Stochastic Systems Modeling for Wireless Charging Electric Vehicle

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Goal of the Talk

- **Introduce the new type EV**
  - Dynamic wireless charging
- **Report the current progress of the research**
  - Allocation of charging infrastructure
  - Battery sizes
- **Provide the research directions**

Topics

- Dynamic wireless charging EV
- On-Line Electric Vehicle (OLEV) at KAIST
- System issues
- Micro model
- Macro model
- Summary & conclusion

Electric Vehicle: Problem with the Current Solution

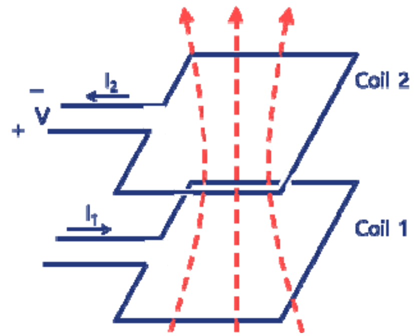
- **A battery-EV (also called a pure EV) is a vehicle powered entirely by electric energy, typically via a large electric motor and a large battery pack**

- **Charging 24kWh battery**
  - 7 hours (Level 2 – 240V AC/3.3kW)
  - 30 min (Level 3 – 480V DC/50kW)

Wireless Power Transfer History

- **Introduction to wireless power transfer**
  - Nikola Tesla (1904)
    - Tesla's Tower
    - Supply Wireless Power to Run All the Earth's Industry
    - Faraday's Law of Induction in Maxwell's Equations

$$\nabla \times E = -\frac{dB}{dt}$$



Wireless Charging Applications

- **Applications of wireless charging**

Wireless Charging EV

- **Technology development of EV using wireless charging**

Plug-In Electric Vehicle → Stationary Wireless Charging E..V. → Dynamic Charging E.V. KAIST - OLEV

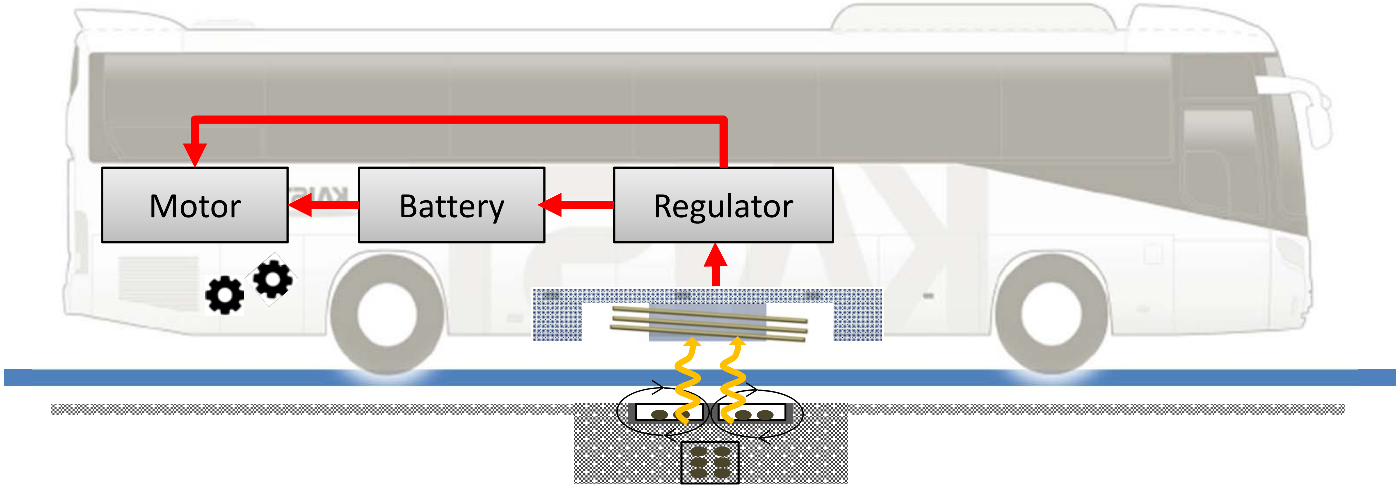
Dynamic Charging EV

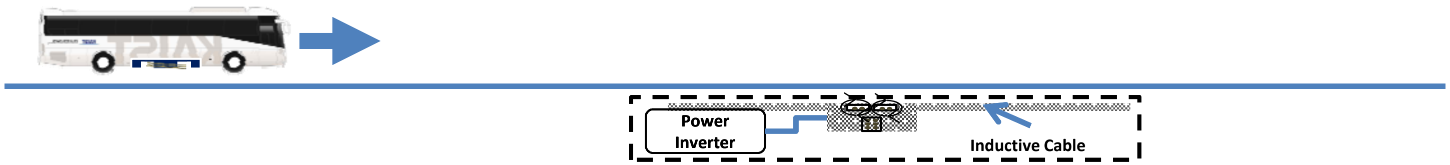
Roadway Charging EV

Move-and-Charge EV

KAIST On-Line Electric Vehicle (OLEV) is the brand name

Dynamic Charging EV Operation





"Power-track"

Topics

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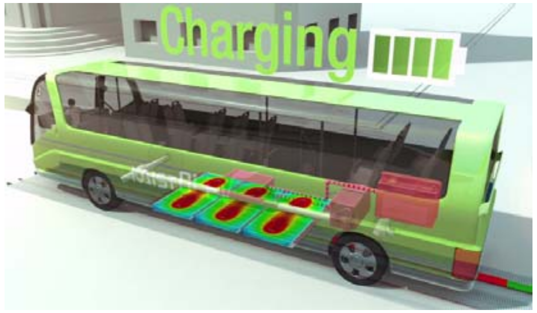
KAIST On-Line Electric Vehicle (OLEV)

- **The first commercialized dynamic wireless charging EV**
- **YouTube:**
  - http://www.youtube.com/watch?v=xwuNc9SrRYw



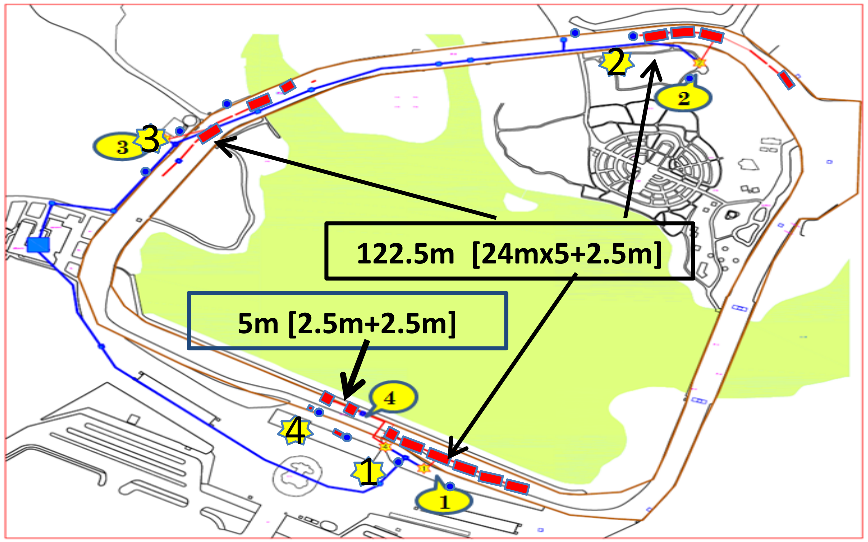
Movie Clip

Commercialization of OLEV Systems

Seoul Grand Park

◆ Test operation started through pilot test project at Seoul Grand Park in Mar. 2010
◆ Commercial operation of three OLEV trams started in July 2011

Installation length of power line: 372.5m(16%) of total 2,200m



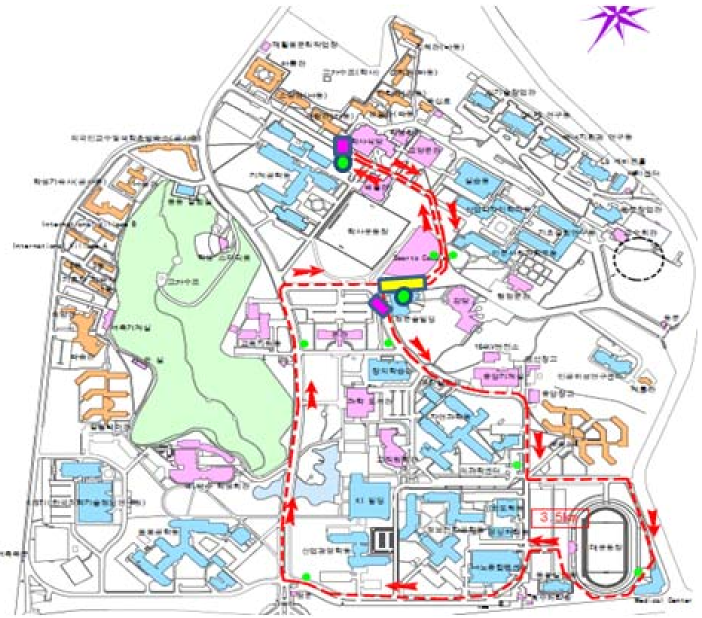
Inverter Manhole Segment Power distribution line

Commercialization of OLEV Systems

OLEV Shuttle Bus at KAIST

◈ Demonstration operation started in Oct. 2012 as an on-campus shuttle Bus at KAIST

Installation length of power line: 60m(1.6%) of total 3,760m



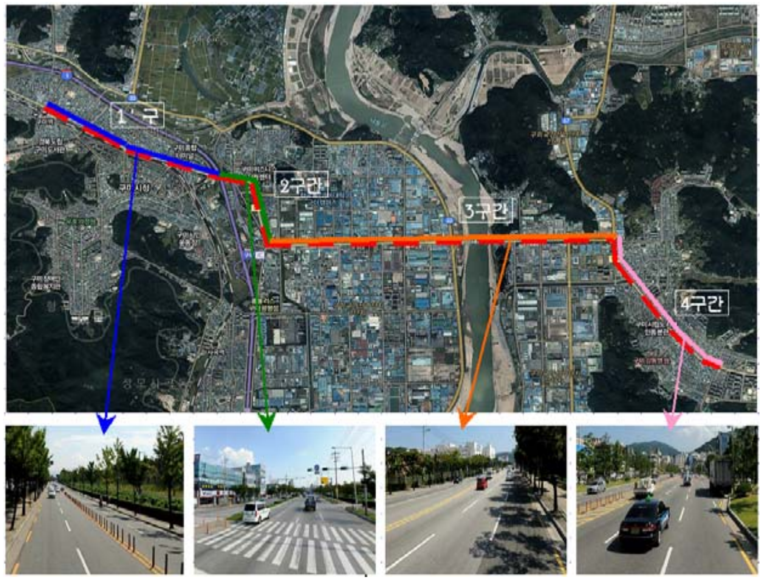
Commercialization of OLEV Systems

OLEV Bus Operation at Gumi City in Korea

◈ Two OLEV buses run an inner city route between Gumi Train Station and In-dong district, for a total of 24 km roundtrip (Demonstration operation from Aug. to Dec. 2013)

◈ Real commercial operation will start in Jan. 2014.

