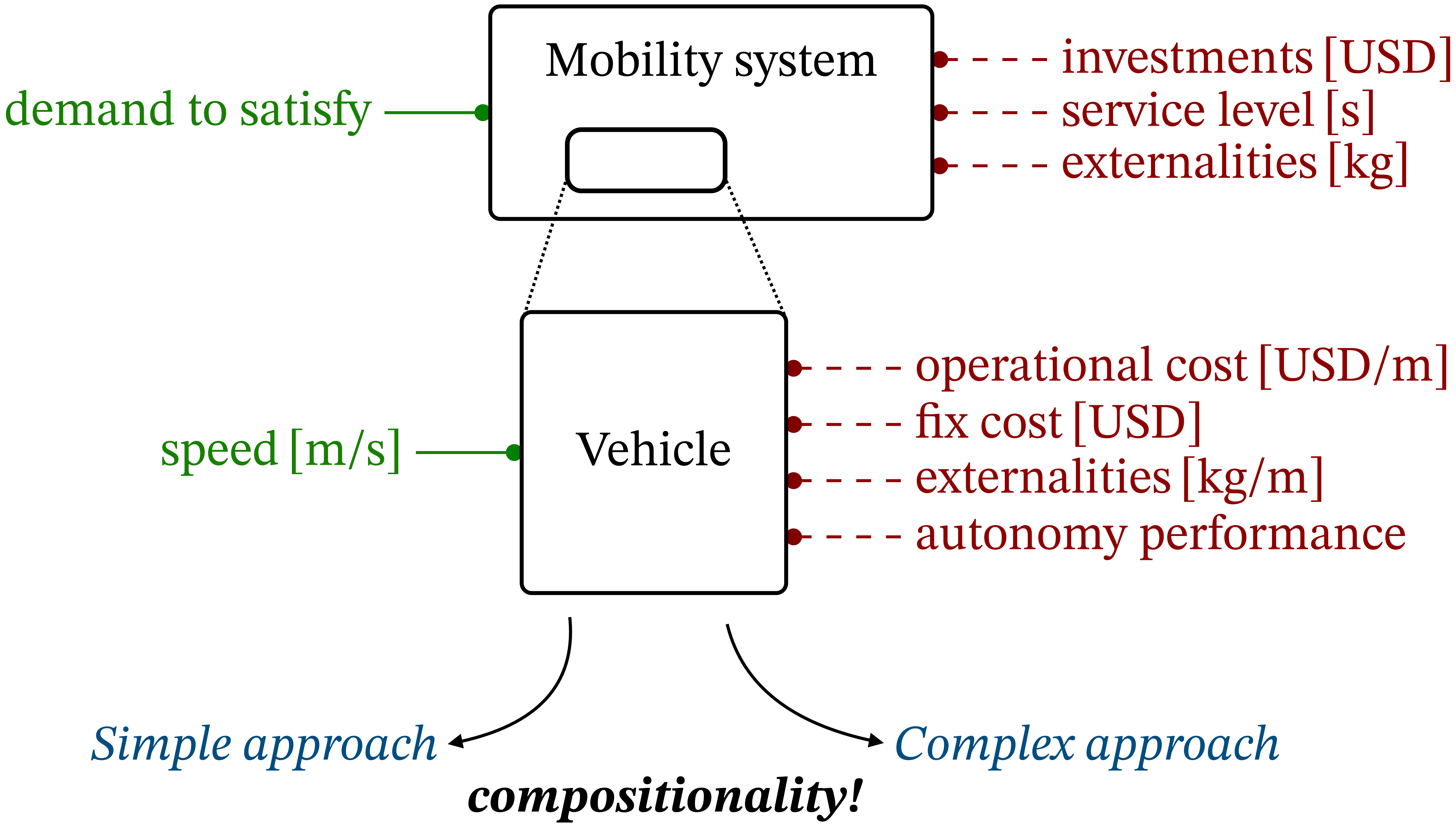
Application: Co-design of future mobility systems

- **Now**: Co-design of vehicle and future mobility systems
  - Co-Design to Enable User-Friendly Tools to Assess the Impact of Future Mobility Solutions
  - Co-Design of Embodied Intelligence: A Structured Approach

- **Takeways:**
  - Using co-design, it is easy to formalize **hierarchical models** (never possible before)
  - Very **intuitive** modeling approach (no "acrobatics" needed)
  - **Rich modeling capabilities**: analytic models, catalogues, simulations
  - **Compositionality** and **modularity** allow **interdisciplinary collaboration**
  - Co-design produces **actionable information** for designers to **reason** about their problems

Co-design of vehicle and future mobility systems

- Co-Design to Enable User-Friendly Tools to Assess the Impact of Future Mobility Solutions
  - We co-design **intermodal mobility solutions** (AVs, micromobility) with the **infrastructure** (trains, roads)
- Co-Design of Embodied Intelligence: A Structured Approach
  - We co-design an AV, all the way from **hardware** (vehicle, sensors, computers, ..) to **software** (perception, control, ..) components



Co-design of future mobility systems

- We look at the problem from the perspective of **municipalities** and **policy makers**
  - Important decisions to make:

    How many AVs should we allow?

    What's the influence of AVs on public transit systems?

    How performant should AVs be?

    How many trains should we buy?

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    How performant should they be? *How many trains should we buy?*

- Existing work only solves **specific problems** and does not **co-design** the whole system:
  - No **joint** design of **mobility solutions** and the **system** they enable
  - No **modularity** and **compositionality**: problem-specific
  - Often, not producing **actionable information** for stakeholders

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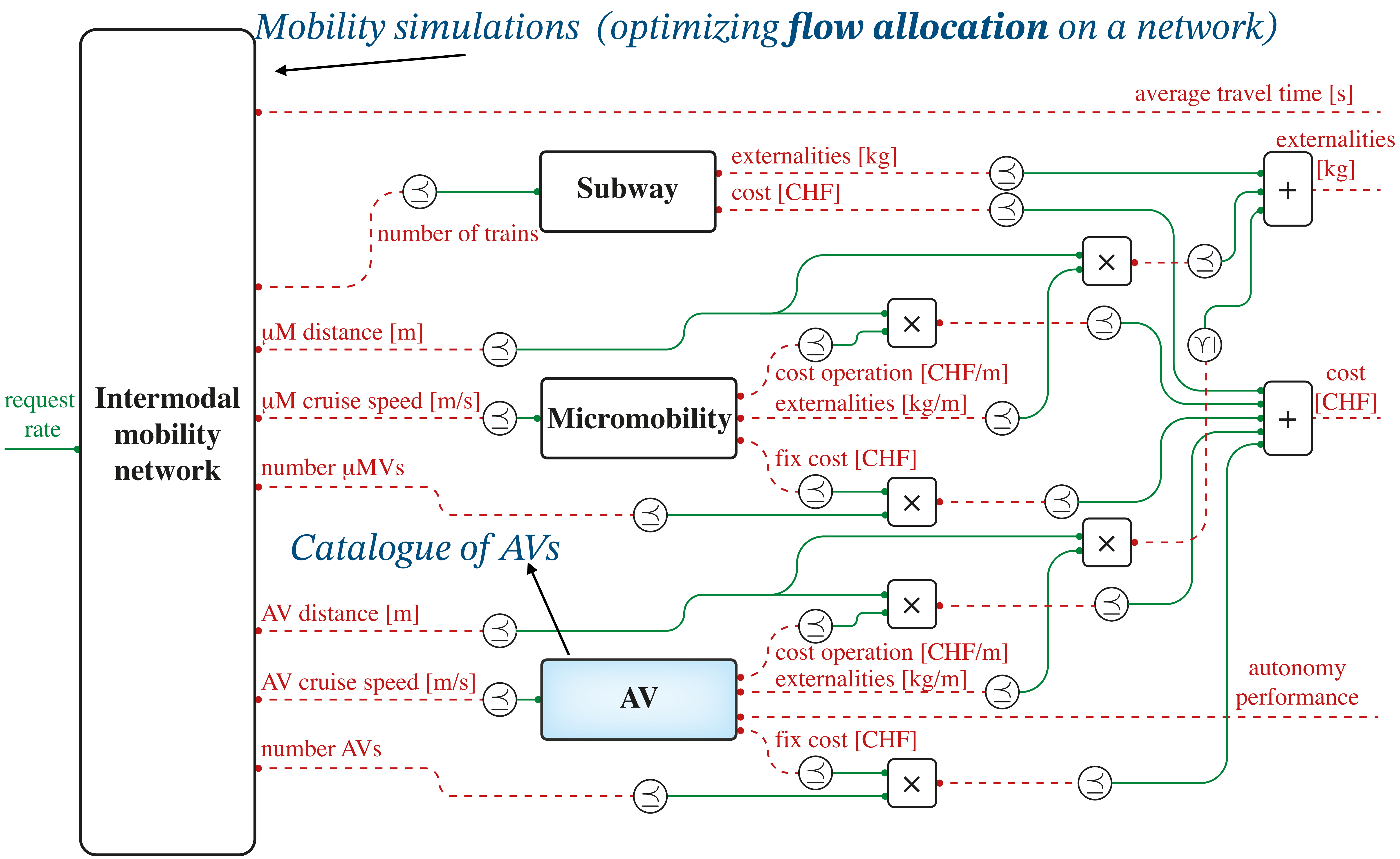
- Several **disciplines** involved (transportation science, autonomy, economics, policy-making)

- We allow **interfaces** between them via **co-design**:
  - **Functionality**: **demand** to be satisfied
  - **Costs**: **investments** ($), **externalities** ($CO_2$ kg), **service level** (average waiting time, s)

- Co-design highlights the **structure** of the problem and provides **tools** to reason about it

