energy spent accelerating or going uphill by the energy gained from decceleration and going downhill, the previous equation show speed in 40-55 kmh range. It is assumed that the vehicle is not fully loaded and only wheights 150 kg, yielding a Power density of 1W/kg. The second argument beyond being able to accomodate both terrain and traffic conditions is that it provides an incentive to keep the rider active, which has been shown to have a positive health impact. The third argument in favor is that it allow to legally consider the vehicle as a "cycle" according to the OETV[4], which state the main difference between a cycle and the other category is the external energy needed to make the vehicle move. One could argue that as long as we only compensate loss using an external source and average out the power by storing the user production, then it's a "cycle".

3.3 Travel Time and Speed Requirements

The marginal gain in travel time beyond 50 km/h in cities is due to intersections, traffic lights, pedestrian crossings, and overall traffic congestion. To assess the impact of speed caps, we compare ideal and capped speed profiles for typical trips.

For most short trips (< 10 km), the difference between a capped vehicle (e.g., max 60 km/h) and a conventional car (max 120 km/h) is minimal, as higher speed segments are rare in urban settings. Empirical studies show that the median speed of urban car trips typically lies between 10 and 40 km/h [14], indicating that speed caps do not meaningfully affect travel time in such contexts. Thus, the energy efficiency and safety benefits of capping the top speed far outweigh the negligible loss in time.

If greater precision is needed, we could directly use a Markov model of vehicle states parameterized by real-world measurements of driving regimes.

4 User-Centered Design

While technical performance and environmental impact are often emphasized in vehicle design, user adoption ultimately hinges on satisfying real human needs, real or perceived. This section highlights the limitations of current electric velomobiles and bicycles from a user-centered perspective and explains how our concept seeks to overcome them.

4.1 Human Elements

User satisfaction depends on a holistic experience that includes not only mobility but also comfort, safety and convenience. Multiple studies confirm that key decision factors in choosing a personal vehicle go beyond speed or energy use and include subjective feelings of safety, practicality and comfort. Among many factors, below are the ones we identified as actionable :

- **Feeling visible and protected:** One of the most frequently cited concerns among cyclists is the lack of safety feeling, especially in mixed traffic environments [15]. Low-seated vehicles like velomobiles and trikes often exacerbate this issue by limiting eye contact and visibility. In contrast, automotive design trends show a steady increase in H-point height reflecting both consumer preference and perceived improvements in safety and comfort[5]. Higher seating positions offer better road visibility and make occupants feel more secure, which helps explain the popularity of SUVs and crossovers. Applying this principle to lightweight vehicles can enhance user confidence and comfort in urban settings.
- **Physical effort:** High or inconsistent effort discourages regular cycling. The PASTA study [6] showed that e-bikes reduce physical strain while enabling longer trips, helping users maintain consistent daily use. By smoothing effort and lowering peak demands, electric assistance improves accessibility and long-term retention, especially for commuters.
- **Storage and passenger flexibility:** Although data from EU transport surveys show that cars generally carry only one person [9], occasional cargo (e.g., groceries, luggage) and passengers (children, partner) must be accommodated. Thus, capacity for a second seat or generous cargo area is essential.
- **Weather and thermal protection:** Exposure to cold air and rain are commonly cited deterrents to cycling and velomobile use. The study by Nankervis [16] confirms that weather and seasonal conditions do influence cycling frequency, especially among less-committed riders, suggesting that improved weather protection and thermal comfort can help support regular use. In warm climates cooling, also becomes relevant.
- **Cabin privacy and comfort:** Cars provide a personal enclosure that protects occupants from external elements such as weather, noise, and pollution. This enclosed space creates a “personal bubble” that enhances comfort and a sense of security. In contrast, bicycles and velomobiles generally lack such comprehensive protection, which has been identified as one of the factors behind why many users prefer enclosed vehicles [1].
- **Ease of entry and exit:** The amount of automotive research dedicated to optimizing ingress and egress highlights its importance in vehicle usability and user satisfaction. [8] [12] [7]. The popularity of SUVs, in part, stems from their elevated stance, which allows users to enter and exit without crouching is particularly beneficial for older adults.

5 Evaluation of Existing Concepts

5.1 Limitations of Cycle-Based Vehicles in Urban Use

The table below compares key performance and user experience parameters of E-bikes and velomobiles, grouped into three categories: efficiency, urban usability, and human factors. While both vehicle types demonstrate strong performance in terms of drivetrain efficiency, low aerodynamic drag, and compact form factors suitable for urban environments, they score notably lower on human-centered criteria. These include aspects such as protection, comfort, perceived visibility, and ease of access factors that play a significant role in perceived usability and day-to-day convenience.

Although this analysis does not establish causation, the correlation between low user adoption and poor performance on human-centered parameters is striking. It is the author's view that even without a guaranteed improvement in acceptance, addressing these user experience limitations is a worthwhile design direction that could help bridge the gap between technical efficiency and real-world desirability.

Table 5.1: Limitations of Cycle-Based Vehicles in Urban Use

Parameter	**E-Bike**	**Velomobile**
Section 1: Efficiency		
Drive train efficiency	$\geq 70\%$	$\geq 70\%$
C_d (drag coefficient)	1.1	0.15
Frontal area	0.5 m^2	0.35 m^2
Mass m	≈85 kg	≈110 kg
C_{rr} (rolling resistance)	0.004	0.004
Section 2: Urban Elements		
Width	≈ 50 cm	≈ 70 cm
Parking space requirement	≈ 1 m^2	≈ 1.5 m^2
Speed	45 kmh	45 kmh
Power-to-weight (continuous)	13 W/kg	10 W/kg
Power-to-weight (peak)	16 W/kg	13 W/kg
Section 3: Human Elements		
Feeling visible / high road	Good	bad
Feeling protected	Poor	Fair
Physical effort	Medium	Medium
Cargo & passenger capacity	Low	Fair
Weather / thermal protection	Minimal	Good
Privacy / comfort	Poor	Fair
Ease of entry / exit	Fair	Difficult

5.2 Limitations of Car for Urban Use

The table bellow highlights the performance of internal combustion engine (ICE) and electric cars across efficiency, urban suitability, and human-centered aspects. While both types of cars excel in comfort, safety, and user convenience, they face significant limitations in terms of efficiency and urban compatibility. ICE cars, in particular, suffer from very low drivetrain efficiency, while both vehicle types share drawbacks like high mass, large frontal area, and substantial parking space requirements. These factors not only reduce energy efficiency, but also exacerbate urban challenges such as traffic congestion, noise pollution, and the challenge of space scarcity in dense urban environments.