Installation length of power line: 144m(0.6%) of total 24km



State of the Art

Institute	Year	Nation	Project Type	Vehicle Type	Power	Air gap	Efficiency
KAIST	2009	Korea	Prototype (Dynamic)	Golf Cart	3 kW	10 mm	80%
KAIST	2009	Korea	Prototype (Dynamic)	Bus	6 kW	170 mm	72%
KAIST	2009	Korea	Prototype (Dynamic)	SUV	17 kW	170 mm	71%
KAIST	2010	Korea	Public Demo (Dynamic)	Tram	62 kW	130 mm	74%
KAIST	2012	Korea	Public Demo (Dynamic)	Bus	100 kW	200 mm	75%
ORNL	2010	US	Prototype (Dynamic)	-	4.2 kW	254 mm	92%
ORNL	2012	US	Prototype (Stationary)	-	7.7 kW	200 mm	93%
ORNL	2012	US	Prototype (Stationary/Dynamic)	GEM EV	2 kW	75 mm	91%
Auckland Univ & Conductix –Wampfler	1997	New Zealand	Public Demo (Stationary)	Golf Bus	20 kW	50 mm	91%
Auckland Univ & Conductix –Wampfler	2002	Italy	Public Demo (Stationary)	Mini Bus	60 kW	30 mm	-
Auckland Univ & Qualcomm Halo	2010	New Zealand	Evaluation Kit (Stationary)	Private EV	3 kW	180 mm	85%
Auckland Univ & Qualcomm Halo	2012	UK	Public Demo (Stationary/Dynamic)	-	-	-	-
MIT WiTricity & Delphi	2010	US	Commercial kits (Stationary)	Private EV	3.3 kW	180 mm	90%
Evantran	2010	US	Commercial product (Stationary)	Private EV	3.3 kW	100 mm	90%

State of the Art

- **British government working on a pilot project**
- **Renault developing DWC systems**

British Highway Will Recharge Your Batteries as You Drive

By Philip E. Ross
Posted 14 Aug 2015 | 14:00 GMT

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Renault demos on-the-move EV charging

Renault has demonstrated dynamic wireless electric vehicle charging (DEVC), which allows electric vehicles to charge while driving. On a designated section of test track near Paris, two Kangoo Z.E. vans were able to absorb charges of up to 20 kilowatts at speeds over 60mph. Testing and development will continue, with a view to real-world adoption of the technology.

"This project has enabled us to test and further research dynamic charging on our Kangoo Z.E. vehicles," said Eric Feunteun, Renault's electric vehicle program director, "we see dynamic charging as a great vision to further enhance the ease of use of EVs, and the accessibility of EVs for all."

Topics

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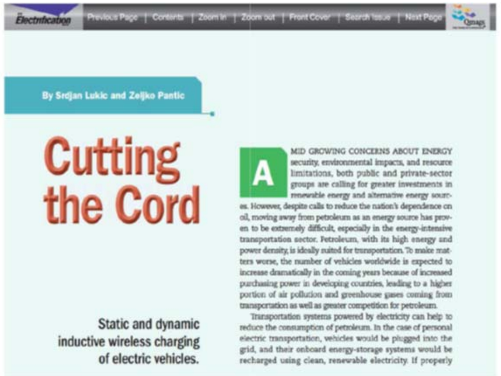
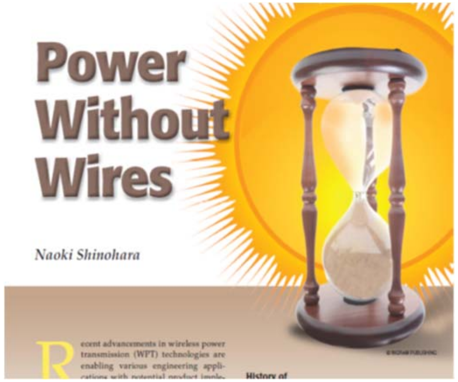
"Hot" Topic in Power Electronics

- **Wireless Charging EV has been established as an emerging research topic in the area of power electronics and other electrical engineering related fields**



IEEE Electrification (2013)



IEEE Microwave Mag (2011)

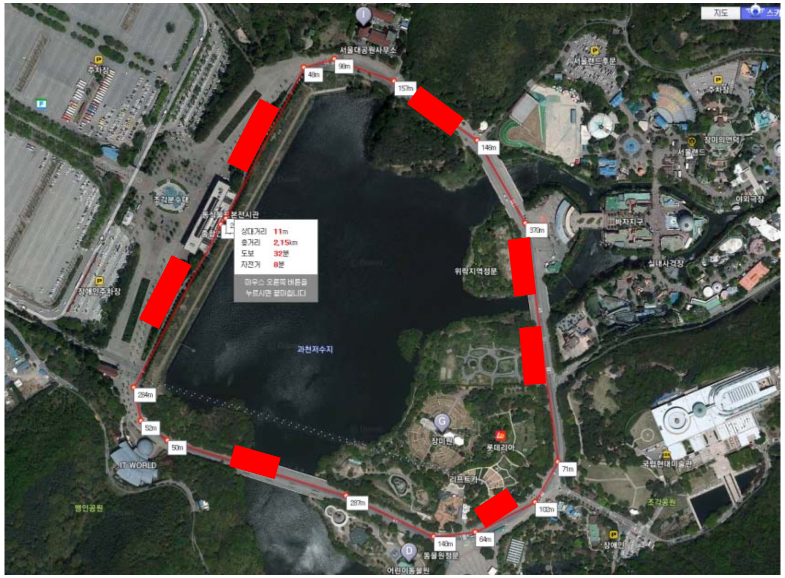
Special Issue
of the IEEE Transactions on Power Electronics on
Wireless Power Transfer

IEEE Trans. Power Electronics Special Issue on Wireless Power (2014)

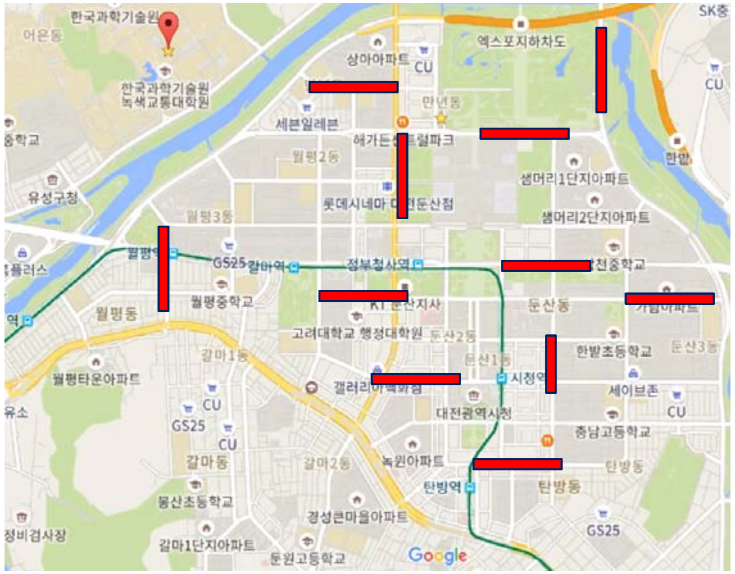
However, Wireless Charging EV is still new to other research communities (IE and OR)

System Design Issues

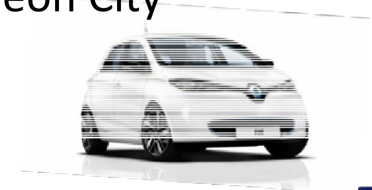
- **Allocation of the power tracks & battery size**



Seoul Grand Park



Daejeon City



Trade-off Issue

- **Trade-off between the battery size and the allocation of the power transmitter**
- **Two extreme cases**
  - The transmitter units are installed on the entire route – No battery is needed
  - No transmitter is installed and the vehicle is equipped with a large battery – Normal electric vehicle

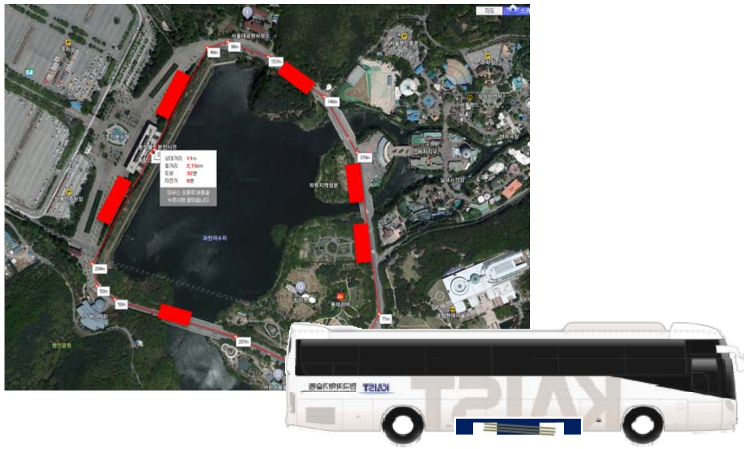
Battery cost

Power Track cost

Two Models

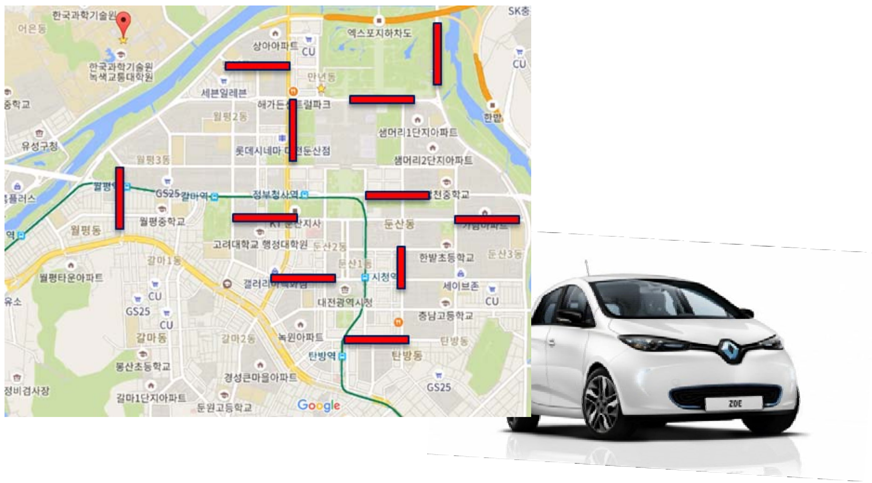
Micro-Model

- Travel route is known
- Velocity profile is predictable
- Operation is scheduled
- Application: public bus system
- Objective: operational level system planning – power track allocation and battery size