Modeling the mobility system as a co-design problem

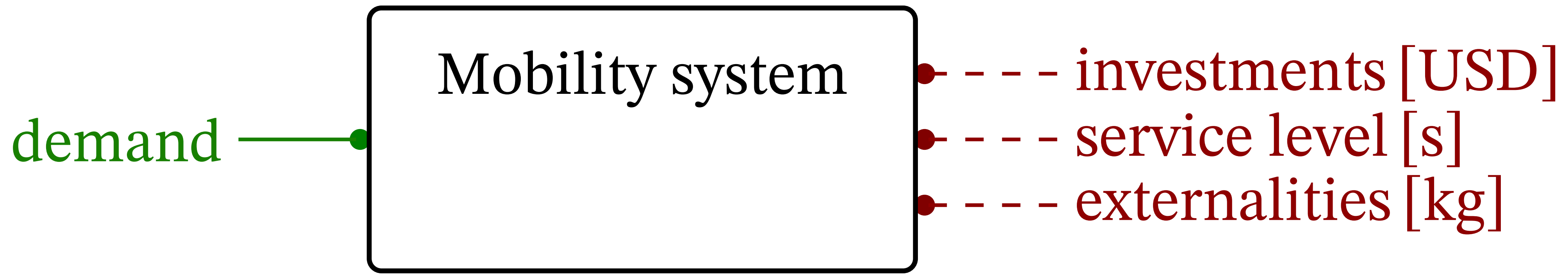


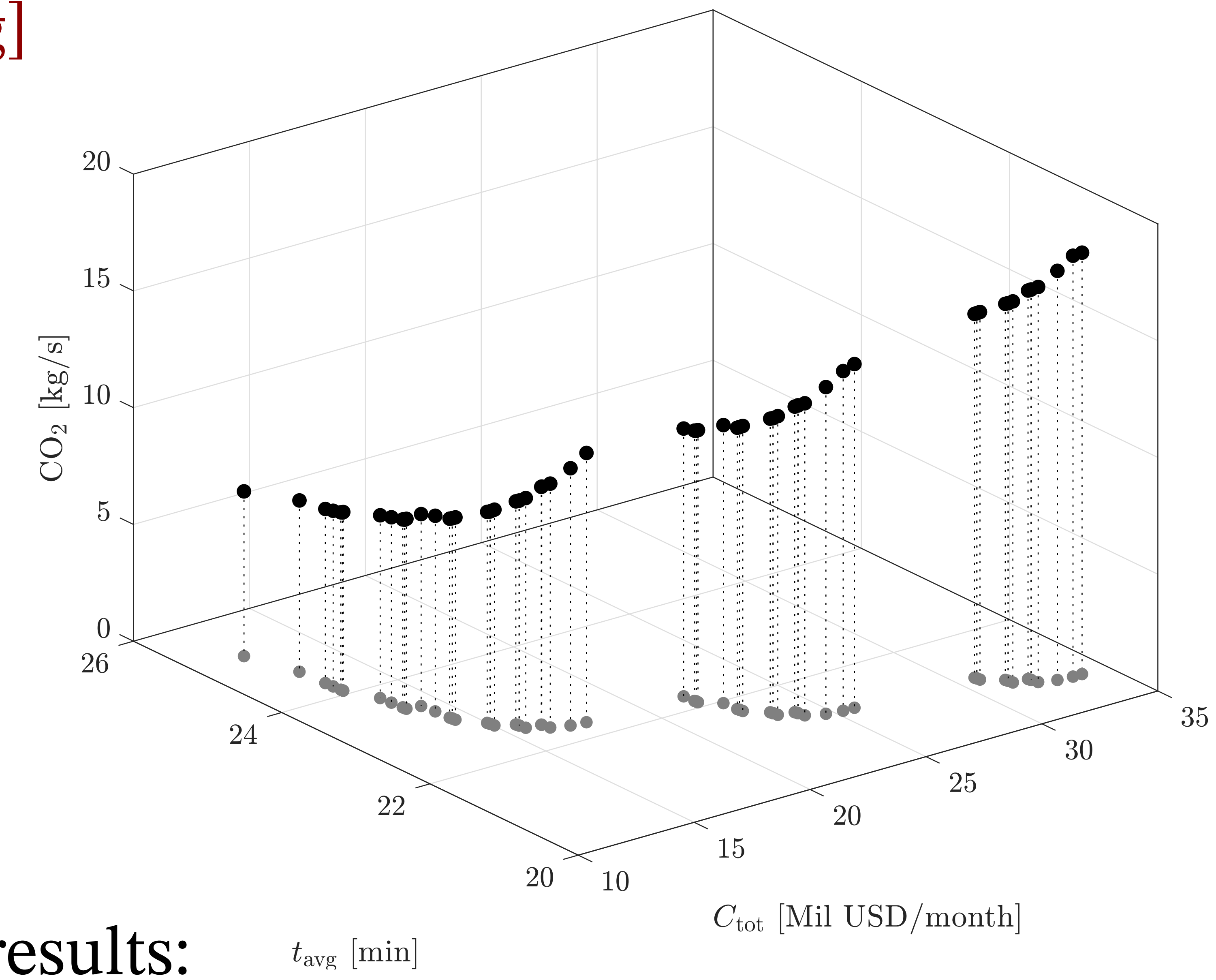
Subway:
Fun: *number* of trains to buy
Res: *costs* and *externalities*
Imp: acquisition *contracts*

Micromobility:
Fun: *speed* of the vehicle
Res: costs and *externalities*
Imp: vehicle *models*

AV:
Fun: *speed* of the vehicle
Res: costs, *externalities, performance*
Imp: vehicle *models* and autonomy

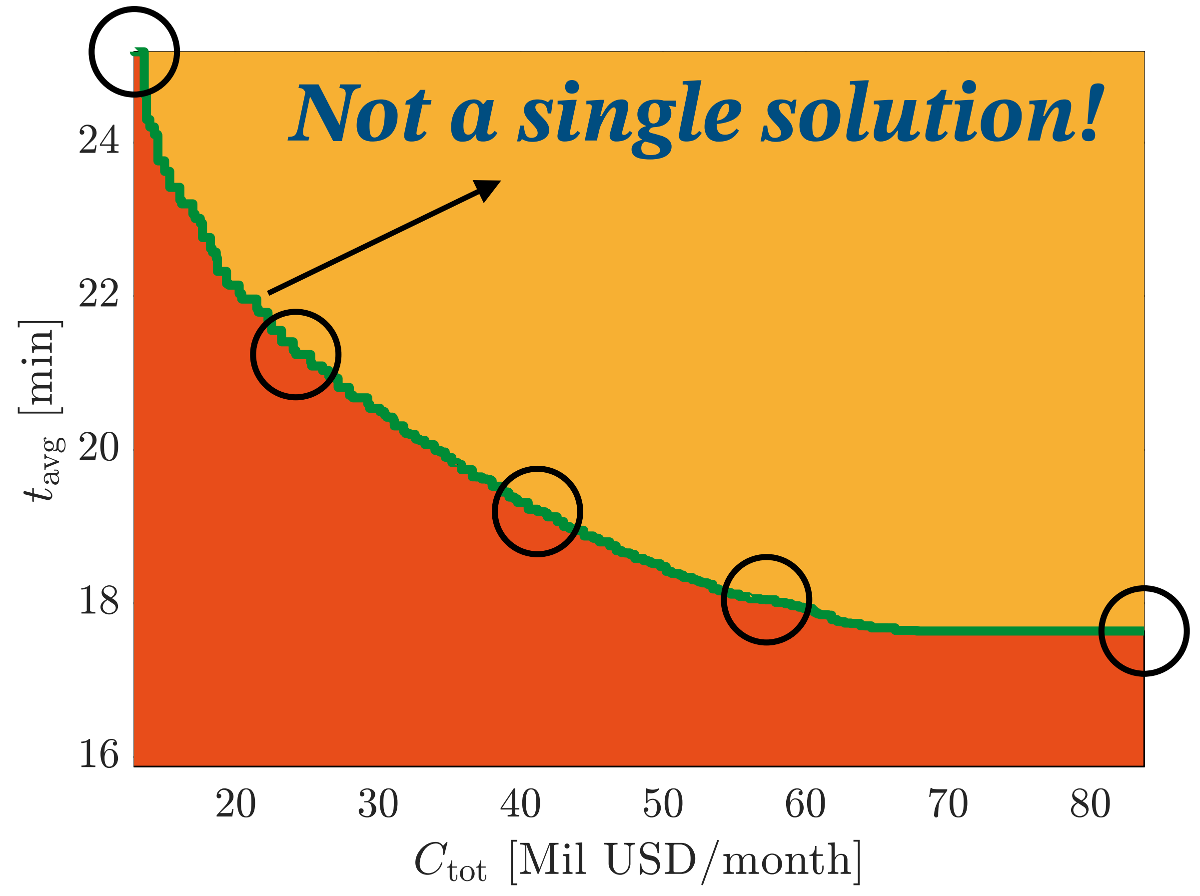
Co-Design produces actionable information for stakeholders

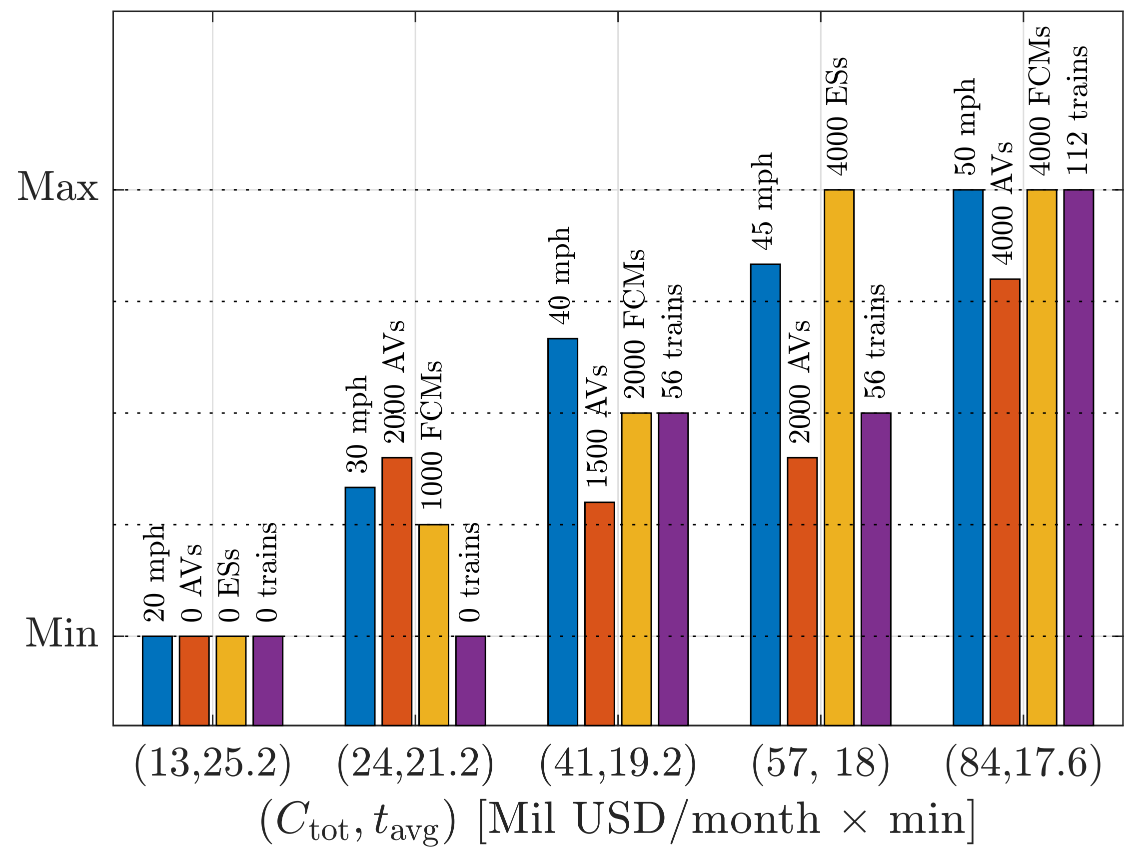




Fixed a **demand**, we find the **Pareto front** of **incomparable**, **minimal solutions** as **cost**, **time**, and **externalities**