Addressing these inefficiencies is critical both for the urgent need to reduce CO_2 emissions, and the increasing strain on urban infrastructure. Optimizing for smaller, lighter, and more space-efficient vehicles could significantly alleviate traffic jams and parking shortages, while also supporting broader sustainability goals. Therefore, it should be a key focus of future mobility solutions, but as cycle based vehicle addoption show, this should not be done at the expense of user comfort and practicality.

Table 5.2: Limitations of Cycle-Based Vehicles in Urban Use

Parameter	**ICE Car**	**Electric Car**
Section 1: Efficiency		
Drive train efficiency	$\leq 30\%$	$\geq 80\%$
C_d (drag coefficient)	0.3	0.2
Frontal area	2.3 m²	2.3 m²
Mass m	≈1100 kg	≈1300 kg
C_{rr} (rolling resistance)	0.01	0.01
Section 2: Urban Elements		
Width	≈ 180 cm	≈ 180 cm
Parking space requirement	≈ 12 m²	≈ 12 m²
Speed	120 kmh	120 kmh
Power-to-weight (continuous)	50 W/kg	60 W/kg
Power-to-weight (peak)	50 W/kg	120 W/kg
Section 3: Human Elements		
Feeling visible / high road	Good	Good
Feeling protected	Good	Good
Physical effort	None	None
Cargo & passenger capacity	Good	Good
Weather / thermal protection	Good	Good
Privacy / comfort	Good	Good
Ease of entry / exit	Good	Good

5.3 Narrow Track Vehicles: Literature Overview and Modeling Considerations

As detailed in the following chapter, our proposed solution to the shortcomings of conventional urban mobility takes the form of a **Narrow Track Vehicle (NTV)**. These vehicles, which actively lean into turns, aim to combine the compact footprint and energy efficiency of two-wheelers with the stability and enclosure benefits of multi-wheeled vehicles.

Historical Background and Evolution of NTV Research

Tilting vehicles have been studied since at least the 1950s. However, significant progress in their design and implementation only emerged in the 1990s, driven by advances in control theory and numerical simulation. Increasing urban density and demand for compact mobility solutions redirected attention toward narrow-track configurations.

Today, these vehicles are referred to under various terms such as *tilting three-wheelers*, *man-wide vehicles*, or more generally, *Narrow Track Vehicles (NTVs)*. Their key characteristic is the necessity to actively manage lateral stability during dynamic maneuvers. Without tilting, such narrow vehicles are prone to roll instability and fallover during turns. Early NTV attempts frequently failed due to transient instabilities, sudden and dangerous behaviors triggered during abrupt direction changes or when encountering irregular road conditions. Such behaviors cannot be predicted by simplified static or kinematic models.

The Need for Multibody Simulation and Control

Accurate modeling of NTV dynamics requires multibody simulation. As demonstrated by Docquier [10], high-fidelity dynamic modeling is essential to capture nonlinear and transient phenomena such as tipping under rapid maneuvers, delayed responses, and steering-induced oscillations. Simplified planar models or bicycle-model approximations fall short when analyzing these effects and are insufficient for control design and geometry comparison.

Stability and handling in tilting NTVs are achieved through active control of lean angle and steering angle. Unlike conventional four-wheelers, which are statically and dynamically stable, NTVs behave more like bicycles or motorcycles. Their dynamics involve coupling between steering and roll motion and this tend to require advanced control scheme.

Control Strategies and User Interaction

Two dominant control strategies can be found in the literature:

- **Indirect tilt control**, where steering input generates roll motion via inertial and tire forces. This is typical of motorcycles and some passive or semi-active tilting trikes. The user must perform a countersteering maneuver (i.e., momentarily steering in the opposite direction) to initiate the lean and turn.
- **Direct tilt control**, where the lean angle is explicitly actuated (e.g., via hydraulic actuators or linear motors), and steering is either coupled or controlled in parallel. This allows the vehicle to follow a commanded trajectory without requiring complex rider input and may feel more natural in enclosed or drive-by-wire platforms.

Indirect control strategies rely heavily on the rider's skill and experience, while direct control strategies increase system complexity and demand robust sensor fusion, trajectory planning, and closed-loop control. Both approaches are still actively studied.

Reliability and Safety Considerations

As NTVs rely on active control to ensure lateral stability, their reliability under fault conditions is a major concern. In the event of actuator failure, power loss, or sensor dropout, the vehicle could lose its ability to stabilize itself and become hazardous.

Some concepts address this by incorporating passive fallback modes, such as mechanically locking the tilt mechanism, reverting to a stable tripod configuration, or gradually reducing speed to regain static stability. Others explore redundant actuation or degraded-mode control schemes. However, few studies systematically address fault detection, diagnosis, and safe-state transitions. More research is needed to ensure that tilting NTVs can handle real-world disturbances and hardware failures without endangering occupants or surrounding traffic.

Model Simplification for Preliminary Control Design

To avoid having to design a dynamic controller, as this is very time consumming and would justify it's own semester or master project, we simplify the problem by demonstrating the existence of a steady-state controller for straight-line motion and constant-radius turns using simple tuned PID. While this does not capture transient or disturbance behavior, it will allow to compute some metrics to start comparing the designs.

Performance Metrics for Dynamic Comparison

Once a basic control scheme is in place, it becomes possible to assess and compare different vehicle architectures based on dynamic performance. However, due to the simplified nature of our current model and the lack of a full feedback controller, only a subset of these metrics can be meaningfully evaluated at this stage.