Macro-Model

- Travel route is not known
- Velocity profile is not predictable
- Operation is not scheduled
- Application: personal vehicle (or taxi)
- Objective: high-level insight and guideline for standardization



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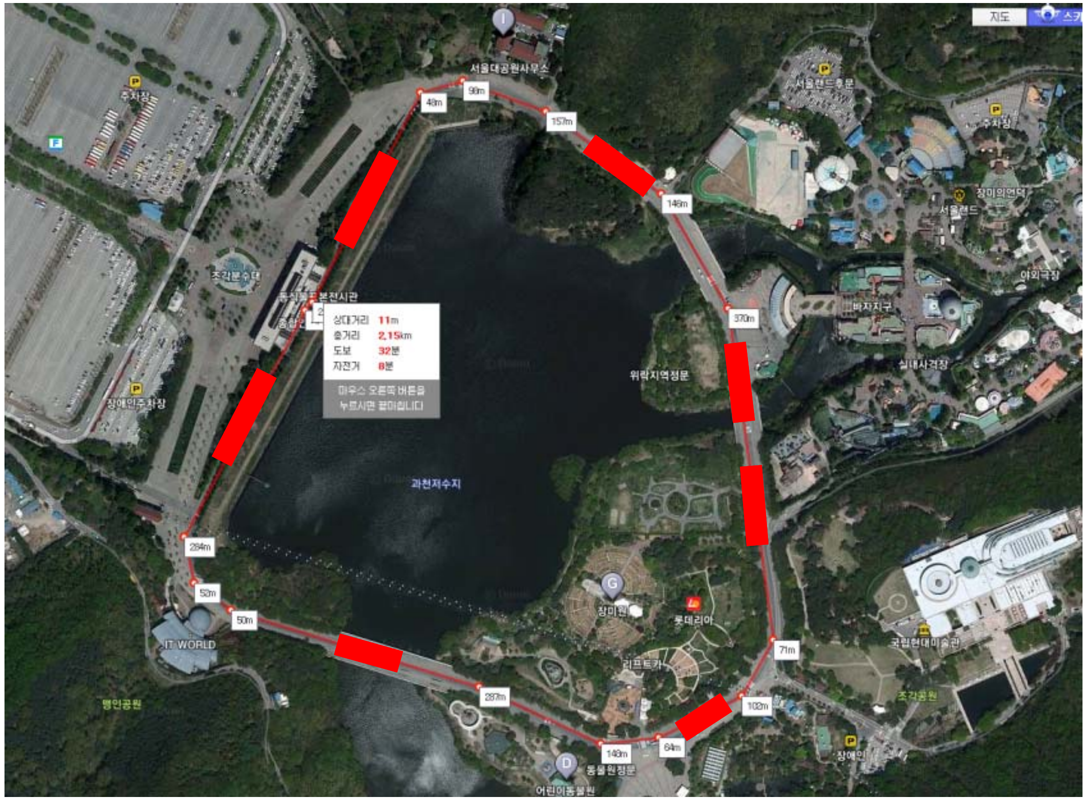
System Design Issue

- **Allocation of the power tracks & battery size**



Charging Facility Allocation Problem

- **Charging infrastructure (power track) allocation**

- **Setup cost per power track (fixed cost)**
  - Inverter + grid connection
  - For 100 kW inverter
    - ~$50,000
- **Variable cost of power track (variable cost)**
  - proportional to **length of power track**
  - For 1 m of power track
    - ~$10,000

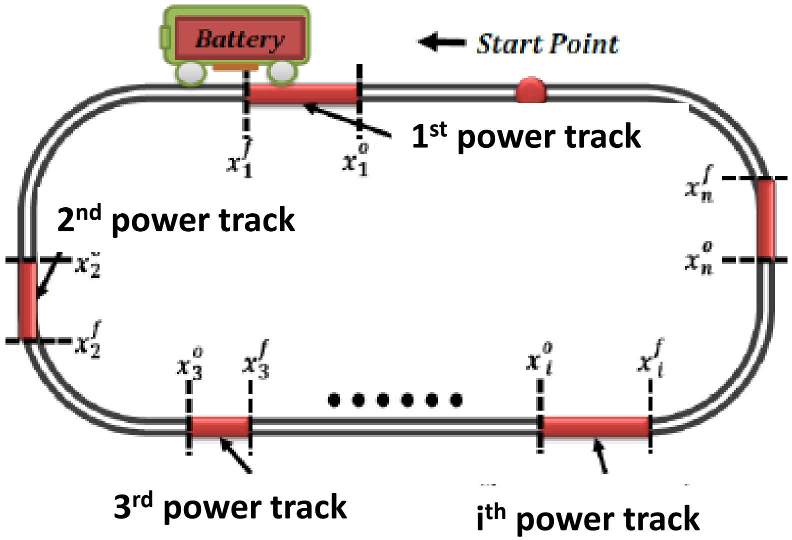
Basic Model: Optimization Modeling

• The decision variables

- What is the optimal size of the battery
- Where are the power tracks allocated?
- What is the length of each power track?

→

- Size of the battery
- Start and end position of each power track
- No. of power tracks



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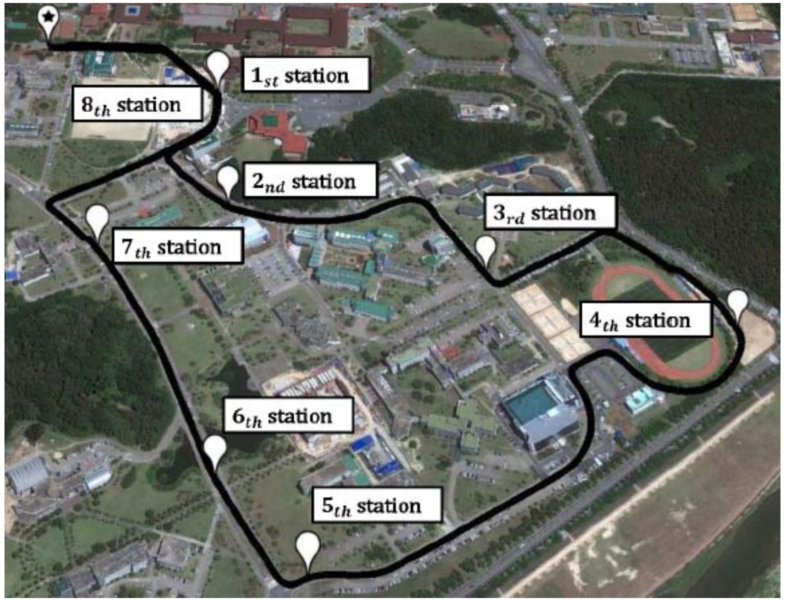
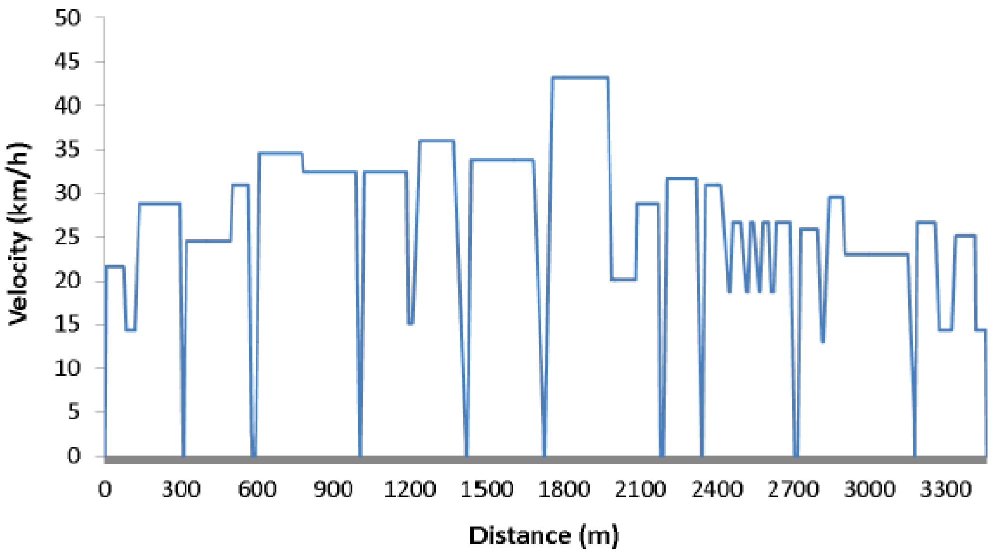
Basic Model: Modeling Assumptions

- There are *k* identical vehicles are in service
- Velocity profile is known
- Drivers follow the velocity regulations

SERVICE SCHEDULE OF THE KAIST OLEV

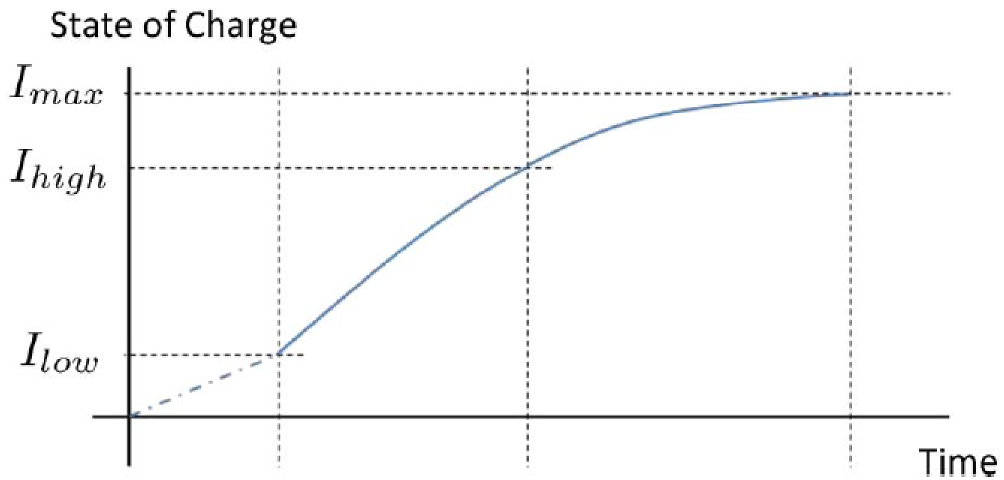
No. of Stations	Locations	Arriving Time
Start	Base Station(Start)	00:00
1st Station	Sports Complex	01:00
2nd Station	Creative Learning Center	02:00
3rd Station	East Dormitory Hall	03:30
4th Station	Medical Center	04:40
5th Station	Main Entrance	06:40
6th Station	Central Pond	07:20
7th Station	Main Building	08:20
8th Station	Sports Complex	10:00
9th Station	Base Station(End)	11:00