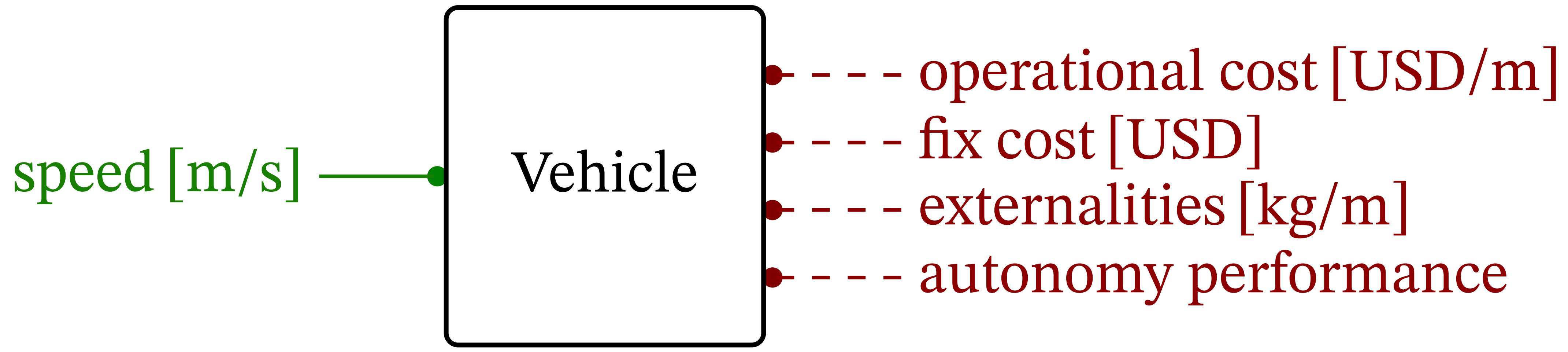
Convert **externalities** into **cost** and interpret the results:





Which one is the best? Depends on what is at upper level (policy-making, etc.)

Co-design of an autonomous vehicle



- Simple approach: a **catalogue** of existing **AVs**
- We want to model **AVs** more in detail, from the perspective of the **developers**
- We look at an example of the **methodology** to apply:
  - Can be applied to other autonomous systems
  - *Proof of concept* implementation (*no* real data)

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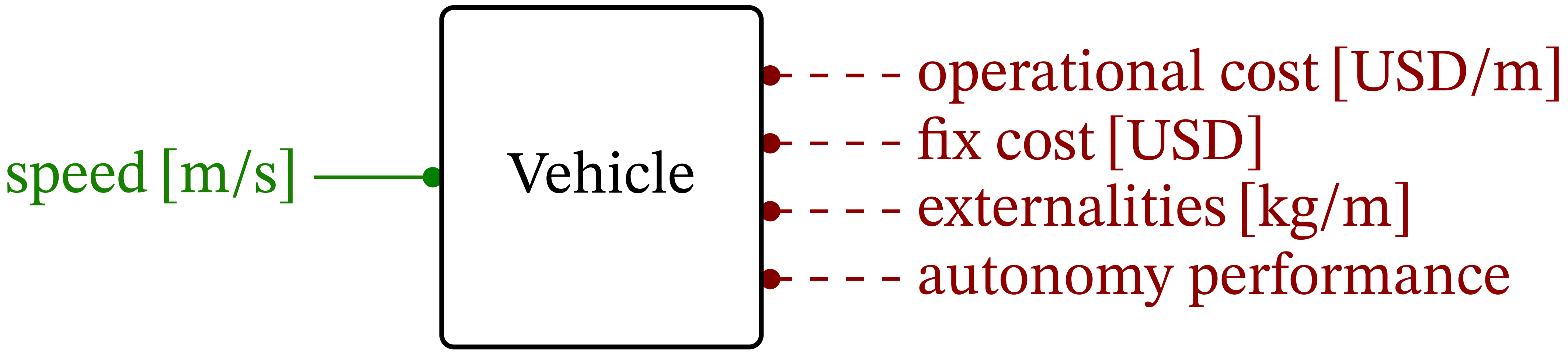

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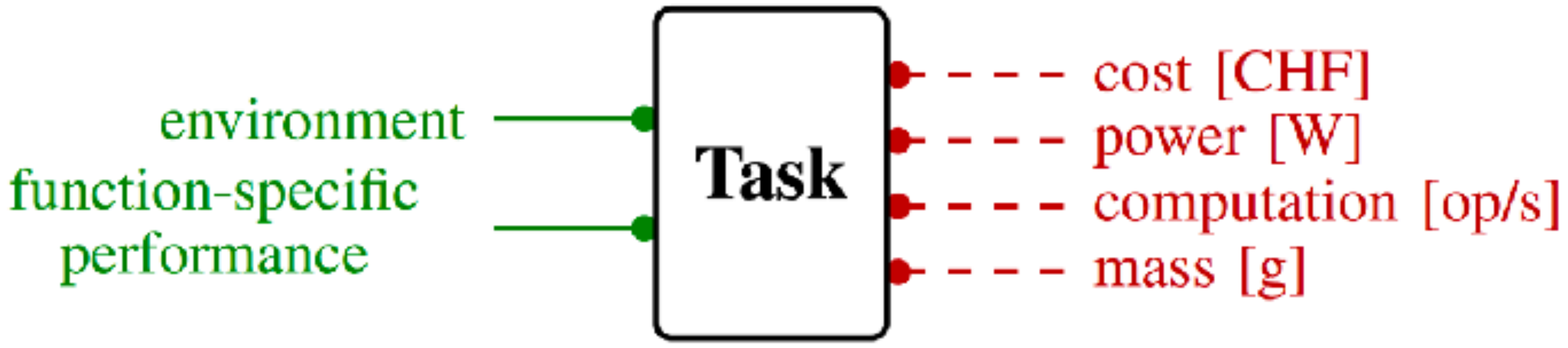
- **Modeling approach**:
  - **Task** - *what do we need to do*?
  - **Functional decomposition** - *how to decompose*?
  - **Find components** - *decompose until you find components* (hardware and software)
  - **Find common resources** - For instance, size, weight, power, computation, latency

- **Implementation**:
  - **Skeleton** - *write structure using the formal language*
  - **Fill-in the holes**: *catalogues, analytic models, simulations*

Task abstraction and functional decomposition in autonomy

- Autonomy tasks can be usually characterized as a **design problem:**



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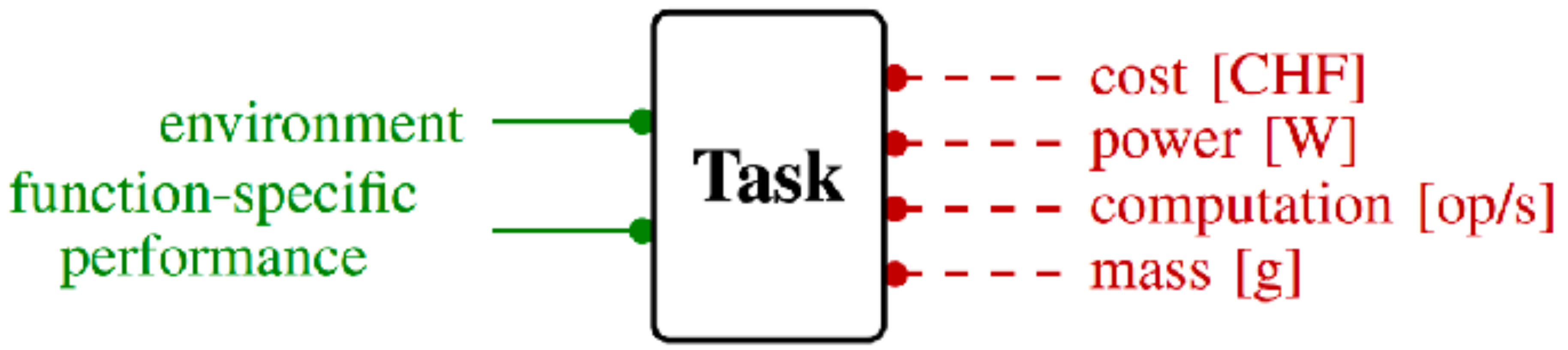
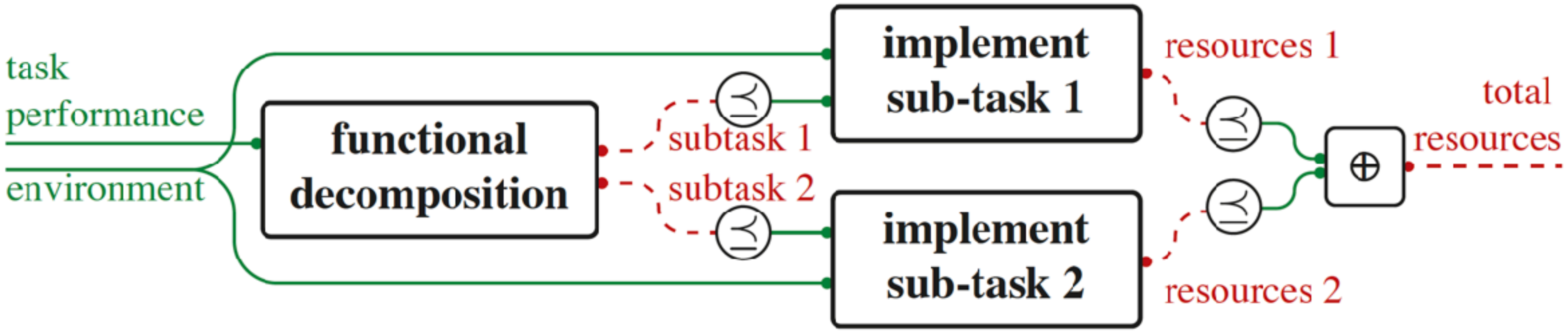


- Given the **sub-tasks**, we can interconnect them



- Note that composing tasks gives a task (**compositionality**)

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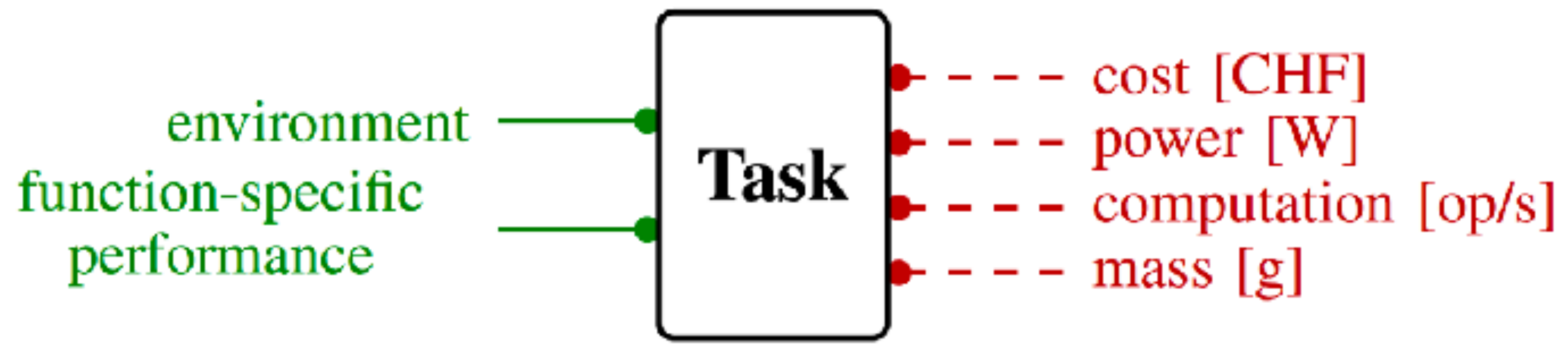