The following categories illustrate typical metrics used in the literature to evaluate tilting NTVs:

- **existence of steady state stability:** For a given vehicle speed and heading, we show that by tunning a PID, the vehicle can be stabilised. It is not a definitive proof; however, it helps identify the most promising designs.
- **Roll Angle vs. Turn Radius:** For a given vehicle speed, the required steady-state roll angle to maintain a stable corner is a function of geometry and mass distribution. This can be derived analytically and used to evaluate how much lean is needed in typical maneuvers. This is done in section 7.
- **Steady-State Control Effort:** The required steering or tilt input torque under steady cornering provides insight into actuator sizing and energy efficiency. These values are geometry-dependent and can be computed under the assumption of ideal controllers.
- **Cornering Stability Margin:** This refers to the difference between the equilibrium lean angle and the critical tipping angle. It provides a static safety margin but does not account for transient or delayed responses.
- **Transient Recovery Time and Overshoot:** These metrics, which assess how quickly and smoothly a system responds to changes in command or disturbances, require a full dynamic controller to simulate and are therefore not addressed in this initial study. However, they are essential for understanding rider comfort and system robustness in a final implementation.
- **Disturbance Rejection and Fault Resilience:** Evaluating how the system responds to crosswinds, road bumps, or sensor noise also necessitates a closed-loop controller with disturbance modeling. These factors play a critical role in real-world safety but cannot be fully quantified at this stage.
- **Natural Frequency and Damping of Lean Oscillations:** These can provide insight into the passive dynamics of the vehicle frame and its propensity for wobble or instability. This will not be measured due to time constraint.

In summary, while many of the most informative performance metrics require a full closed-loop control system to simulate realistically, geometry-dependent indicators like roll angle requirements and equilibrium tipping margins can still offer valuable early insight. These form the basis for comparative studies between NTV designs prior to full control implementation. Once a dynamic controller is available, more complete evaluation including maneuverability, ride comfort, and fault handling become possible.

6 Proposed Designs

Our design aims to retain the high energy efficiency potential demonstrated in Section 2, while integrating the urban constraints discussed in Section 3 and the user requirements outlined in Section 4. The result is a narrow, lightweight, enclosed vehicle conceptually close to a cycle.

1. Efficiency: By minimizing mass and frontal area, using low rolling resistance wheels, and optimizing aerodynamics (target $C_d \approx 0.15$), the proposed vehicle matches the energy performance of state-of-the-art velomobiles and outperforms an electric car and an ICE car by a factor of 10 and 50, respectively, on an efficiency level.

2. Human experience: Unlike velomobiles or e-bikes, this concept improves rider visibility and perceived safety by raising the riding position without compromising stability, thanks to a leaning mechanism. This system also simplifies ingress and egress (the vehicle tilts forward to assist the user) and allows for vertical parking, improving usability in dense urban settings.

3. Urban compatibility: The vehicle occupies far less road and parking space than a car, and remains legally within bicycle limits, allowing access to bike lanes while being able to keep up with traffic.

Although existing solutions will be examined in more detail later, we can see that :
E-bikes and velomobiles often come short from a user standpoint, as they fail to address minimal comfort and safety requirement. While **Cars**, on the other hand, fail on efficiency and urban integration by being oversized in both energy and space usage.

Here, the two main parameters of the design space that we will study on a dynamic standpoint are presented: the choice between a three or four-wheel configuration (figure 6.1), and two leaning mechanisms (figure 6.2) that use either pivot arm vs. linear-guided suspension to ensure stability while enabling an elevated riding position.

Figure 6.3 highlights how the proposed layout benefits egress/ingress and vertical storage by allowing to recline the seat and let the user easily redress the vehicle.

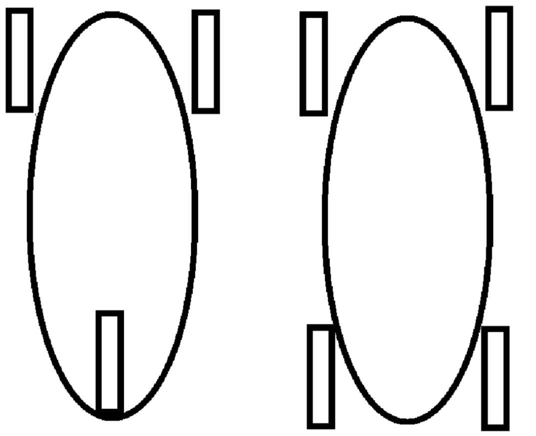


Figure 6.1: Three and Four wheeler configuration

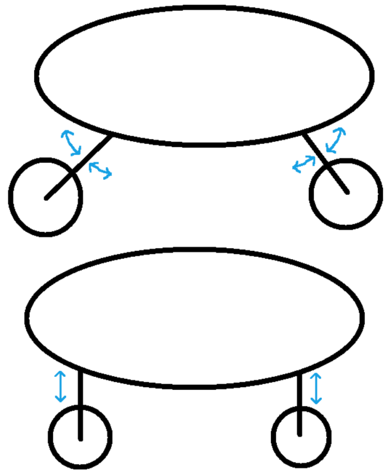


Figure 6.2: Leaning mechanism based either on a pivot or a linear-guided suspension