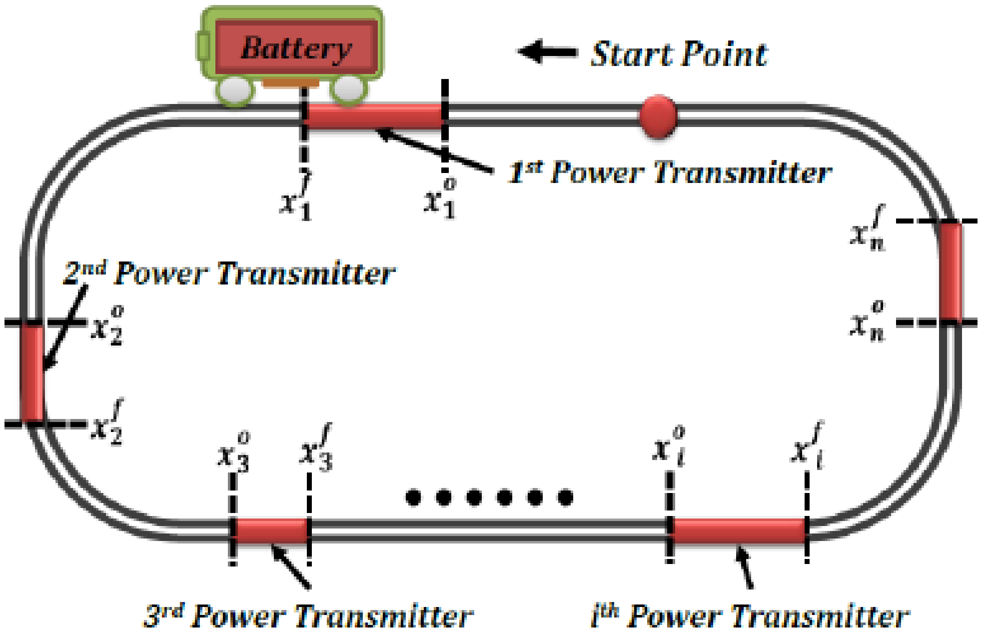
Basic Model: Modeling Assumptions

- Linear modeling for the battery SOC
- SOC linearly proportional to the charging time
- SOH not considered in the modeling



Basic Model: Notations

- **Decision variables**
  - x_i^0: start point of the ith power track, $i \in \{1, \dots, n\}$
  - x_i^f: end point of the ith power track, $i \in \{1, \dots, n\}$
  - n: number of power tracks
  - I_{max}: battery size

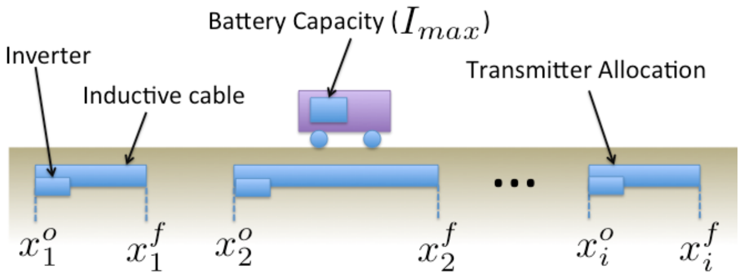


Basic Model: Notations

- **Parameters**
  - k : number of buses
  - t_i^0: time at x_i^0
  - t_i^f: time at x_i^f
  - $P_{bat}(t)$: energy level in the battery at t
  - I_{low}: lower limit of the energy level
  - I_{high}: upper limit of the energy level
  - c_{inv}: fixed cost of the power track
  - c_{cable}: variable cost of the power track

Basic Model: Cost Function

- **Objective Function**

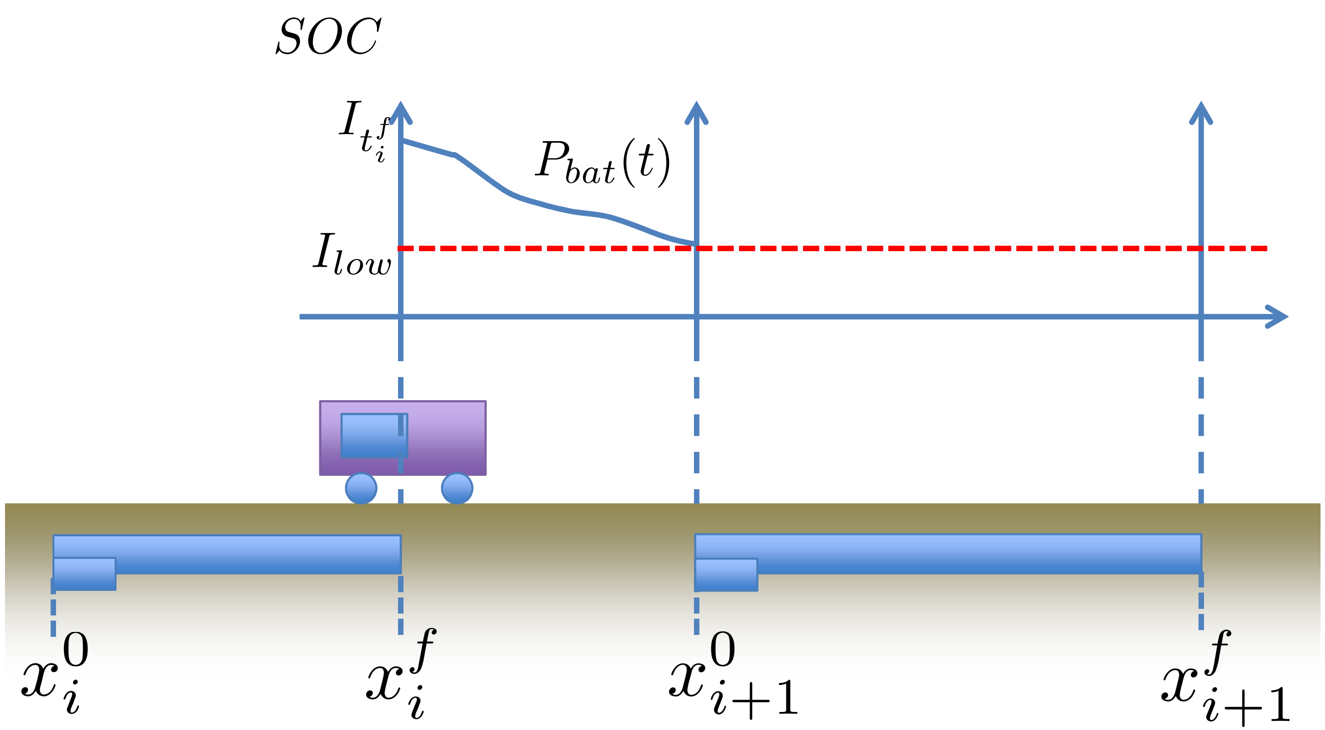


The OLEV System and Decision Variables

$$\text{Min}\ \boxed{k \cdot F_p(I_{max})} + \boxed{n \cdot c_{inv} + \sum_{i=1}^{n} c_{cable} \cdot (x_i^f - x_i^o)}$$

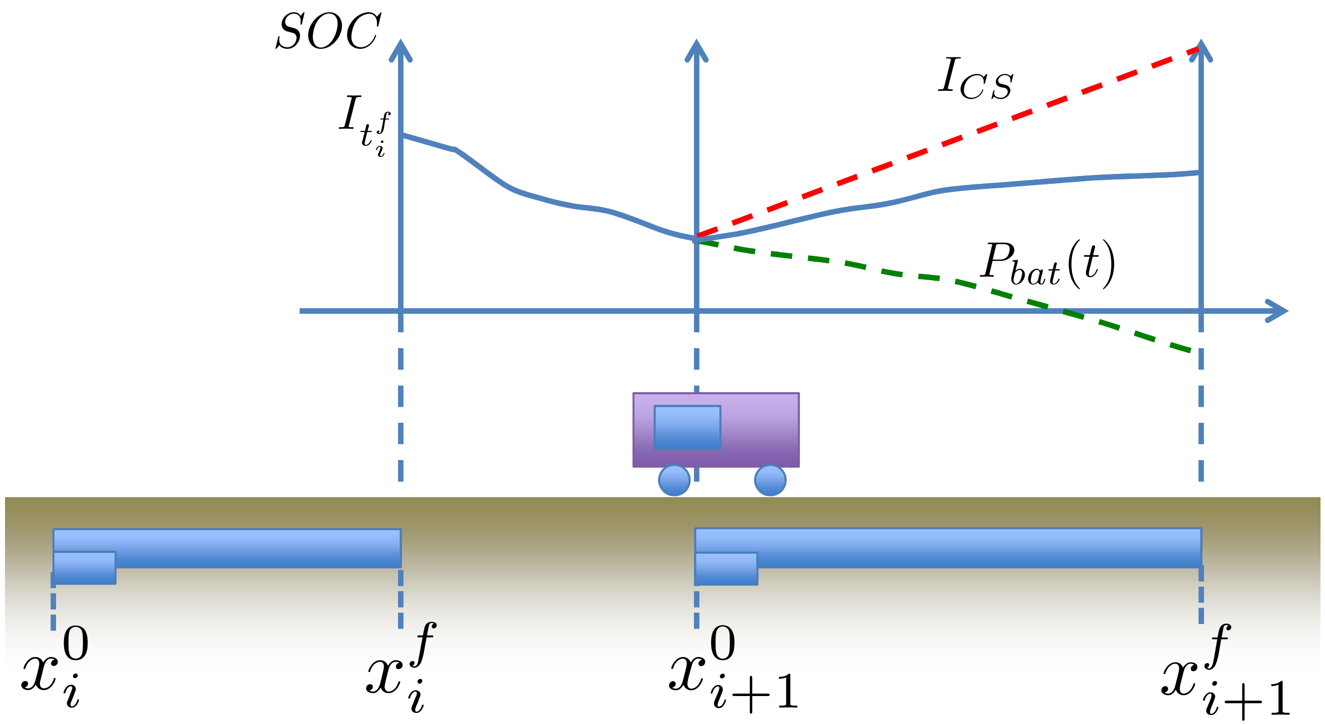
Total battery cost   Total power track cost