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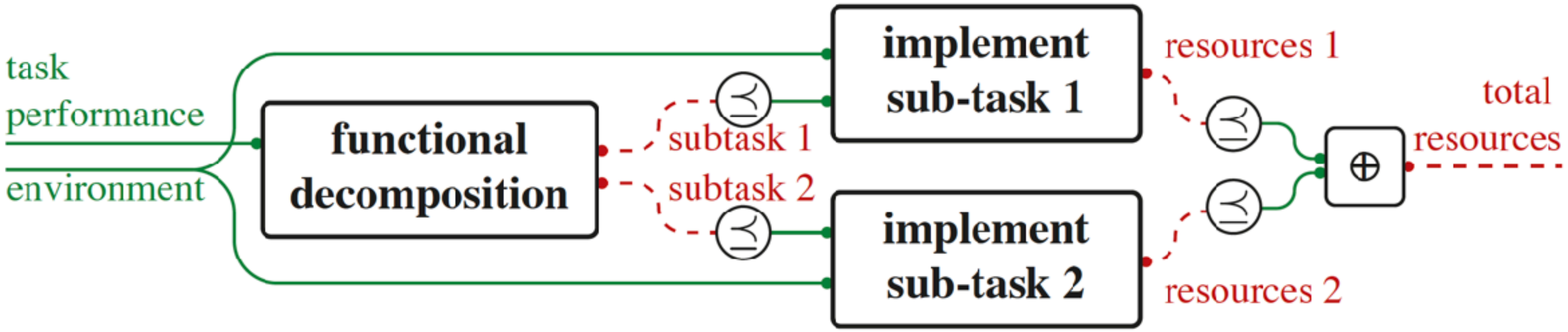

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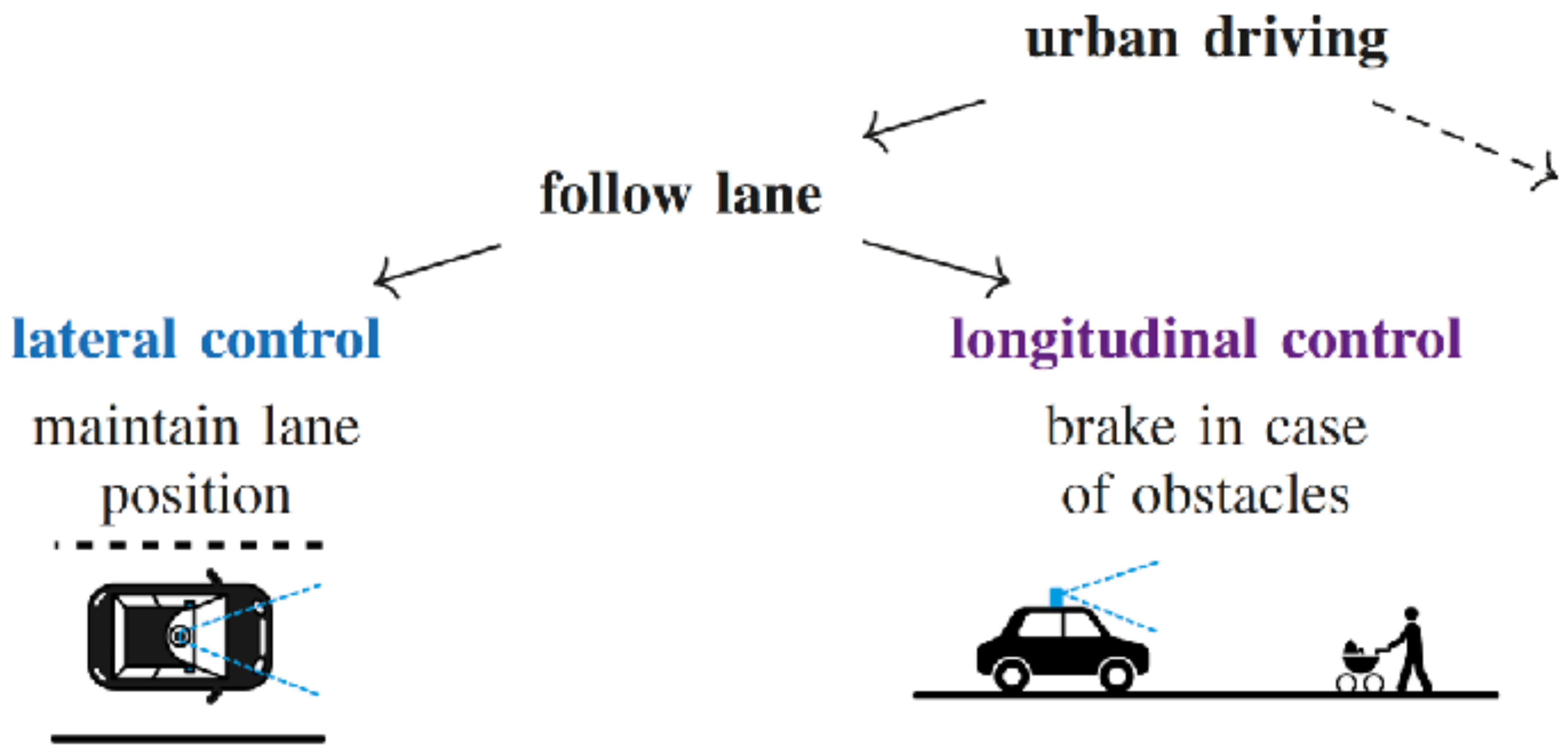
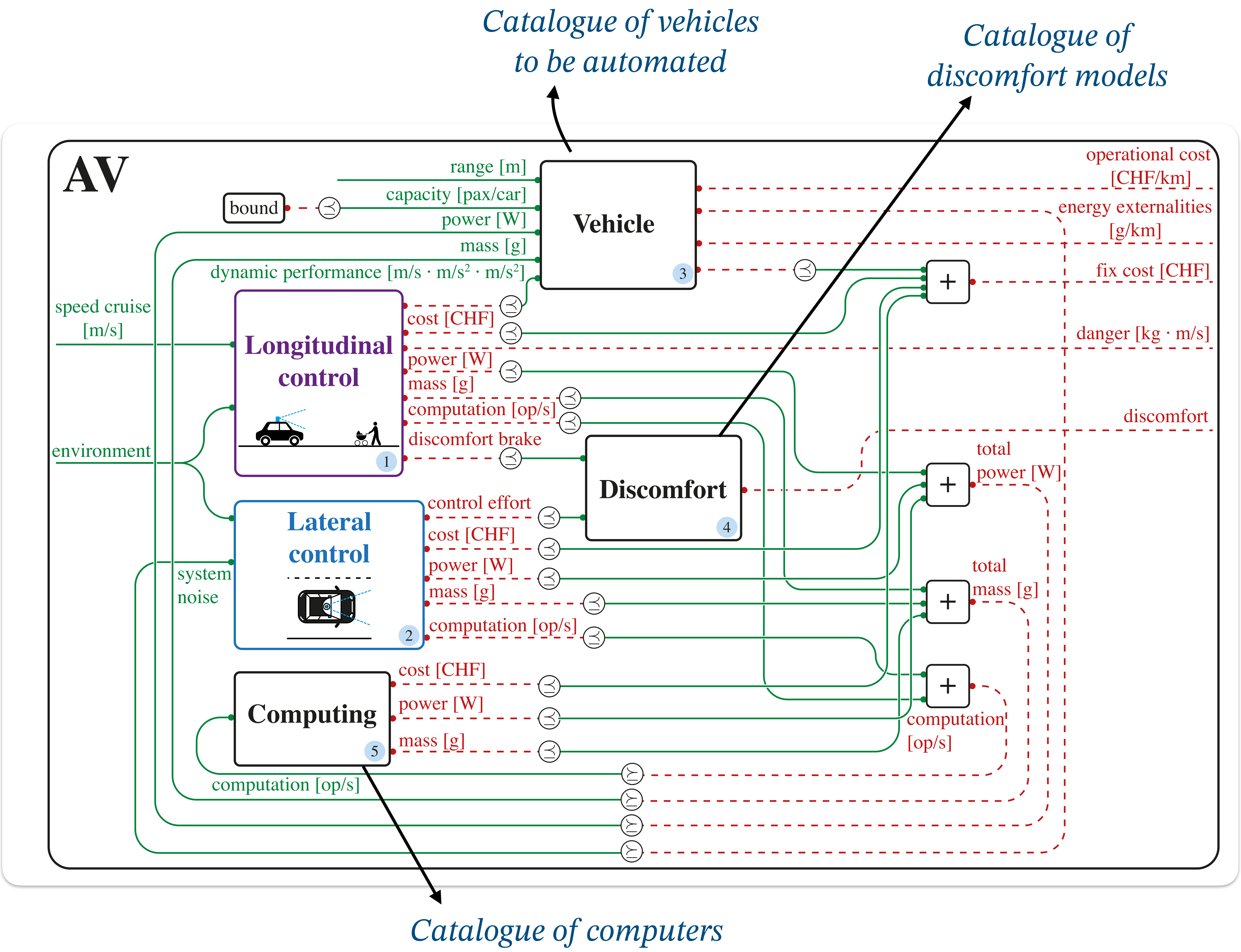
- Let's try with **urban driving**:



Co-design model of an autonomous vehicle



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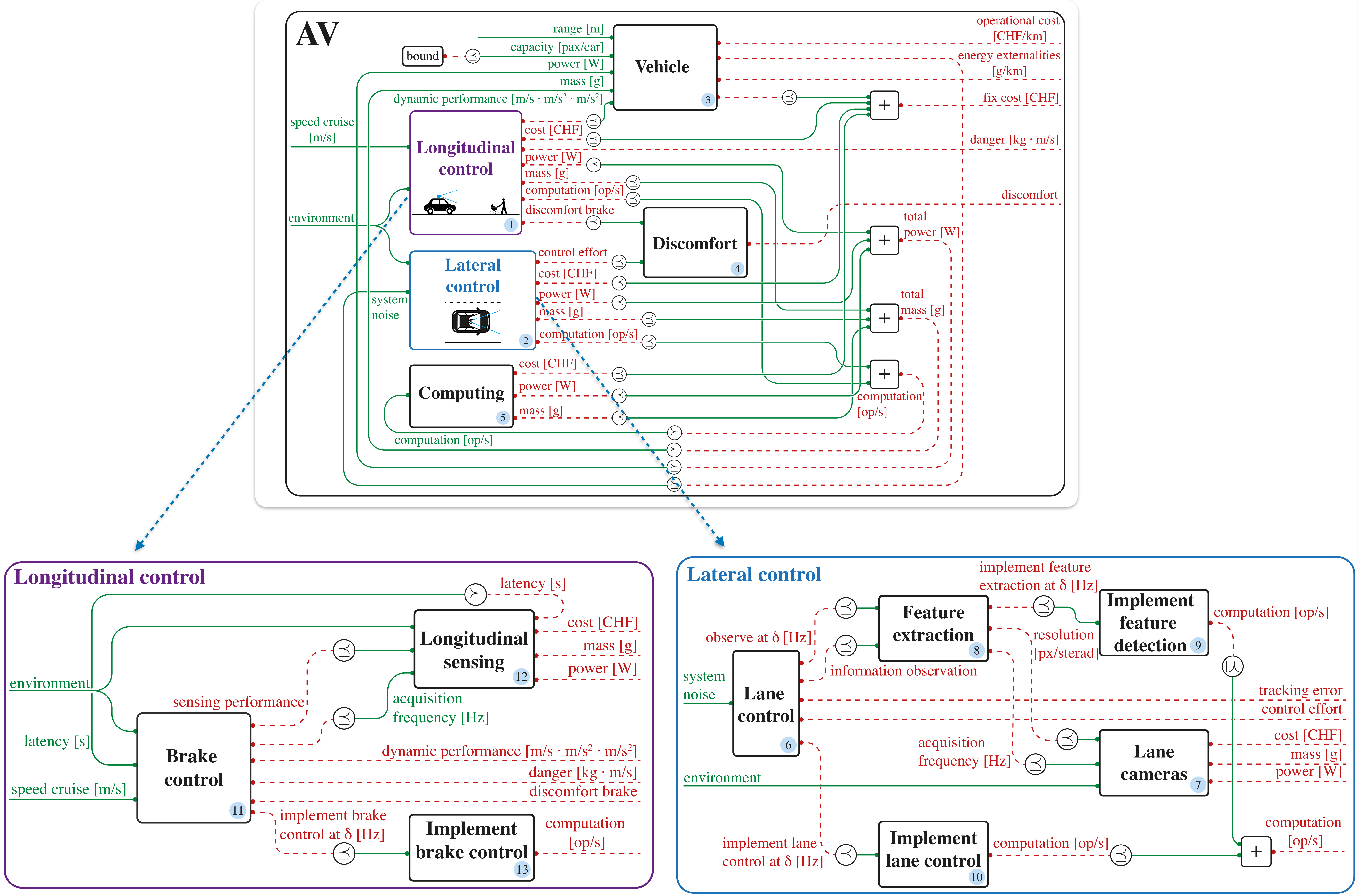
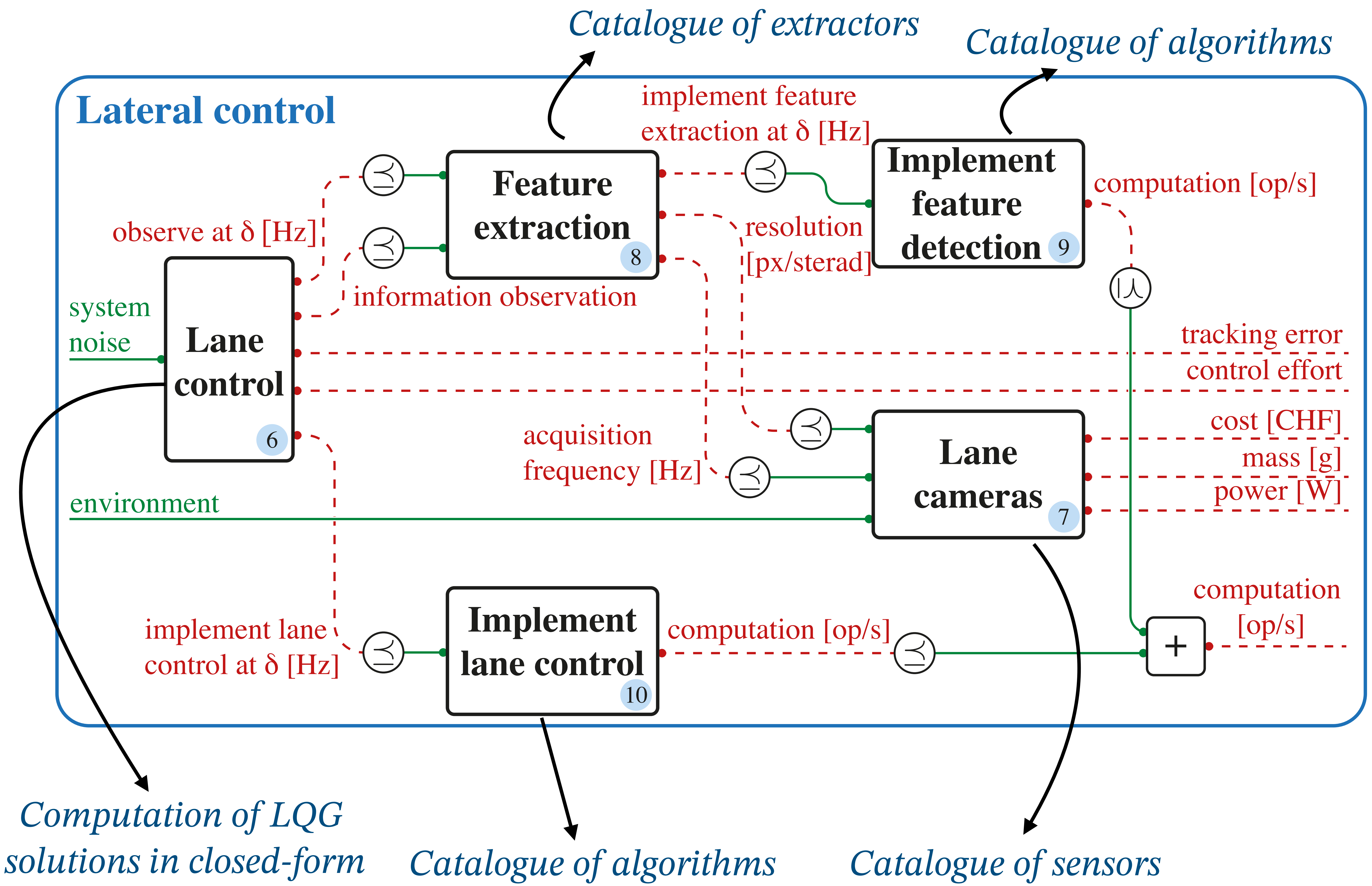


Co-design of a intermodal mobility system

- Lateral control can be decomposed in **sub-tasks**:



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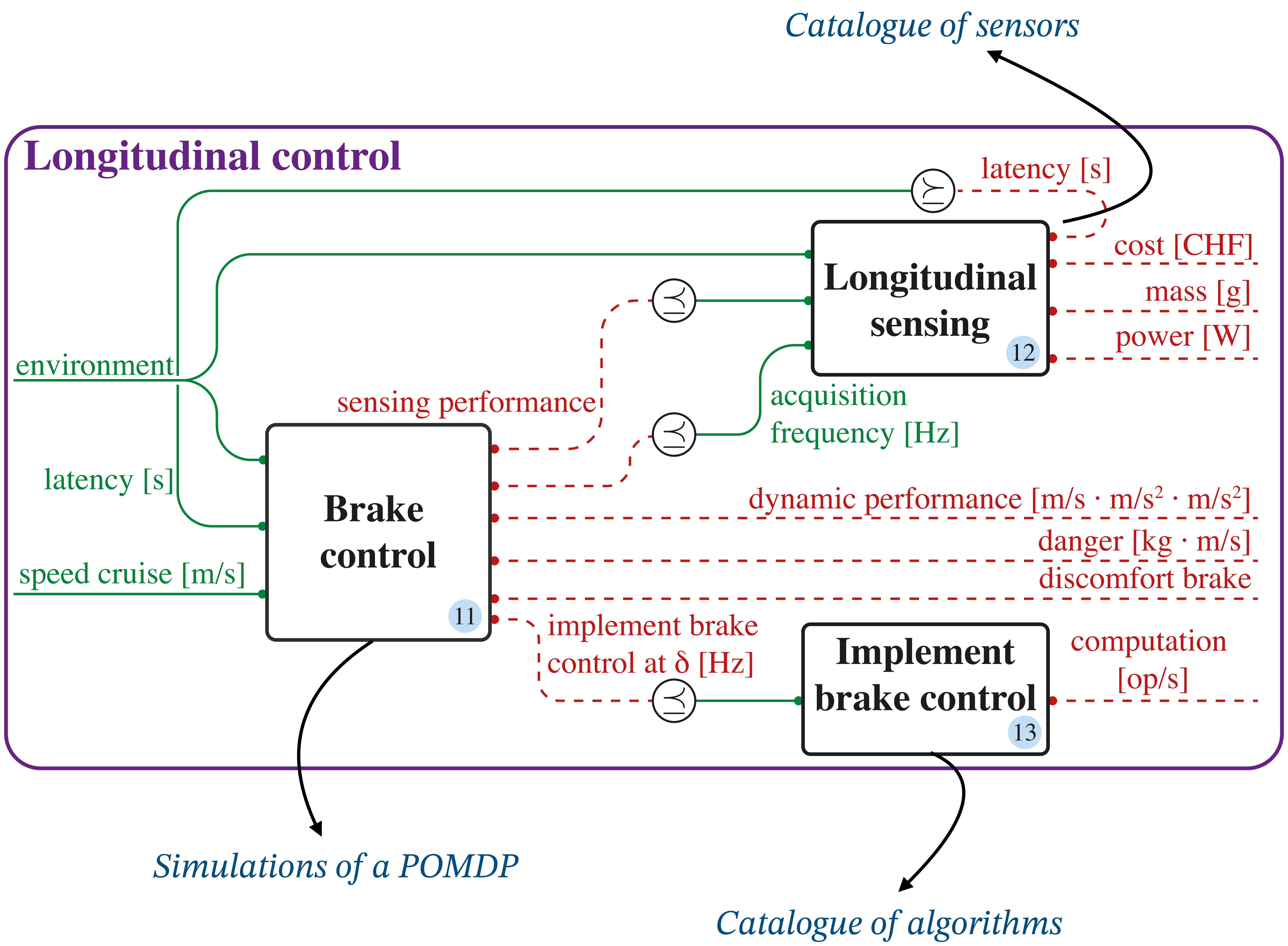
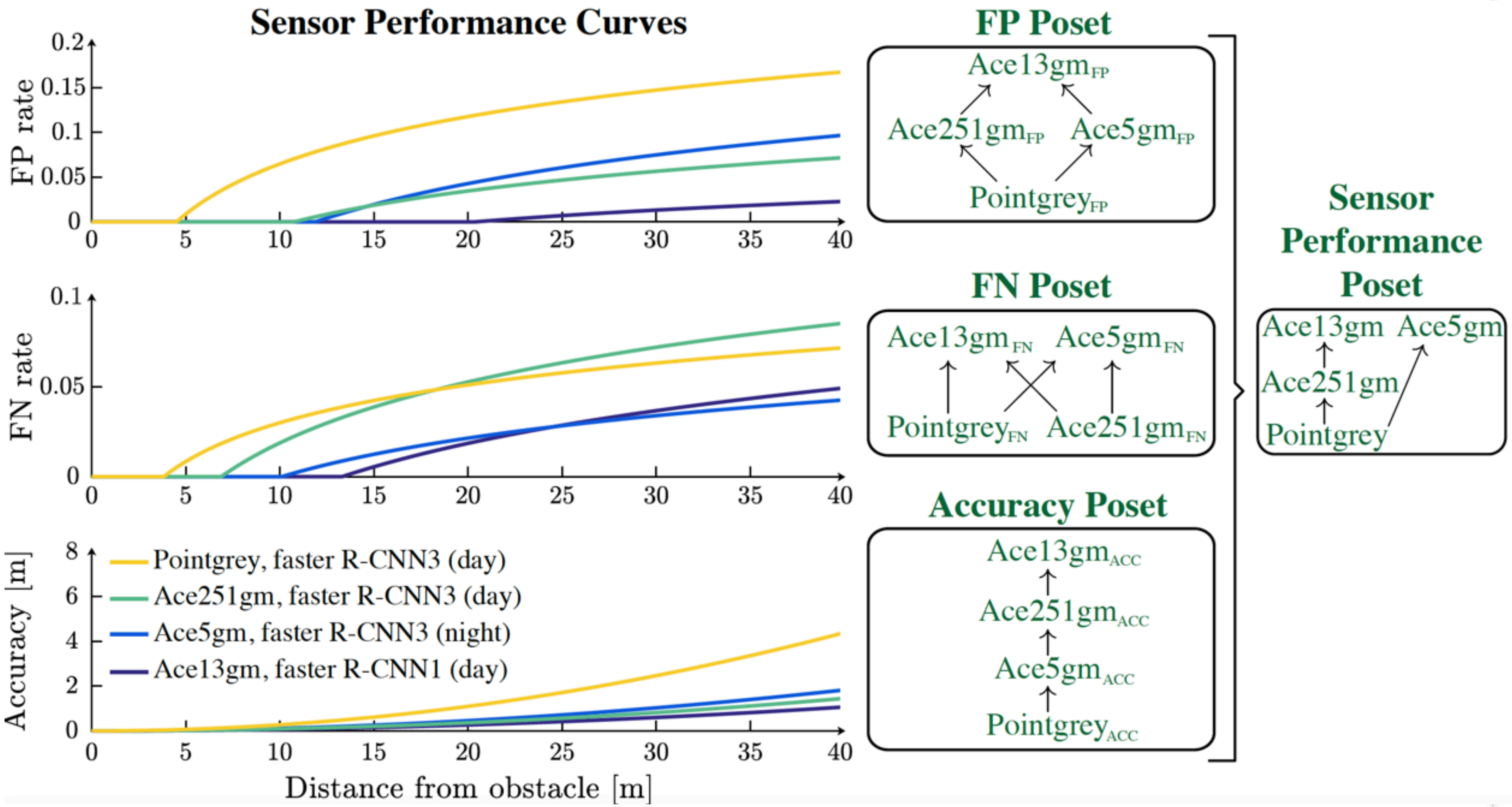