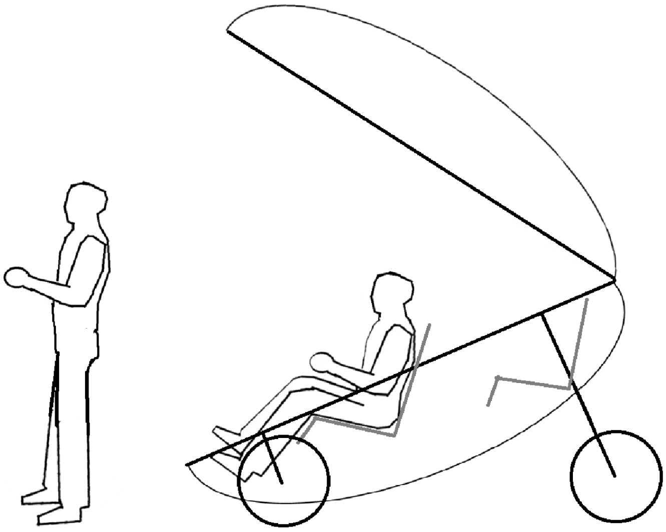


Figure 6.3: Simplified Egress and vertical parking

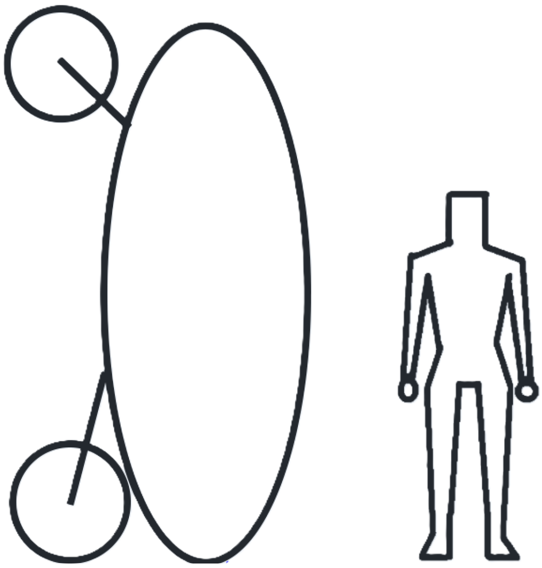


Figure 6.4: parked configuration of the proposed design

6.1 Comparative Evaluation

The proposed design consistently scores higher across efficiency, urban integration, and human experience compared to both cars and cycle-based alternatives. By combining a compact footprint with enhanced protection and usability, it bridges the gap between comfort and sustainability. However, this performance comes at the cost of increased mechanical and control complexity, inherent to narrow-track vehicles. To address these challenges, we evaluate multiple mechanical configurations, including three-wheel and four-wheel variants, as well as different leaning actuation strategies based on linear actuators or pivot mechanisms. These configurations will be analyzed both from a static standpoint to assess tipping stability and from a dynamic perspective. The following chapters dive into these aspects, starting with the analysis of static behavior before transitioning to the more demanding problem of dynamic stabilization and control.

Table 6.1: Performance Comparison

Parameter	E-Bike	Velomobile	ICE Car	Electric Car	Proposed Design
Section 1: Efficiency					
Drive train efficiency	$\geq 70\%$	$\geq 70\%$	$\leq 30\%$	$\geq 80\%$	$\geq 80\%$
C_d (drag coefficient)	1	0.15	0.3	0.2	0.15
Frontal area (m^2)	0.5	0.35	2.3	2.3	$\leq$0.7
Mass m (kg)	85	110	1100	1300	<250
C_{rr} (rolling resistance)	0.004	0.004	0.01	0.01	0.004
Section 2: Urban Elements					
Width (cm)	50	70	180	180	<70
Parking space (m^2)	1	1.5	12	12	$\approx$0.7
Speed (km/h)	45	45	120	120	60-80
Power-to-weight (continuous)	13 W/kg	10 W/kg	50 W/kg	60 W/kg	1–25W/kg^*
Power-to-weight (peak)	16 W/kg	13 W/kg	50 W/kg	120 W/kg	60 W/kg
Section 3: Human Elements					
Feeling visible / high road	Good	Bad	Good	Good	Good
Feeling protected	Poor	Fair	Good	Good	Good
Physical effort	Medium	Medium	None	None	minimal & Constant
Cargo & passenger capacity	Low	Fair	Good	Good	2 adult or 4-5 bag
Weather / thermal protection	Minimal	Good	Good	Good	Good
Privacy / comfort	Poor	Fair	Good	Good	Good
Ease of entry / exit	Fair	Difficult	Good	Good	Front-tilt, upright

Note on Power-to-Weight Ratio (*): The continuous power-to-weight ratio marked with an asterisk refers to the average sustained power a person can provide, typically around **1 W/kg**. This estimate is sufficient for flat terrain and steady-state cruising, where only aerodynamic and rolling resistance need to be overcome.

While slope climbing and acceleration phases require much higher instantaneous power, up to **25 W/kg**, the energy spent climbing is largely recovered when descending. As a result, over the course of a typical ride, elevation changes and accelerations tend to cancel out in terms of net energy expenditure assuming the losses are compensated.

Therefore, even though higher peak power is occasionally needed, a continuous input of **1 W/kg** is generally enough to sustain average cruising performance, effectively allowing the user to achieve what would otherwise require a **25 W/kg** system, provided that energy buffering (e.g., a battery or gravity) absorbs the transient demands.

7 Static Behavior and control margin

Computing the control margin is essential to understand how much the effective resultant vector at the vehicle's center of mass (CoM) influenced by gravity, road slope, and centrifugal forces can vary before the vehicle tips over. This margin quantifies the allowable tilt angle range within which the vehicle remains stable. The leaning controller continuously adjusts the vehicle's tilt to keep it safely within this window, maintaining enough margin on each side so it has sufficient time to react to disturbances. Properly sizing this stability margin is critical because it directly informs the required response speed of the actuator responsible for leaning control, ensuring the vehicle remains balanced under dynamic conditions.

The vehicle tips over when:

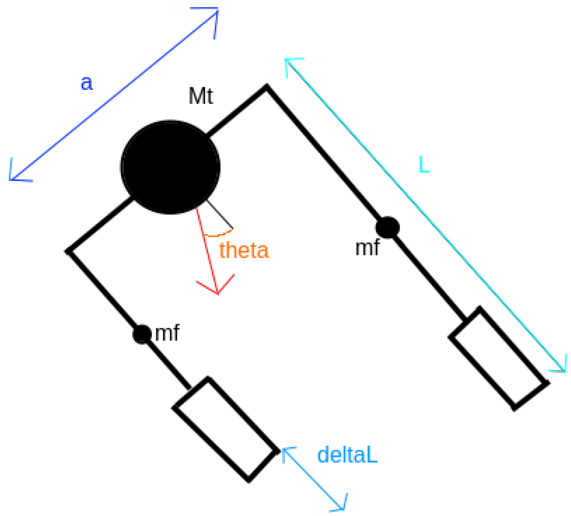


Figure 7.1: Simplified model of vehicle tipping point

$$\tan\left(\arctan\left(\frac{\delta L}{a}\right) + \theta\right) > \frac{a(M_t + 4m_f)}{2((M_t + 2m_f)L - m_f\delta L)}$$