Basic Model: Energy Dynamics



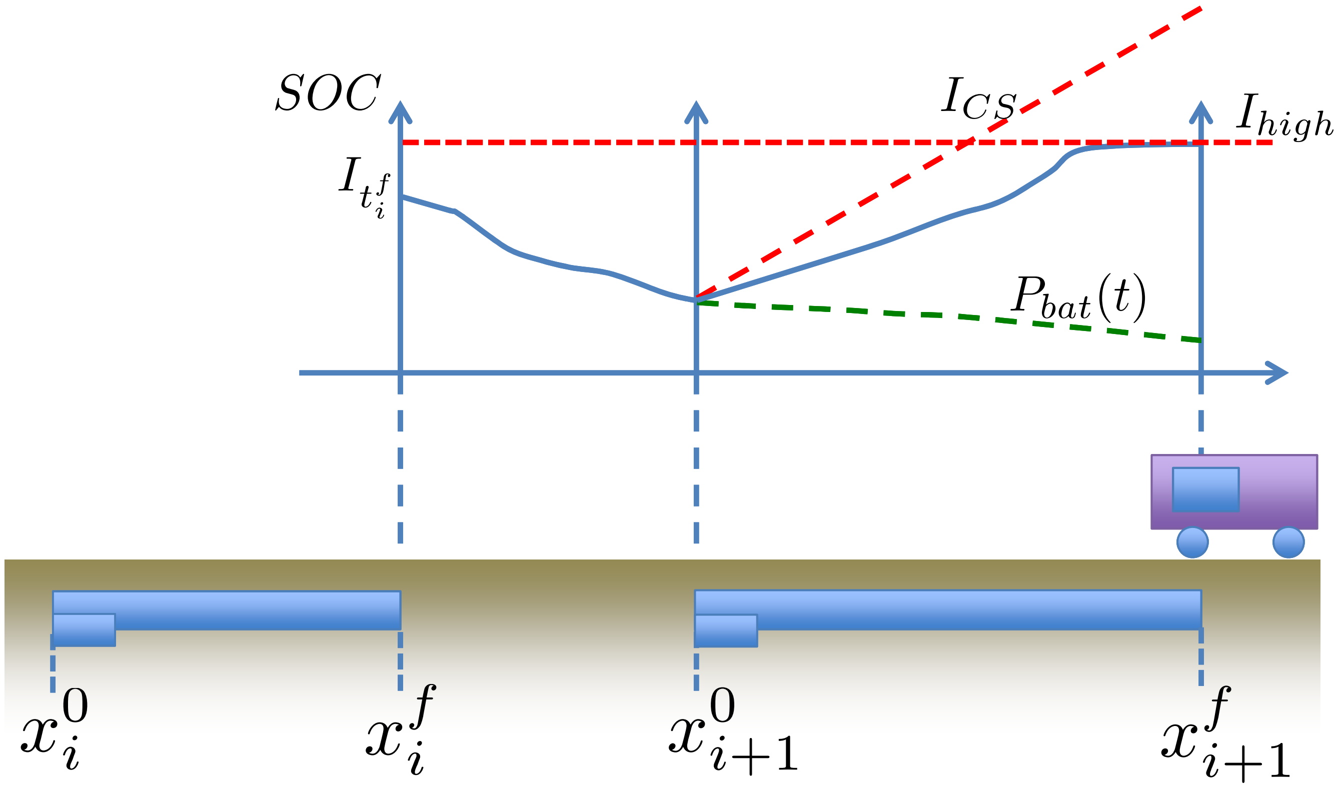
$$I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^o} P_{bat}(t)\,dt > I_{low}, \quad i = 1,2,\ldots,n-1$$

Basic Model: Energy Dynamics



$$I_{t_{i+1}^f} = Min\left\{ I_{high}, I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^f} P_{bat}(t)\,dt + I_{CS}(t_{i+1}^f - t_{i+1}^o) \right\},\ i = 1, 2, \ldots, n-1$$

Basic Model: Energy Dynamics



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Basic Model: Optimization Model

$$\text{Min } k \cdot F_p(I_{max}) + n \cdot c_{inv} + \sum_{i=1}^{n} c_{cable} \cdot (x_i^f - x_i^o)$$

$$I_{high} - \int_0^{t_1^o} P_{bat}(t)\,dt > I_{low}$$

Initial bound

$$I_{t_1^f} = Min\left\{ I_{high}, I_{high} - \int_0^{t_1^f} P_{bat}(t)\,dt + I_{CS}(t_i^f - t_i^o) \right\}$$

$$I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^o} P_{bat}(t)\,dt > I_{low}, \quad i = 1,2,\ldots,n-1$$

lower bound

$$I_{t_{i+1}^f} = Min\left\{ I_{high}, I_{t_i^f} - \int_{t_i^f}^{t_{i+1}^f} P_{bat}(t)\,dt + I_{CS}(t_{i+1}^f - t_{i+1}^o) \right\}, \; i = 1,2,\ldots,n-1$$

Upper bound

$$x_i^f < x_{i+1}^o, \quad i = 1,\ldots,n-1, \text{ and} \qquad x_i^o < x_i^f, \; i = 1,\ldots,n$$

Order of the power tracks

$$\sum_{\forall i} y_i \le L.$$

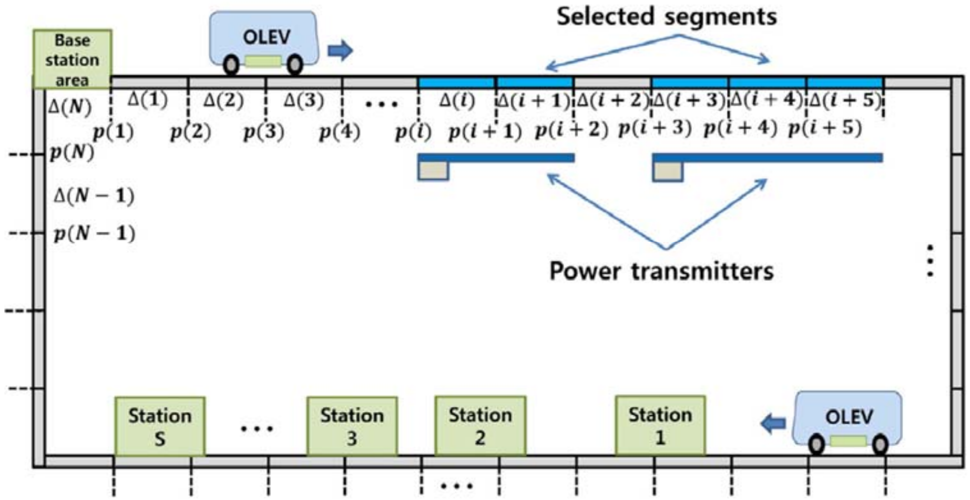
Max power track limit

$$x_i^j = \int_0^{t_i^j} V(t)\,dt, \qquad j \in \{0, f\}$$

Time-space relationship

Solution Algorithm

- **Continuous model – global optimization**
- **Discretized model – MIP optimization/dynamic programming**



$$\min \sum_{n=1}^{N} C^s(n)S(n) + C^l \sum_{n=1}^{N} Z(n) + kC^b E^{max}$$

s.t

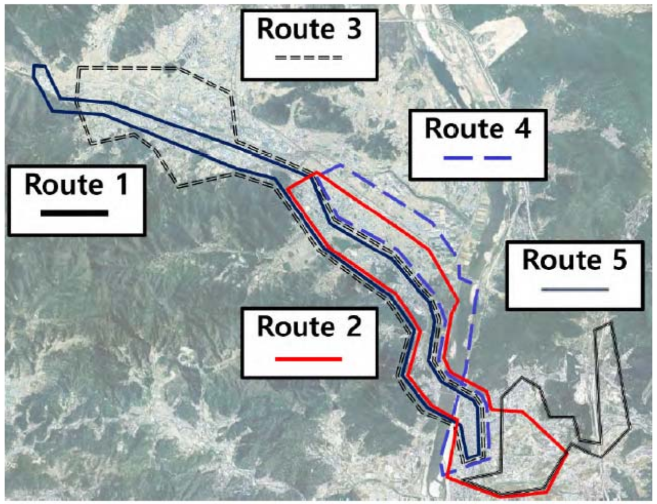
$$\begin{aligned}
&E^{low} \leqslant E(n) \leqslant E^{high}, \\
&S(n) - S(n-1) \leqslant Z(n), \\
&E(n) = E(n-1) + p_c(n)S(n) - p_d(n) - q(n), \\
&S(n) \in \{0,1\}, Z(n) \in \{0,1\}, q(n) \geqslant 0, \text{ and} \\
&E^{max} \geqslant 0.
\end{aligned}$$

$$\frac{dE(t)}{dt} = \begin{cases} -P_d(t) & \text{for } \mathcal{S}_1, \\ P_c(t) - P_d(t) & \text{for } \mathcal{S}_2, \end{cases}$$

- $\mathcal{S}_1$: shuttle operating where no power transmitter is installed;
- $\mathcal{S}_2$: shuttle operating where a power transmitter is installed.

Variations of Micro-Model

- **Multiple route problems**
- **Robust optimization problem**
  - considering charging/discharging uncertainty
- **Battery life considerations**



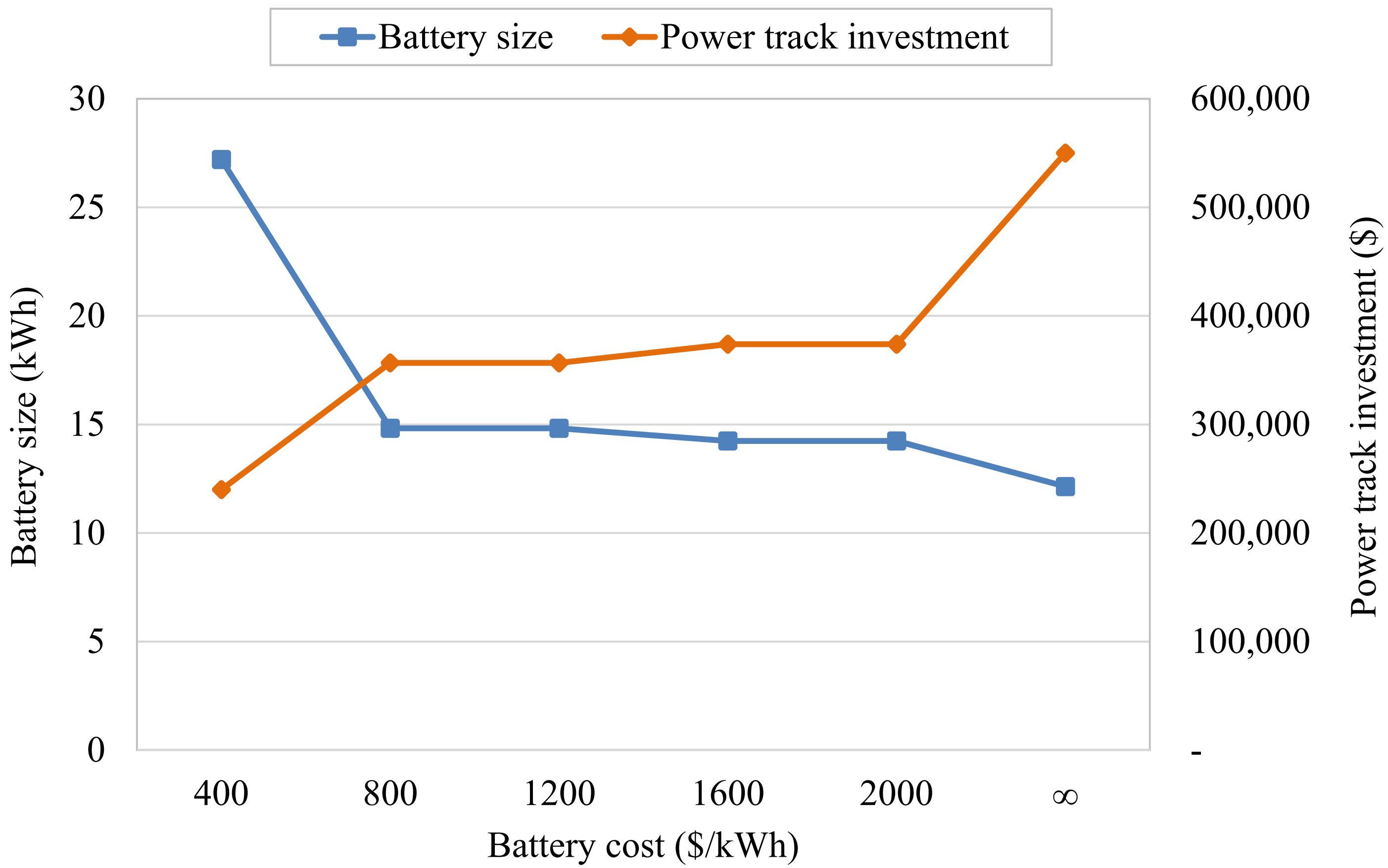
Example Case: Gumi-OLEV case

- **Gumi OLEV Public transit bus system**
  - The bus line 180 in Gumi city consists of 57 stations