We construct a poset of sensor functionalities

- **Sensing performance**:



Co-design of a intermodal mobility system

- The theory comes with a **formal language** and a **solver (MCDP)**

- Very intuitive to use:

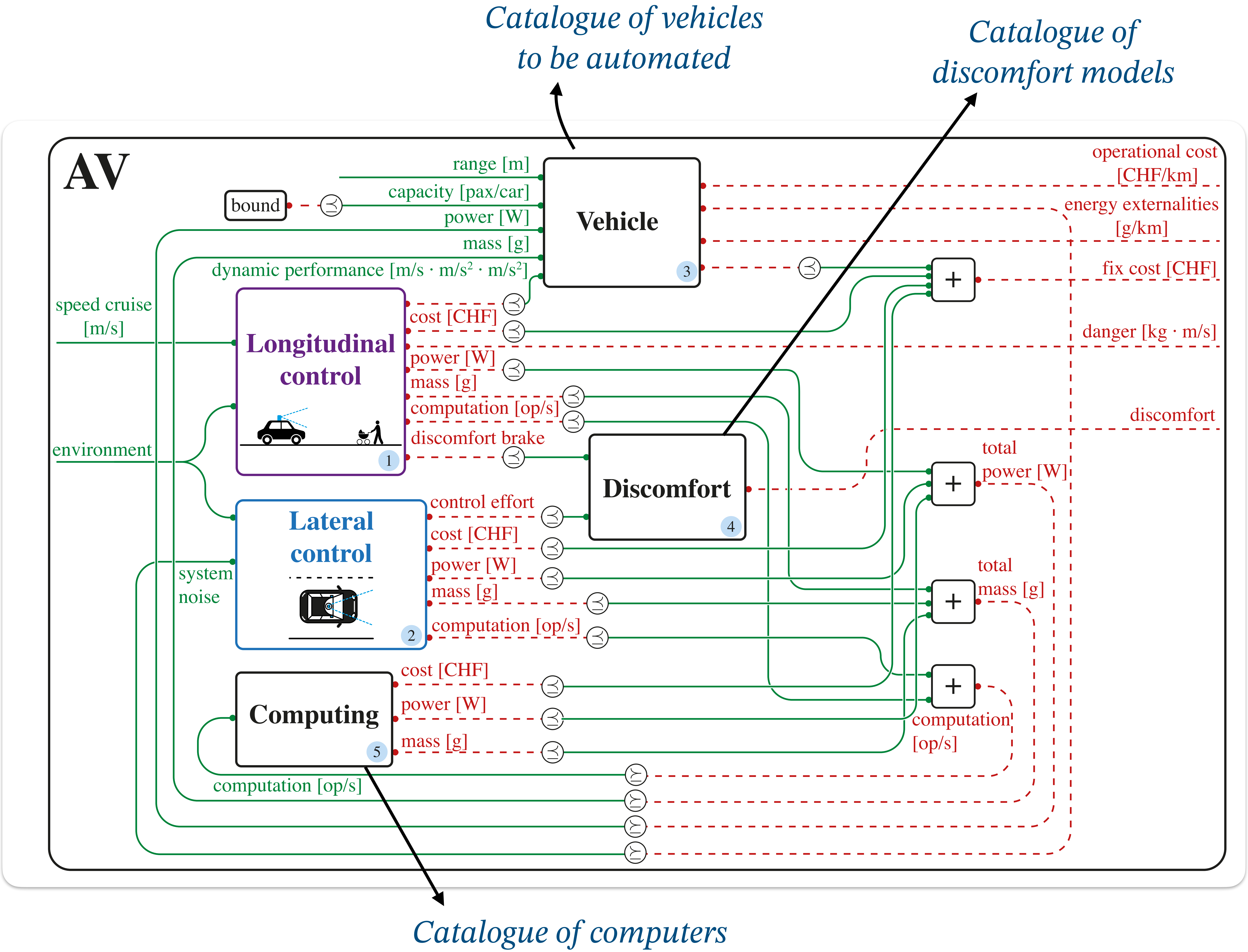
```
mcdp {
   provides computation [op/s]
   requires cost [CHF]
   requires mass [g]
   requires power [W]

}
```

```
choose(
        SedanS: (load Car_SedanS),
        SedanM: (load Car_SedanM),
        SedanL: (load Car_SedanL),
        SUVS: (load Car_SuvS),
        SUVM: (load Car_SuvM),
        Minivan: (load Car_Minivan),
        Shuttle: (load Car_Shuttle),
        Hybrid: (load Car_Hybrid),
        BEV: (load Car_BEV)
)
```

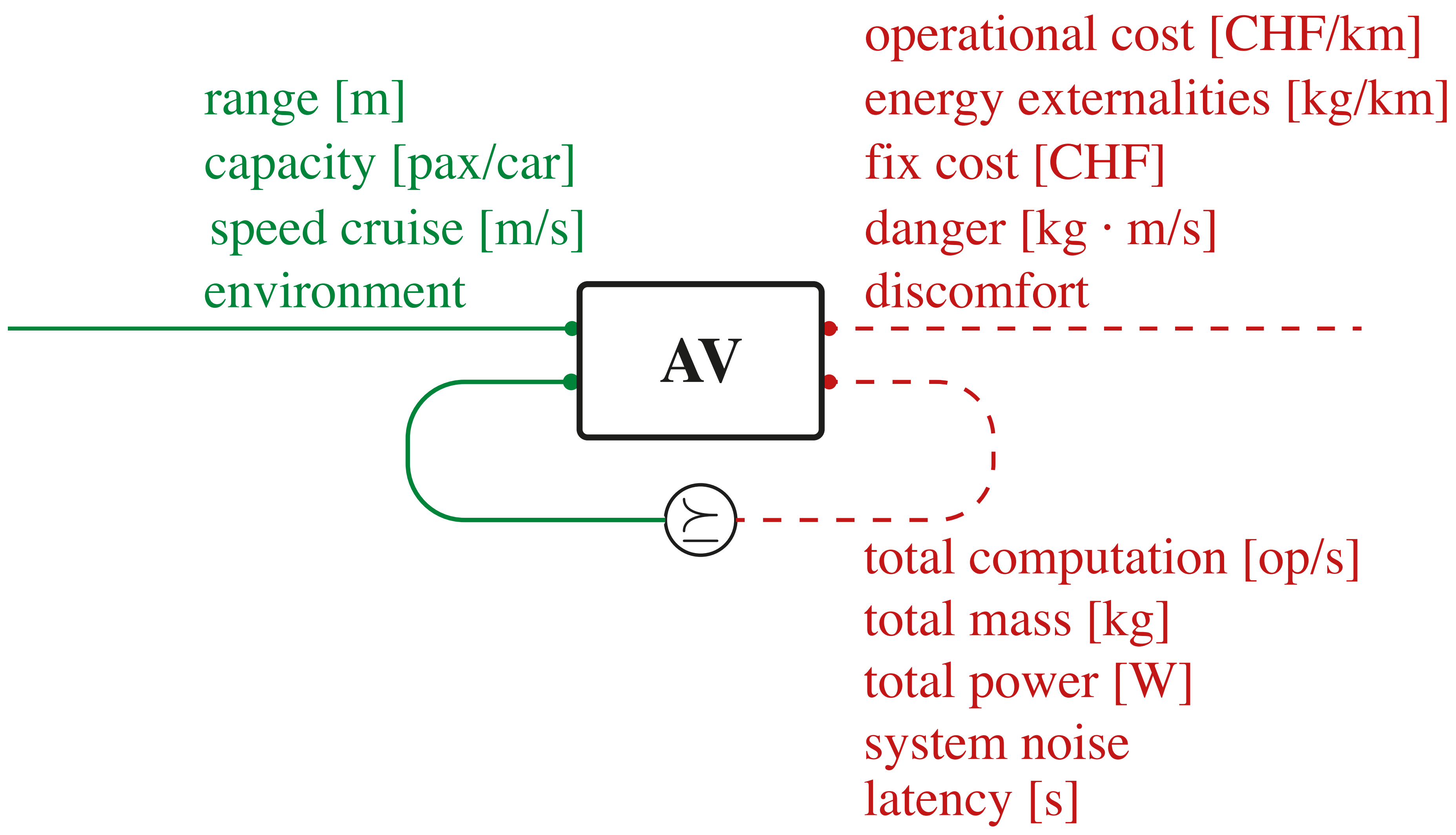
Choose query type:

- Fixed the functionality, minimize the resources.
- Fixed the resources, maximize the functionality.
- Given an implementation, evaluate functionality/resources. [UI not implemented]
- Given min functionality and max resources, determine if there is a feasible implementation. [UI not implemented]
- Given min functionality and max resources, find a feasible implementation. [UI not implemented]
- "Solve for X": find the minimal component that makes the co-design problem feasible. [UI not implemented]

Co-design model of an autonomous vehicle



Solution of DPs



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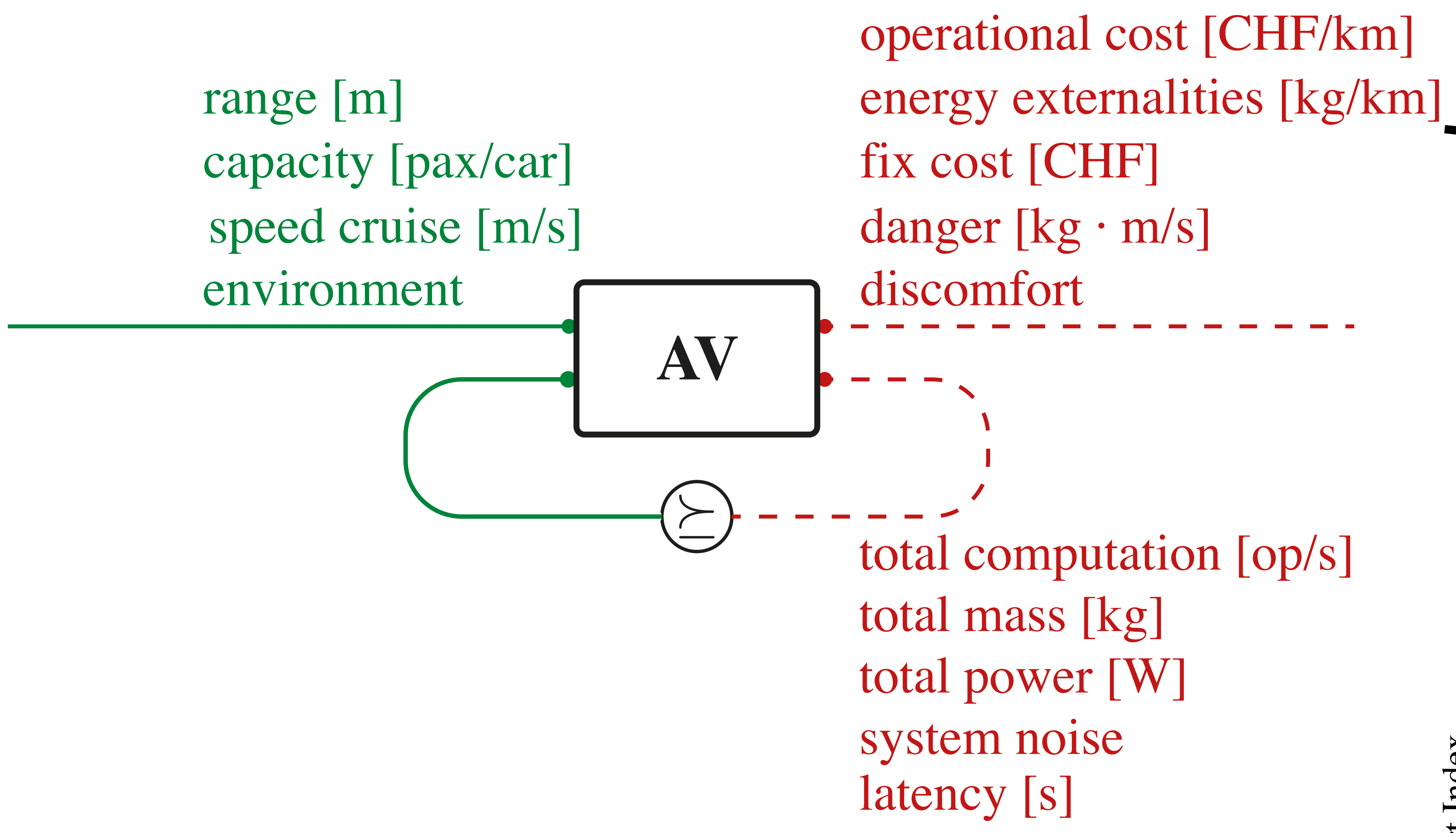
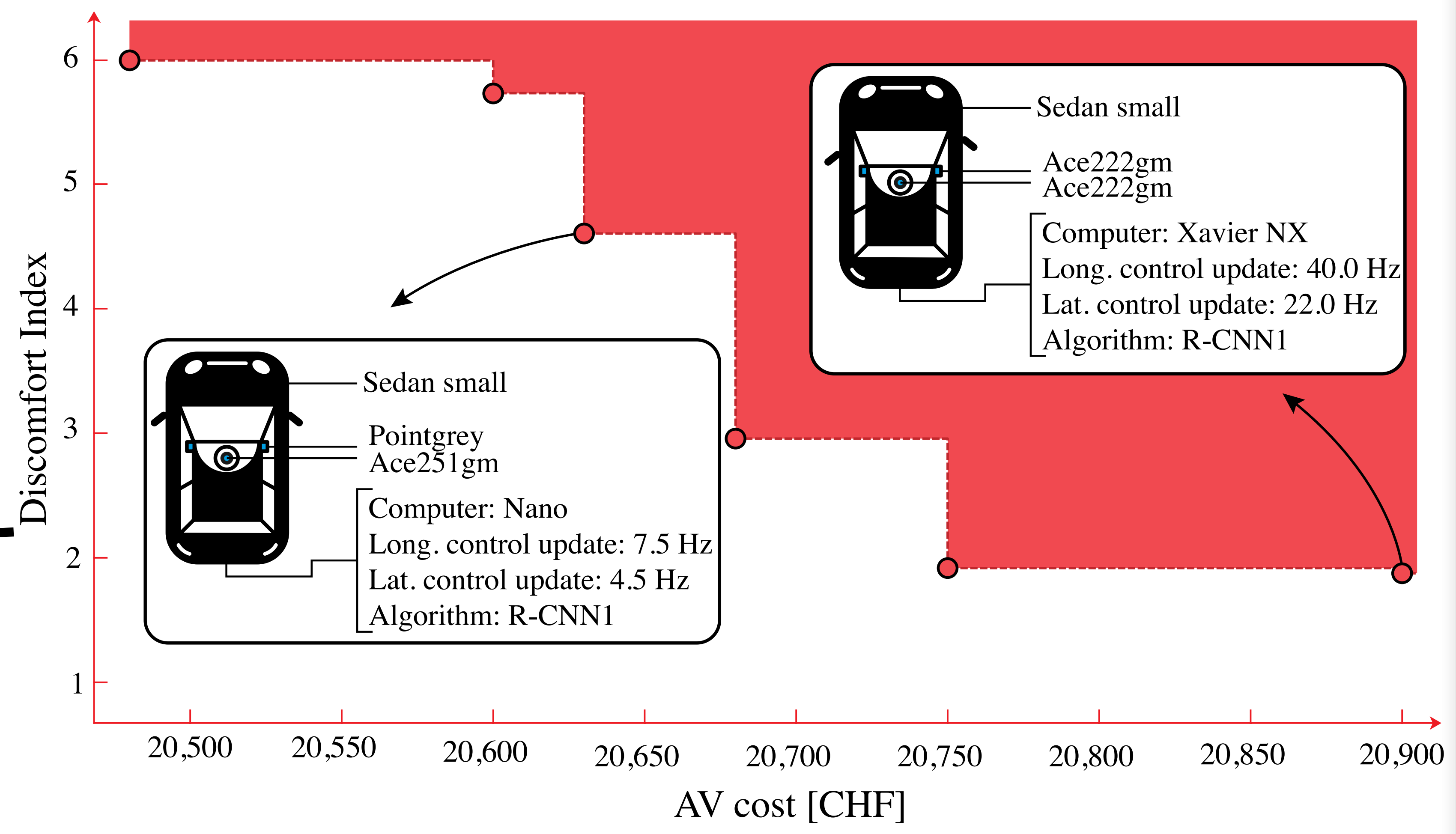