Parameter Definitions

- a: Horizontal distance between the legs (along the tipping direction).
- δL: Height difference between the long and short legs.
- L: Length of the longer legs.
- M_t: Mass of the vehicle cabin.
- m_f: Mass of each leg+wheel (assumed identical for all four legs).
- θ: Angle between the resulting vector on the CoM and the normal of the plane made by the top of the leg, in the tipping direction. This helps to model the gravity if the road is sloped and the centrifugal acceleration:
  - $\theta > 0$: tipping is more likely.
  - $\theta < 0$: tipping is resisted.

we can then compute the stability margin on each side with the following.

$$\theta_{\text{critical,left}} = \arctan\left(\frac{a(M_t + 4m_f)}{2((M_t + 2m_f)L - m_f\delta L)}\right) - \arctan\left(\frac{\delta L}{a}\right)$$
$$\theta_{\text{critical,right}} = \arctan\left(-\frac{a(M_t + 4m_f)}{2((M_t + 2m_f)L - m_f\delta L)}\right) + \arctan\left(\frac{\delta L}{a}\right)$$

$$\text{Stability margin on left side} = \theta_{\text{critical,left}} - \theta$$
$$\text{Stability margin on right side} = \theta - \theta_{\text{critical,right}}$$

Unsurprisingly, to maximize the stability margin, we should make the vehicle as wide as possible and keep the height of the center of mass as low as possible. But as always it's a matter of tradeoff, the final stability margin will be given by the controller, and thus we can tune these parameters to have just what is necessary to avoid losing the benefit of having a NTV. If needed, we could make the leg deploy sideways instead of along the body to temporarily increase the width of the vehicle and thus when the system leans the margin also increases. But this is mechanically more complicated as it requires keeping the mechanical trail constant and wheel plane parallel if we want to avoid adding more non-linear coupling, which make the controller more complicated.

8 Dynamic Behavior and Control

Tilting Narrow Track Vehicles (NTVs) with a high center of mass (CoM) are inherently unstable, necessitating active stabilization to remain upright and controllable. Due to time constraints, a full dynamic controller is beyond the scope of this work. Instead, we demonstrate the viability of steady-state stabilization using a tuned PID controller to maintain balance during straight-line travel and constant-radius turns. The primary goal is to compare the dynamic response of multiple design variants, specifically 3-wheel versus 4-wheel layouts, and rotational versus linear tilt arm mechanisms, under two representative conditions. This results in a total of 8 simulated scenarios. Each simulation is treated as a steady-state configuration, with basic PID control used to stabilize the lean angle. While this does not capture transient or disturbance responses, it is sufficient to evaluate geometry-dependent trends and identify promising configurations for further development.

8.1 Methodology

The simulation framework was built using PyBullet, a real-time physics engine. Each vehicle configuration was modeled using a URDF file that specifies link geometry, mass distribution, and joint constraints. Four base configurations were created by combining two platform layouts (three-wheel and four-wheel) with two leaning mechanisms (pivot-based and linear-guided). Each of these was simulated under two scenarios: straight-line motion and constant-radius turning, yielding eight unique scenarios. The straight line scenario occurred on a bumpy surface, while the curved scenario operated on a flat surface.

For each configuration, the lean angle was controlled via a custom PID controller implemented in the simulation loop. The system was initialized at rest and brought to a constant velocity. For turning scenarios, a fixed-radius turn was imposed by constraining the trajectory. The controller was responsible for adjusting the lean angle to balance centrifugal forces during turning or gravitational instability during straight-line motion.

All simulations recorded joint states (position, velocity, acceleration) and key global metrics such as vehicle lean angle, lateral deviation, and applied control torque. Screenshots of each configuration were captured to document visual differences and posture under dynamic conditions.

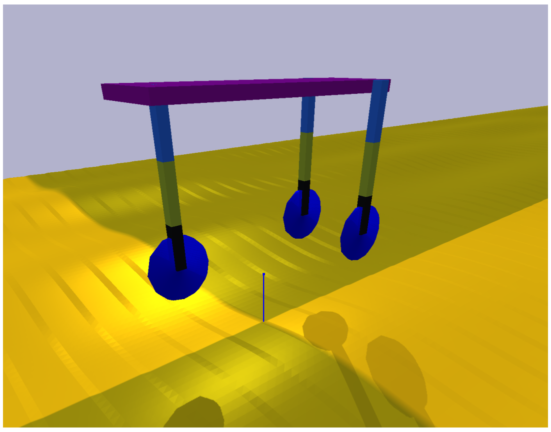
8.2 Implementation

Each vehicle model is defined using a modular URDF structure, with separate subtrees for chassis, suspension, and lean mechanism. The joint-level PID controller operates within the PyBullet simulation loop at a frequency of 240 Hz. The control law follows:

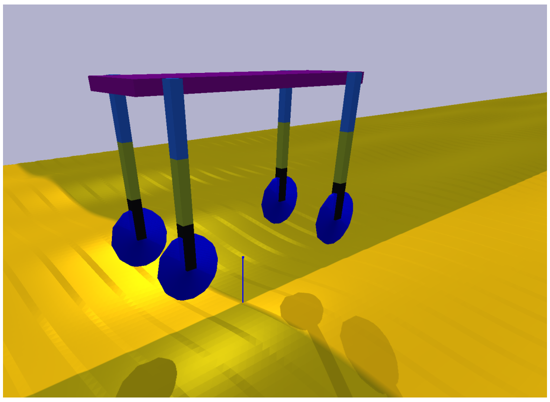
$$\tau = K_p(\theta_{\text{desired}} - \theta) + K_d(\dot{\theta}_{\text{desired}} - \dot{\theta}) + K_i \int (\theta_{\text{desired}} - \theta)\, dt$$

where τ is the control torque, θ is the lean joint state, and $\dot{\theta}$ is its velocity. Gains K_p, K_i, and K_d were manually tuned for each configuration to achieve stable convergence and minimize oscillation.