번호	정류장ID	정류장 이름	정류정 사이 거리 (km)
0	0	차고지	0
1	10080	구미역	0.5
2	10167	농협	0.4
3	10134	금오산사거리	0.3
4	10814	푸르지오캐슬B단지	0.3
5	10794	가톨릭근로자문화센타	0.2
6	10479	송정동번개시장건너	0.3
7	10501	시청후문앞	0.3
8	10251	동아백화점앞	0.4
9	10092	오성예식장앞	0.4
10	10532	신평사거리	0.8
11	10526	신평1동	0.5
12	10259	롯데마트건너	0.3
13	10796	코오롱	0.8
14	10047	공단본부건너	0.6
15	10075	구미세무서건너	0.5
16	10910	LS전선	0.5
17	10245	동락공원	1.4
18	10262	LG디스플레이정문	0.3
19	10380	삼성에스디에스	0.4
20	10486	수도가압장건너편	0.2
21	10383	삼성전자후문	0.7

Example Case: Gumi-OLEV case

- **Robust optimization results**



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- Operation is scheduled
- Application: public bus system
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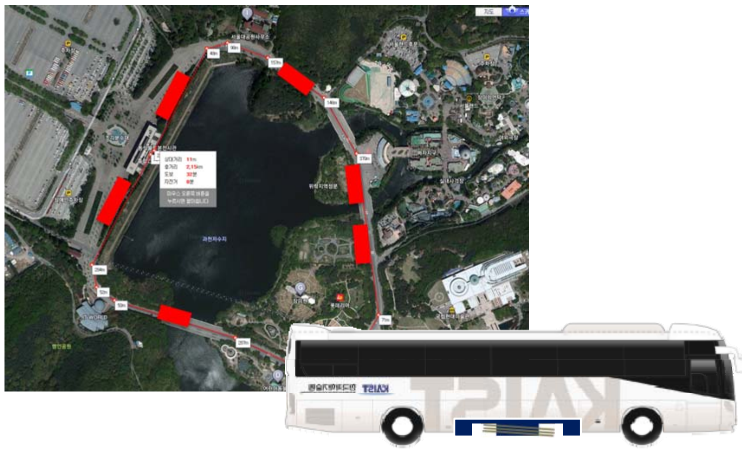

Macro-Model

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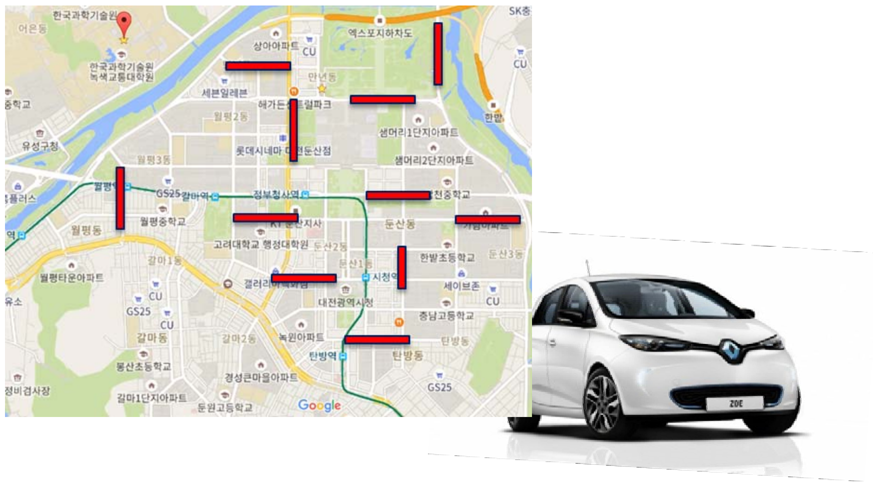
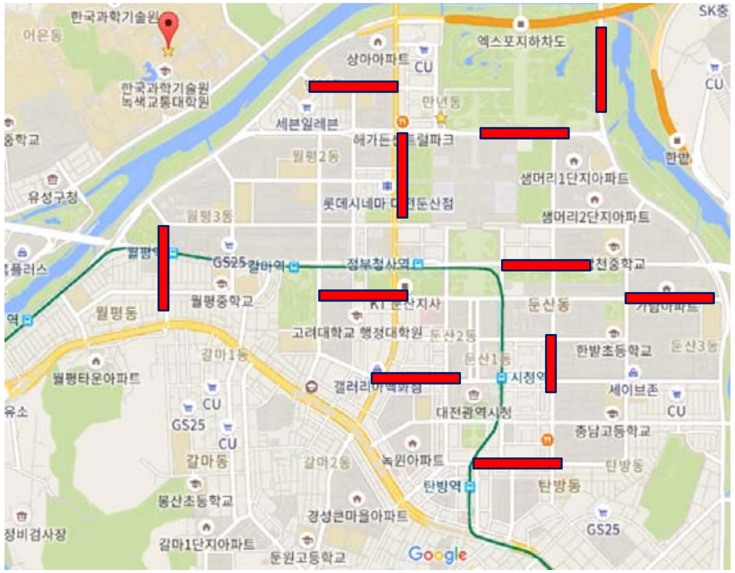


Macro Problem

- **Understand the high-level charging dynamics of the DWC passenger vehicles**
- **Provide engineers and policy makers with insights**
  - What is the appropriate size of the battery?
  - How many power-tracks should be installed for DWC-EV vehicles in a city?
  - Is a sparse installation of long power-tracks better than a dense installation of short power-tracks, or vice versa?

Modeling

- **Scenario**
  - Assume that multiple power tracks are installed in heavily congested intersections in Daejeon City (location of KAIST)
  - A dynamic wireless charging **taxi** is driving around in the city



KAIST

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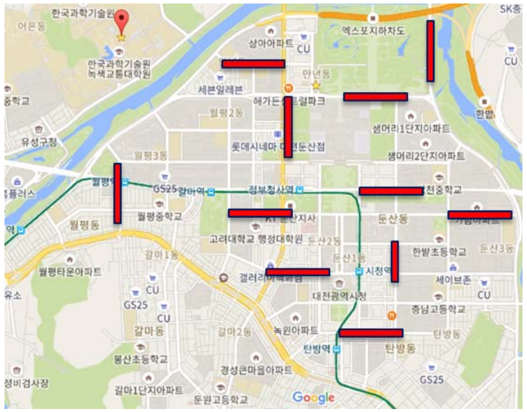
Why Installing at Intersections

- **Previous work supporting installation at intersections**
  - Lukic, Srdjan, and Zeljko Pantic. "Cutting the cord: Static and dynamic inductive wireless charging of electric vehicles." Electrification Magazine, IEEE1.1 (2013): 57-64
  - Chopra, Swagat, and Pavol Bauer. "Driving range extension of EV with on-road contactless power transfer—A case study." Industrial Electronics, IEEE Transactions on 60.1 (2013): 329-338
  - Ou, Chia-Ho, Hao Liang, and Weihua Zhuang. "Investigating wireless charging and mobility of electric vehicles on electricity market." Industrial Electronics, IEEE Transactions on 62.5 (2015): 3123-3133

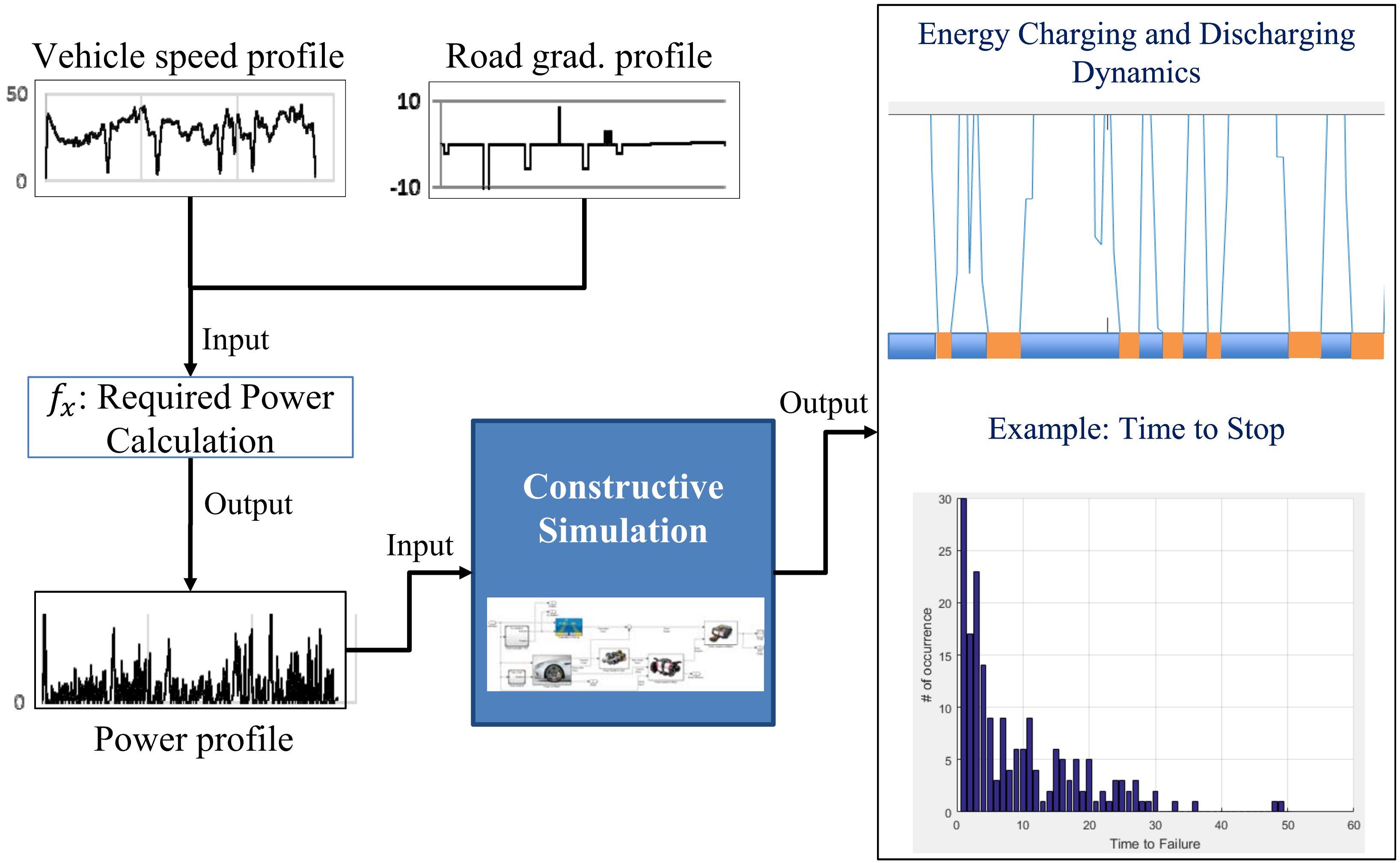
Data Collection and Analysis

- **Constructive (live + virtual) simulation**
  - Collecting actual data for "energy discharging" data (live)
  - Analyzing "energy charging" behavior (virtual)