Fix **functionalities**, look at minimal **cost** and **discomfort**



Details of autonomy,
*both **hardware** and **software***

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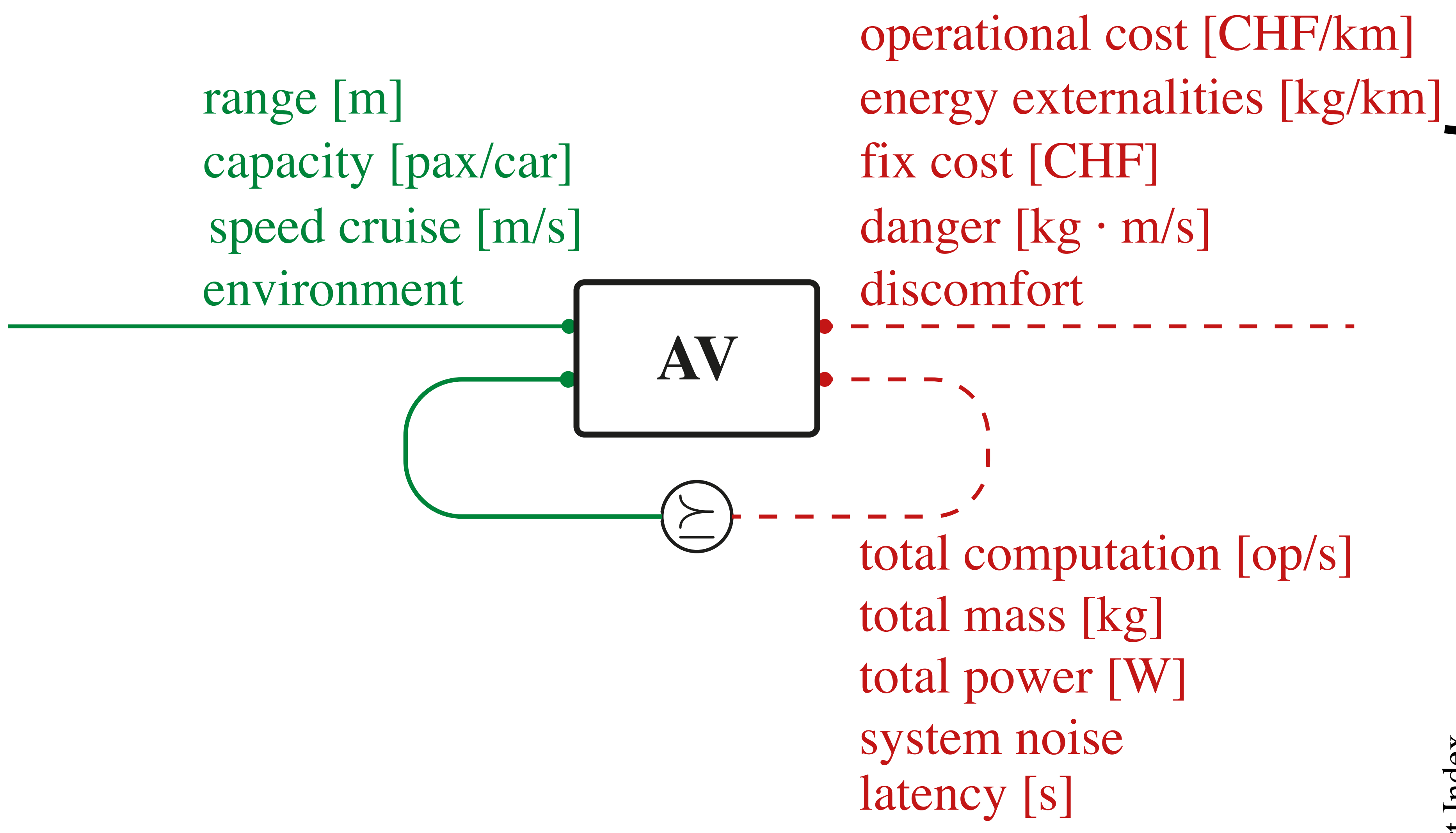

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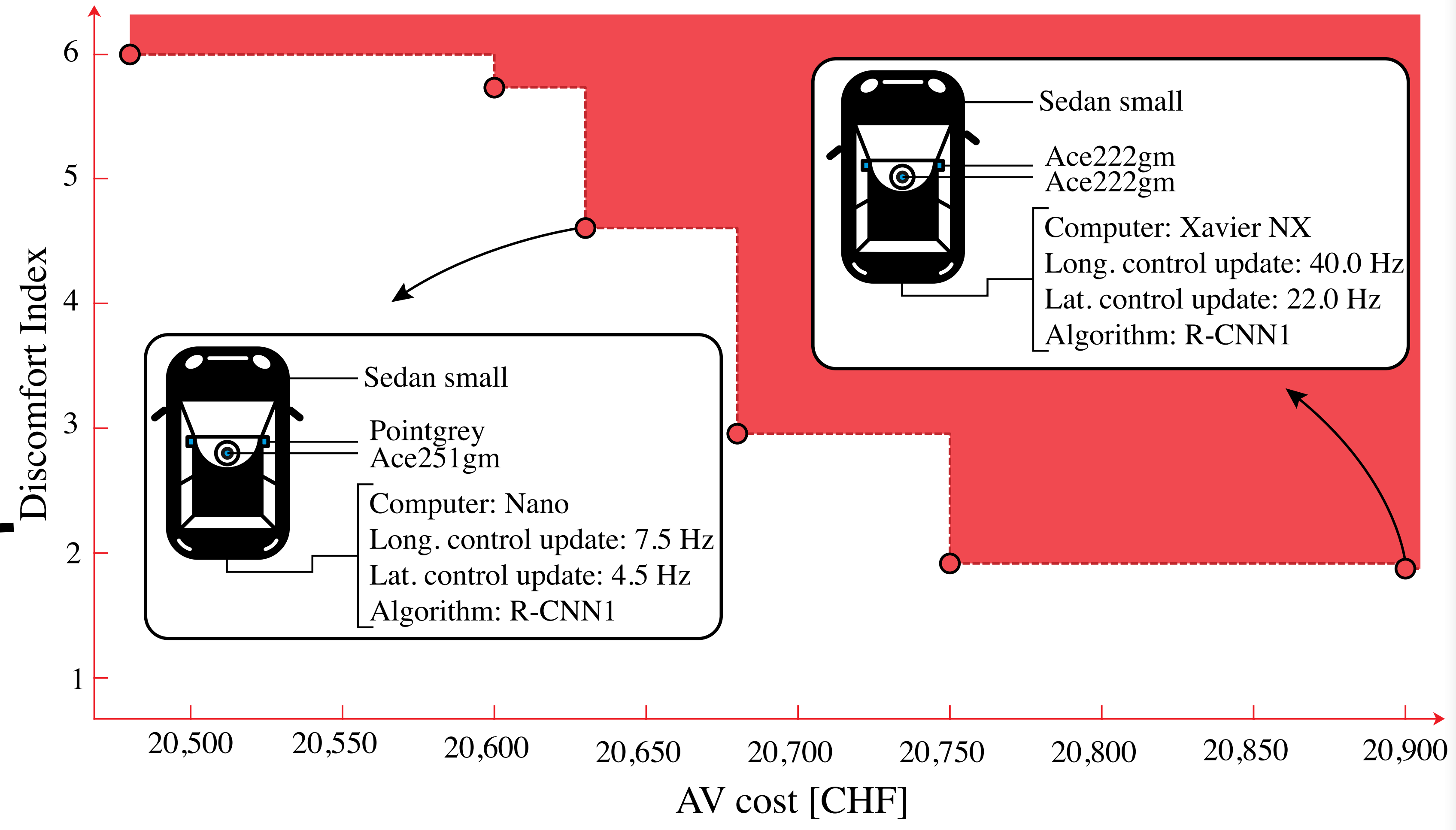

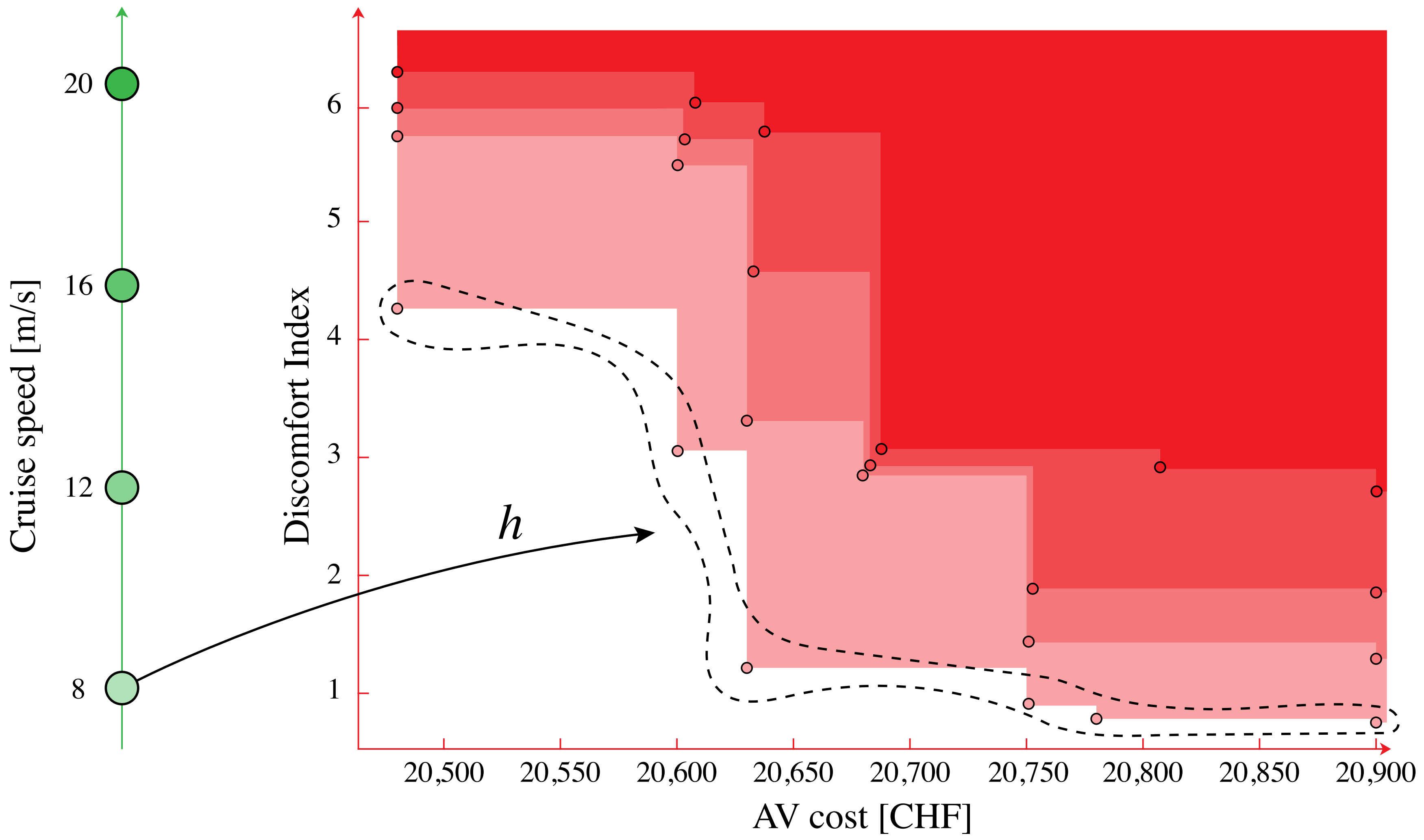

***Monotonicity:** Higher achievable speeds will not require **less** resources*

Conclusions: Takeaways

- Using co-design, it is **easy** to formalize **hierarchical models** (never possible before)
  We formalized mobility systems all the way from sensors on the vehicles to interactions of fleets of AVs with the public infrastructure of a city

- Very **intuitive** modeling approach (no acrobatics like common in optimization theory)
  *The **interpreter** allows one to easily model problems of interest*

- **Rich modeling capabilities:**
  ***Simulation**: Flow optimization for mobility network, POMDP for brake control*
  ***Catalogues**: Sensors, vehicles, computers, algorithms, ...*
  ***Analytical**: LQG closed-form solutions, discomfort models, ...*

- **Compositionality** and **modularity** allow **interdisciplinarity**
  *We did all of it, but technically this could have been possible with different **teams***

- Co-design comes with a **formal language** and an **optimizer**
  *After easily modeling the problem, you can directly solve **queries** of your choice*

- Co-design produces **actionable information** for designers to **reason** about their problems
  *We have shown actionable information for **municipalities**, as well as for **AV developers***