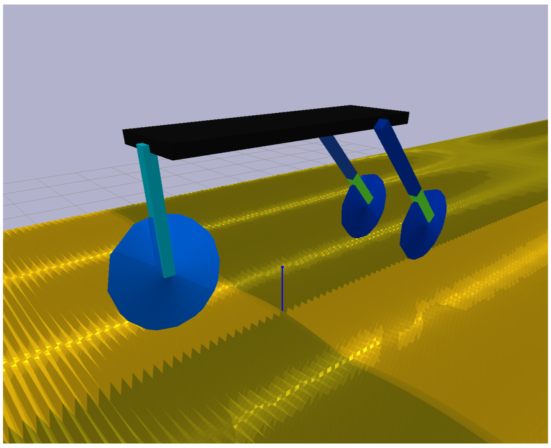
Data was logged for plotting and post-processing. Camera control was implemented to enable 3D inspection of vehicle motion and stability during runtime, facilitating visual validation of lean behavior and dynamic posture. The figure 8.1 show how the different configuration were implemented in pybullet. The Base mass was set to 100 [kg] while the wheel and segment mass were set to 1 [kg] to emphasize the high CoM.



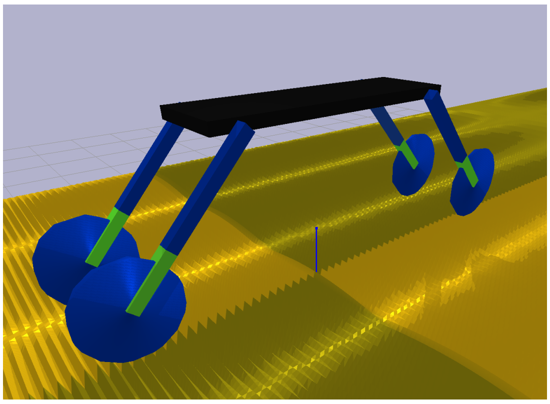
(a) Three Wheeler With Linear Actuator



(b) Four Wheeler With Linear Actuator



(c) Three Wheeler With Pivot Actuator



(d) Four Wheeler With Pivot Actuator

Figure 8.1: Comparison of Linear and Pivot Actuated Configurations for Three- and Four-Wheel Designs

8.3 Results

To assess the dynamic behavior of each configuration, we evaluated their ability to maintain stability under straight-line and constant-radius turning using PID control. Below is a summary of the observed behavior for each of the four combinations of chassis layout (3-wheel vs. 4-wheel) and lean mechanism (pivot vs. linear actuator):

In the pivot-based configurations, especially the 3-wheel version, we observed a strong tendency for wheels to lock inward or outward due to mass loading, as shown in Figure 8.2. This arises from the geometry of the pivot as the mass of the cockpit presses on the leg, which finds a new minimum by having both wheel going inward or outward. If one tries to mitigate the issue by increasing the spring constant of the wheel pivot, the vehicle is not able to turn smoothly and slips instead.

This behavior makes the pivot-based system unsuitable for high-speed or open-loop control.

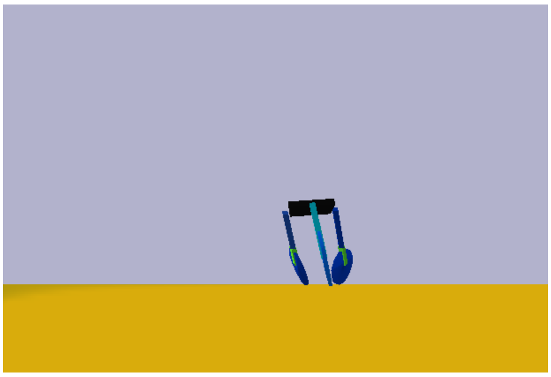


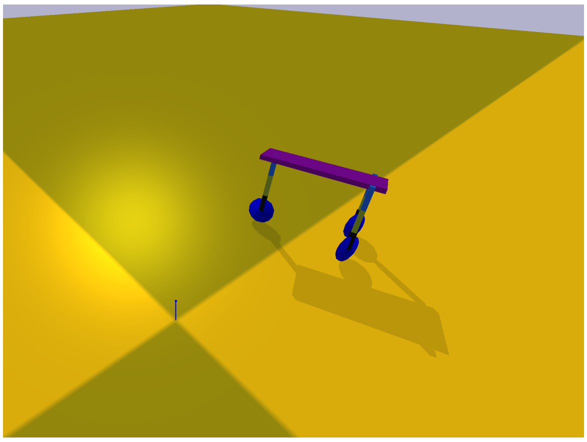
Figure 8.2: Wheel inward locking behavior in pivot-based designs

Furthermore, for both systems, the mechanical trail behind the pivot axis improves stability, which is consistent with known self-aligning behaviors in caster-like systems.

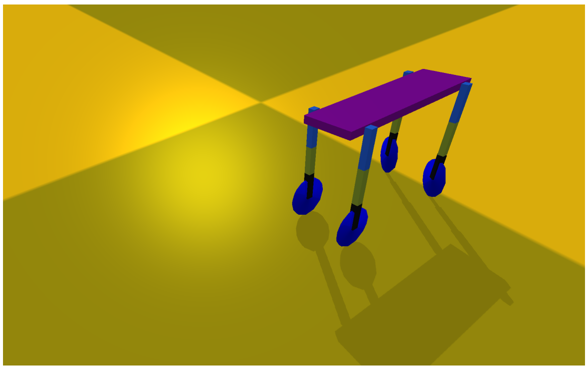
Both linear actuator variants (3- and 4-wheel) responded well to PID control in maintaining lean stability. Wheel wobble emerged at high speeds, particularly in the 3-wheel variant, but was manageable with increased damping and should likely be solved with a controller that adapts the wheel speed to creates a canceling moment. Both the three wheel and four wheel linear actuator variant performed equally well. The four wheel variant has the advantage of allowing the loss of one of the actuator and thus offers some redundancy.

Figure 8.3a and Figure 8.3b show that it is possible to stabilize a steady state turn of the linear actuator based lean control during steady-state turning and straight line driving.

The plot showing the position, speed, acceleration of each element offered limited results except to help tune the PID by looking at the response.



(a) Three-wheel linear actuator turning



(b) Four-wheel linear actuator turning

Figure 8.3: Successful steady-state turning in linear actuator configurations

	Pivot Mechanism	Linear Actuator
3-Wheel	- Wheels tend to lock inward/outward - Unstable	- Less moving parts - Capable of steady-state turning - Requires speed differential control
4-Wheel	- Wheels tend to lock inward/outward - Unstable - Cannot turn with four free caster wheels	- Most stable configuration - Capable of steady-state turning - Requires speed differential control - Cannot turn with four free caster wheels

Table 8.1: Qualitative behavior observed in the four configurations

These results suggest that a high-CoM tilting vehicle can be stabilized, provided the mechanical layout don't add too many non-linear coupling and independent wheel speed control is available.