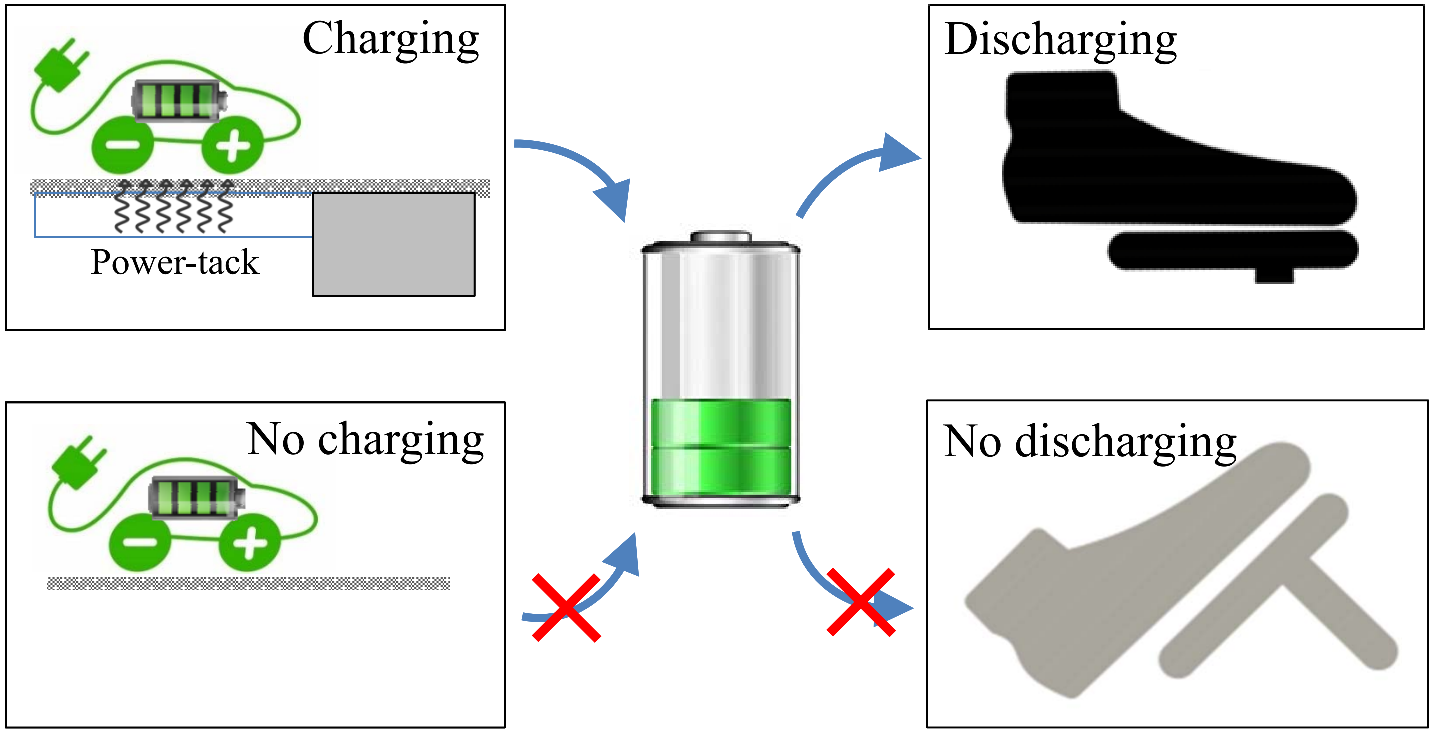
Energy Discharge Evaluation

- **The brief estimation process of parameter**



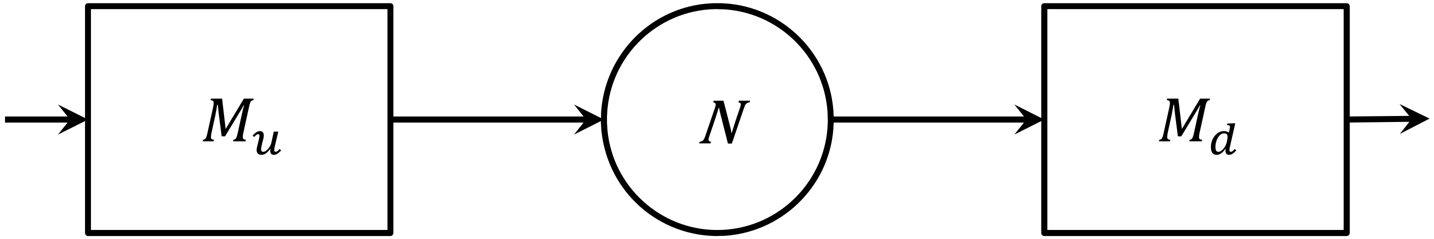
Modeling

- **DWC EV system dynamics** – from the viewpoint of the **battery**
  - ✓ Electric energy = Continuous flow
  - ✓ Stochastic behavior → continuous modeling is required



Modeling

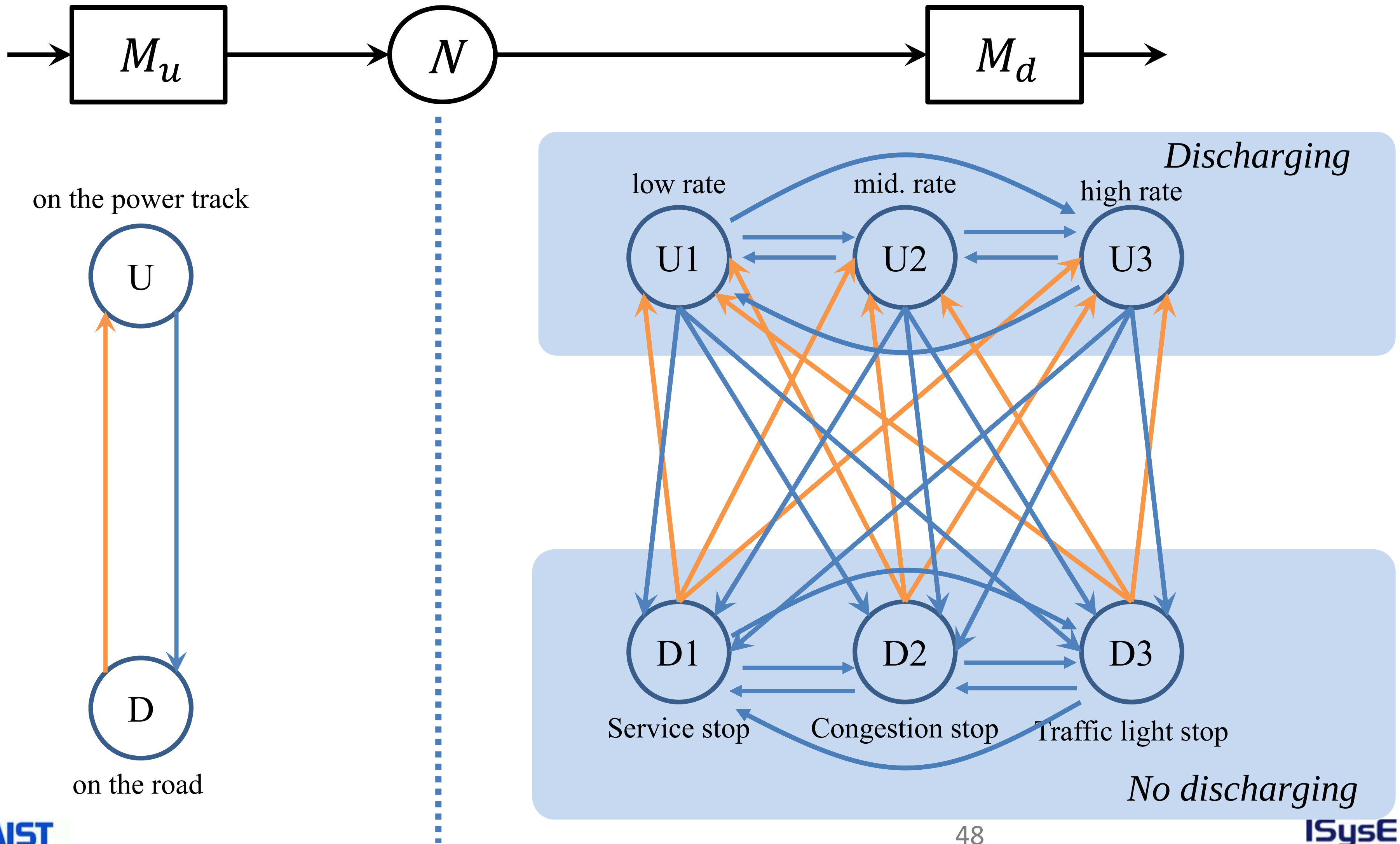
- **Two-stage Markovian continuous flow system with a finite buffer**



Field \ Role	supply the WIP	storage space	pull the WIP
Production line	upstream machine	buffer	downstream machine
DWC-EV	**power track charging**	**battery**	**driving**