9 Conclusion and Future Work

9.1 Summary of Findings

This project defined three main objectives: to analyze the constraints on urban vehicle design from an efficiency, urban, and human standpoint; to propose a better trade-off between efficiency and usability; and to validate the feasibility of such a design using modeling and simulation.

Each of these objectives was addressed. The constraint analysis identified key trade-offs in mass, drag, power, spatial footprint, and user acceptance. Based on these insights, a novel narrow-track vehicle was proposed that aims to combine the strengths of both e-bikes and compact cars.

The proposed design demonstrates high energy efficiency through minimized mass and drag, strong urban integration thanks to its narrow footprint and vertical parking capability, and improved user experience by offering protection, cargo capacity, and a raised cockpit. The final configuration features:

- A lightweight chassis with minimized frontal area and drag coefficient;
- A tandem seating layout with reclining assistance for ingress/egress and vertical parking;
- A leaning mechanism ensuring stability during turns while maintaining a raised riding posture.

Comparative analysis confirmed that the design outperforms conventional vehicles in urban settings on key metrics. Dynamic simulations using PyBullet verified that the proposed geometry can be stabilized under realistic conditions with a basic PID controller. Especially in the four-wheel linear actuator configuration.

Overall, this project provides a compelling argument, both theoretical and in simulation, for the viability of a new vehicle class optimized for urban mobility.

9.2 Challenges and Limitations

Despite promising theoretical and simulation-based results, several considerations limit the direct applicability of the current work:

- **Dynamic control:** Only steady-state PID stabilization was implemented. Real-world usage involves transient events, disturbances, and sensor uncertainties, which demand more sophisticated closed-loop control and fault-tolerant designs.
- **Mechanical feasibility:** While linear-guided leaning mechanisms outperformed pivot-based alternatives in simulation, their real-world mechanical complexity, cost, and maintainability remain untested.
- **No hardware validation:** All results are based on models and simulations. No physical prototype was built, and thus, no experimental validation of control strategies, ergonomic features, or energy efficiency has yet been conducted.
- **Crash safety and passive protection:** Although the low speed and mass reduces collision severity, structural safety under lateral or frontal impact remains unquantified.
- **Interaction with real traffic:** Human behavior and inter-vehicle dynamics in mixed-traffic conditions (e.g., filtering at red lights, occupying bike lanes) are not yet modeled. The impact on traffic flow and perceived safety needs further investigation.

9.3 Suggestions for Future Research

Several open questions and directions emerge from this work:

1. **Prototype Development and Validation:** A functional prototype should be developed to verify the theoretical and simulation results, particularly on:
    - Real-world lean stabilization and ride dynamics;
    - Human factors, including ingress/egress, comfort, visibility;
    - Energy consumption and thermal comfort under typical urban trips.
2. **Comparative Geometry Study:** A systematic comparison with "classic" narrow-track geometries (e.g., non-leaning or passive tilting) should be conducted to establish whether the proposed design is not just feasible, but measurably superior in terms of:
    - Stability margins;
    - Actuator energy demands;
    - User acceptance and safety perception.
3. **Crash Safety and Passive Design Elements:** Safety under collision (especially lateral and rear impact) should be analyzed via finite element analysis or physical crash testing as by its very lightweight nature the vehicle might likely be thrown upon impact from a car.
4. **Urban Traffic Impact Modeling:** If widely adopted, how would such vehicles influence urban traffic? Questions include:
    - Would their ability to skip queue via bike lane reduce average trip times while not impacting the car ?
    - Would it induce positive or negative safety outcomes in mixed traffic?
    - Could dedicated microvehicle lanes be justified ?
5. **Integration into Multimodal Transport:** The potential to "train-board" the vehicle similar to folding bikes warrants study. The rational being that this vehicle would solve the last kilometers problem but is not able to replace the car on long distance trips. Train onboarding might solve that problem. Questions include:
    - What dimensions and weight constraints would be required?
    - Could this reduce the need for park-and-ride infrastructure?
    - What energy/time savings would result from combining short and long-range trips?
6. **Legal and Regulatory Pathfinding:** Further investigation into the legal classification (e.g., whether such a vehicle qualifies as a cycle) and its implications on insurance, road access, and subsidies is essential for deployment.
7. **Actuator Failure and Redundancy:** Given the dependence on active stabilization, future work must address fault tolerance:
    - Can a passive fallback stabilize the vehicle at low speeds?
    - Can wheel differentials be used to passively reorient the lean?

In conclusion, while the proposed design offers a compelling vision for sustainable, compact urban mobility, transforming this vision into reality requires further exploration.

10 Appendix

10.1 Daily kilometers average

on average, less than 5 trips per day

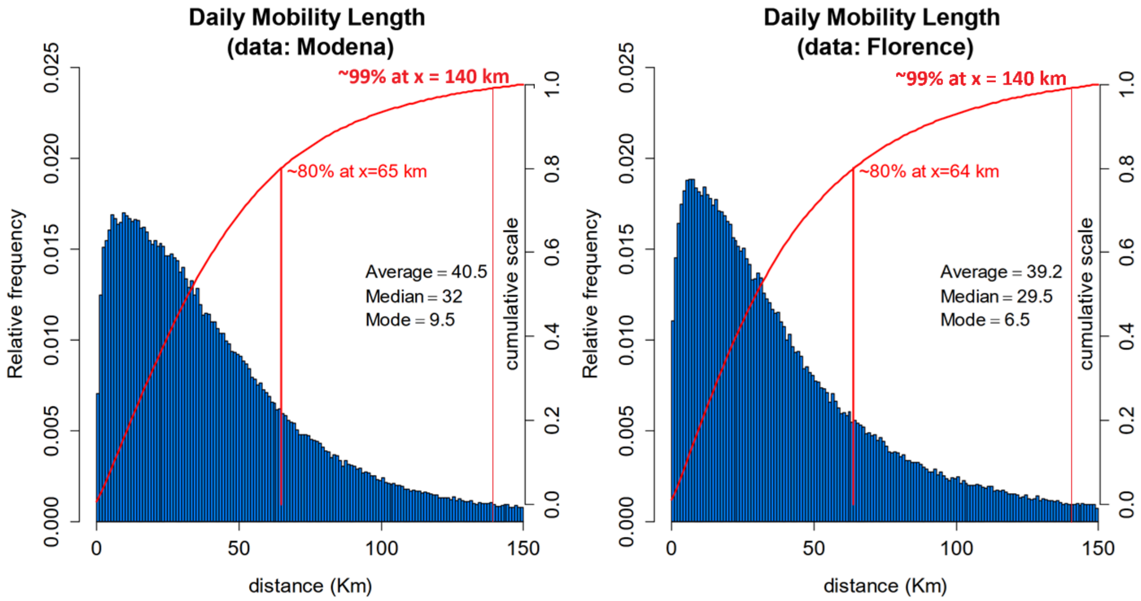


Figure 10.1: Relative frequency (bar) and cumulative (red, solid) distributions of daily mobility distance (from Donati 2015[11])

10.2 Source code of the simulation

All the code is available on GitHub at : github.com/nathmo/DynamicSimulation

10.3 logbook

2025-02-20 Creation of this report, rough layout of the idea in chapter

2025-02-25 Longitudinal kinematic model, research about markov modelling and cycle

2025-02-26 dynamic simulation creation, implemented a basic simulation in pybullet with keybaord navigation and parametric surface + wheel rolling down

2025-02-27 refining efficiency to take into account whole cycle, reading paper

2025-02-28 Writing Idea about improving efficiency trough identified parameters

2025-03-04 Adding graph about car occupancy and real world driving needs + reading paper

2025-03-06 Brainstorming kinematic, reading PHd thesis on narrow track

2025-03-09 URDF is a PAIN to implement to due lack of tool, trying to define a kinematic model in python

2025-03-11 reworking part of chapter 2

2025-03-17 reading paper about cars and bike and limiting factor to adoption

2025-03-18 keep reading paper, also about narrow track vehicle

2025-03-20 trying to structure what I learned from the papers

2025-03-21 defining the know unknown about car adoption factor (human side)

2025-03-24 Clarifying the project goal

2025-03-27 draw figure, added citation

2025-03-28 Manual definition is an epic failure... Two way (createMultiBody -¿ Works but hard to read), Create body and add constraint don't work (rotation constraint crash the simulation.)

2025-04-09 Realized that createMultibody is more stable but has a "ghost" friction problem, Might as well use URDF then.

2025-04-10 learning URDF and how the origin is defined,

2025-05-25 redefined most variant as URDF and how to simulate them. Need spend time to implement basic controller like PID to show steady state stability and control margin

2025-05-28 Meeting, dry run presentation and shown current status.

2025-05-31 Report restructuring, writing

2025-06-02 Chapter 4, 5, 6 writing

2025-06-04 Getting simulation result, finishing first draft of report.

2025-06-08 Proof reading

References

[1] From 'freedom of the open road' to 'cocooning': Understanding resistance to change in personal private automobility | Request PDF. *ResearchGate*.

[2] How many Gs do we feel driving a car?

[3] Regenerative Braking - an overview | ScienceDirect Topics.

[4] RS 741.41 - Ordonnance du 19 juin 1995 concernan... | Fedlex.

[5] Riding High: Auto Makers Jack Up the Car Seat - WSJ.com, May 2008.

[6] Alberto Castro, Mailin Gaupp-Berghausen, Evi Dons, Arnout Standaert, Michelle Laeremans, Anna Clark, Esther Anaya-Boig, Tom Cole-Hunter, Ione Avila-Palencia, David Rojas-Rueda, Mark Nieuwenhuijsen, Regine Gerike, Luc Int Panis, Audrey de Nazelle, Christian Brand, Elisabeth Raser, Sonja Kahlmeier, and Thomas Götschi. Physical activity of electric bicycle users compared to conventional bicycle users and non-cyclists: Insights based on health and transport data from an online survey in seven European cities. *Transportation Research Interdisciplinary Perspectives*, 1:100017, June 2019.

[7] Julien Causse, Elodie Chateauroux, Gilles Monnier, Xuguang Wang, and Lisa Denninger. Dynamic Analysis of Car Ingress/Egress Movement: an Experimental Protocol and Preliminary Results. *SAE International Journal of Passenger Cars - Mechanical Systems*, 2:1633–1640, October 2009.

[8] Julien Causse, Xuguang Wang, and Lisa Denninger. Effects of roof height on car ingress/egress movement. 06 2011.

[9] 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.

[10] Quentin Docquier. Dynamic Analysis and Control of Narrow Track Vehicles via a Multibody Modeling Approach.

[11] 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.

[12] J. Giacomin and S. Quattrocolo. An analysis of human comfort when entering and exiting the rear seat of an automobile. *Applied Ergonomics*, 28(5-6):397–406, 1997.

[13] Henning Lohse-Busch, Michael Duoba, Eric Rask, Kevin Stutenberg, Vivek Gowri, Lee Slezak, and David Anderson. Ambient Temperature (20°F, 72°F and 95°F) Impact on Fuel and Energy Consumption for Several Conventional Vehicles, Hybrid and Plug-In Hybrid Electric Vehicles and Battery Electric Vehicle. pages 2013–01–1462, April 2013.

[14] Ruoyun Ma, Xiaoyi He, Yali Zheng, Boya Zhou, Sheng Lu, and Ye Wu. Real-world driving cycles and energy consumption informed by large-sized vehicle trajectory data. *Journal of Cleaner Production*, 223:564–574, June 2019.

[15] Dimitri Marincek. Comparing E-Bike Users' Perceptions of Safety: The Case of Lausanne, Switzerland. *Active Travel Studies*, 3(1), January 2023. Number: 1 Publisher: University of Westminster Press.

[16] Max Nankervis. The effect of weather and climate on bicycle commuting. *Transportation Research Part A: Policy and Practice*, 33(6):417–431, August 1999.

[17] OAR US EPA. Carbon Pollution from Transportation, September 2015.