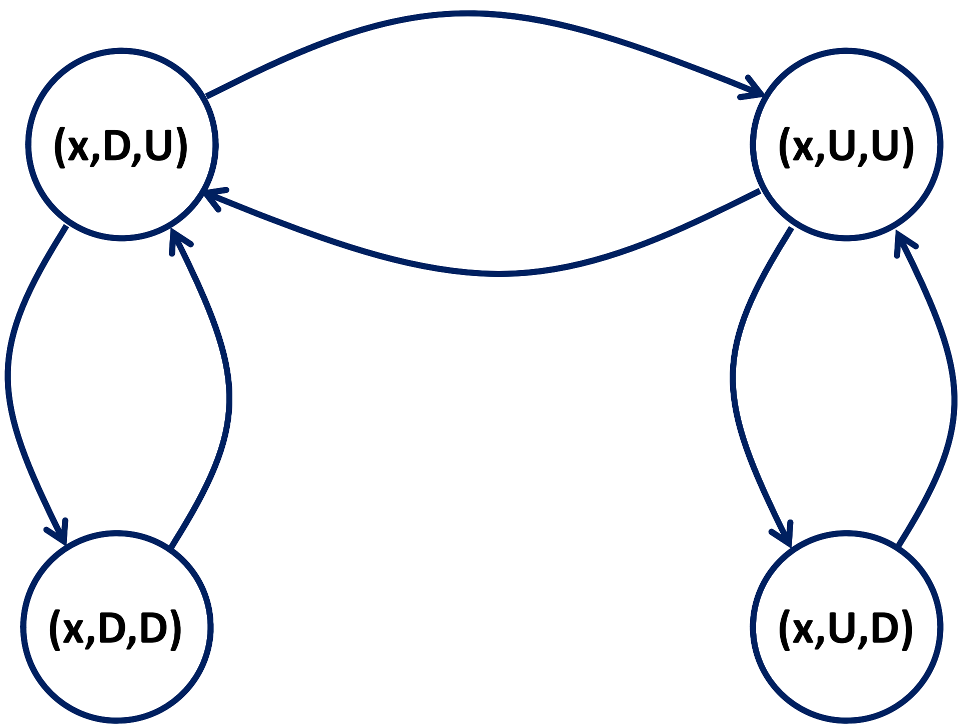
Initial Model

- **Purpose of the model – evaluating starvation rate**



System Dynamics

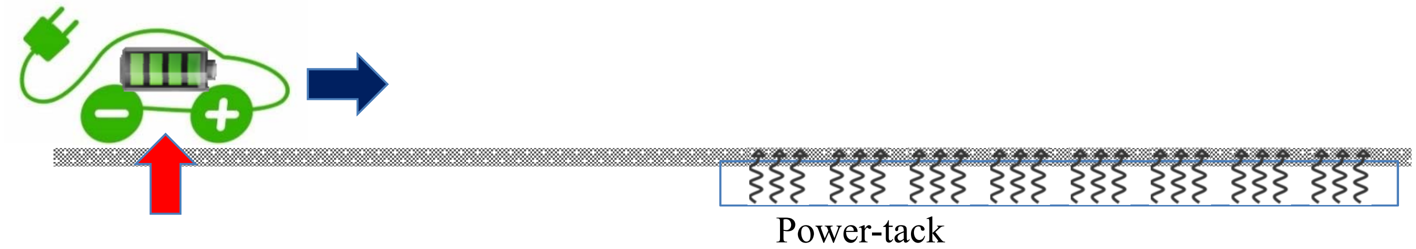
- **Interior processes**
- **State (x, A, B)**
  - x: buffer state, A: upstream machine, B: downstream machine
  - A, B ∈ $\{D, U\}$, wehre D: set of down states, U: set of up states

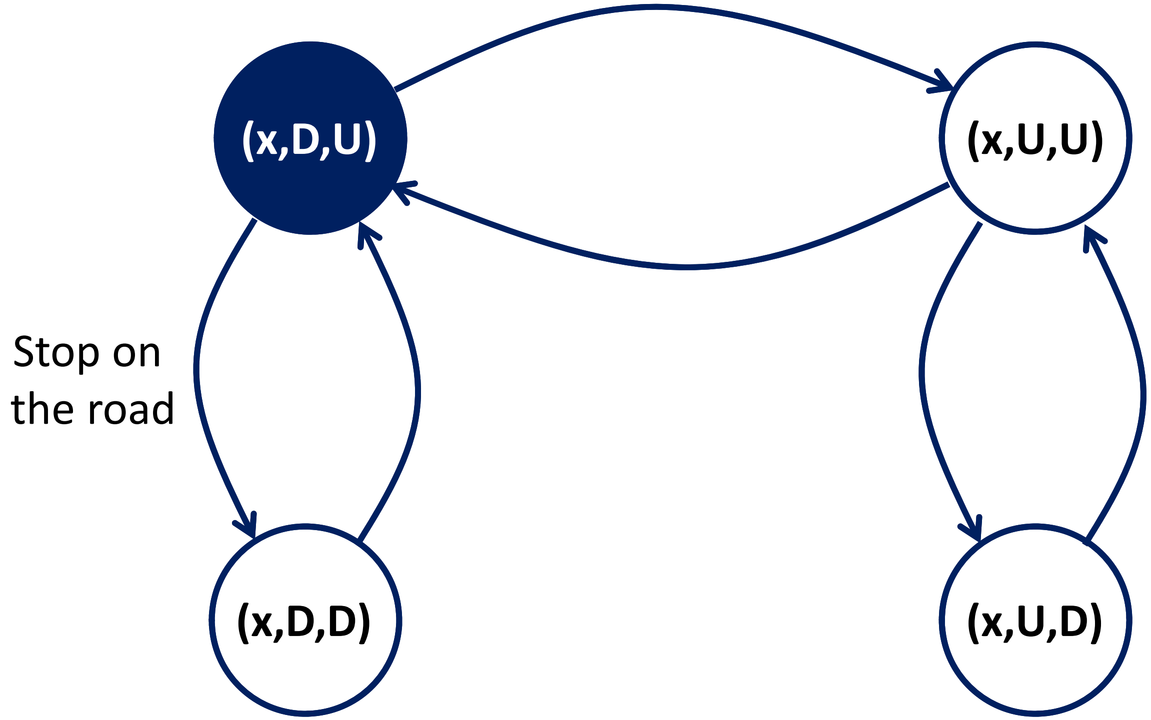


System Dynamics

- **Interior processes**

(x,D,U)

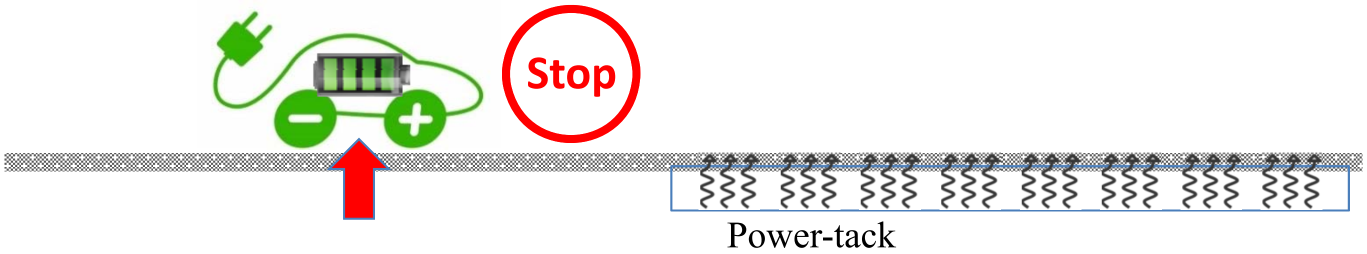


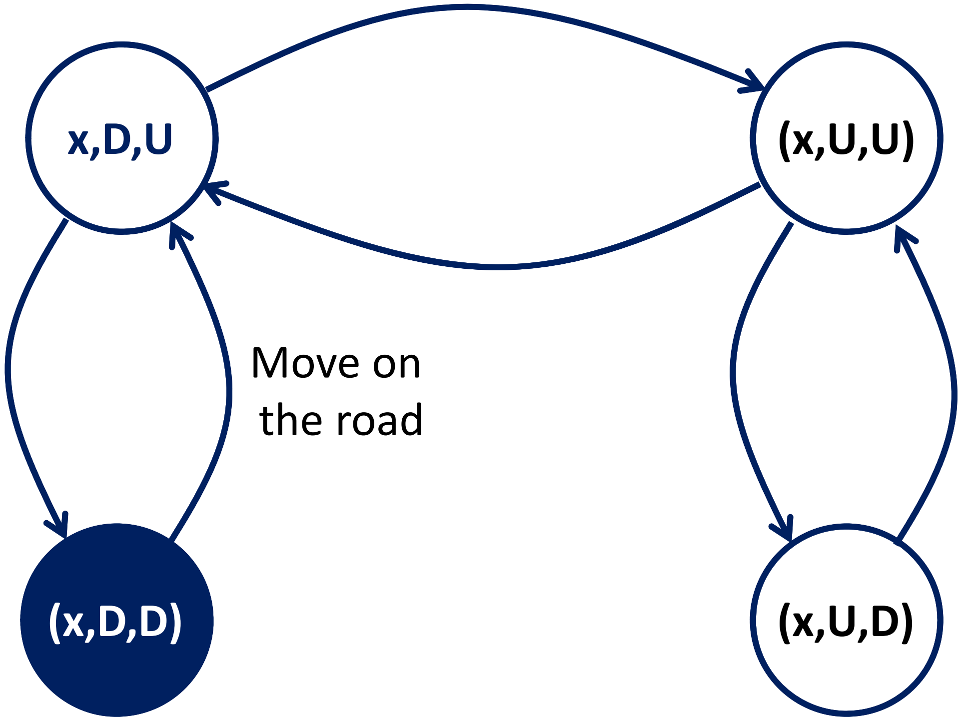


System Dynamics

- **Interior processes**

(x,D,D)

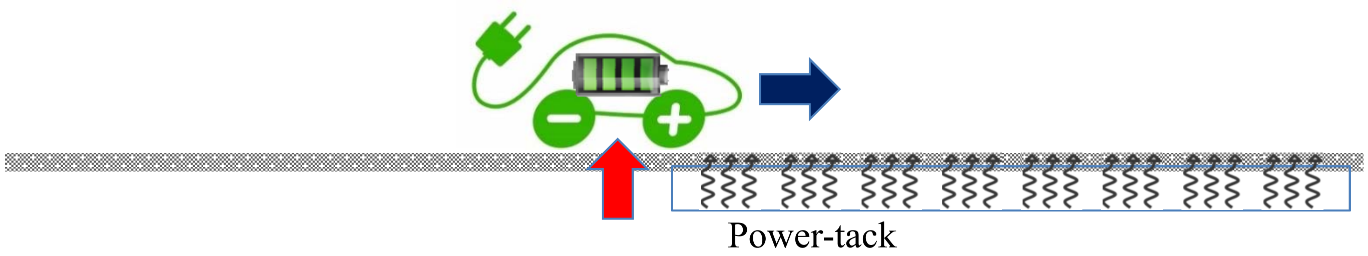


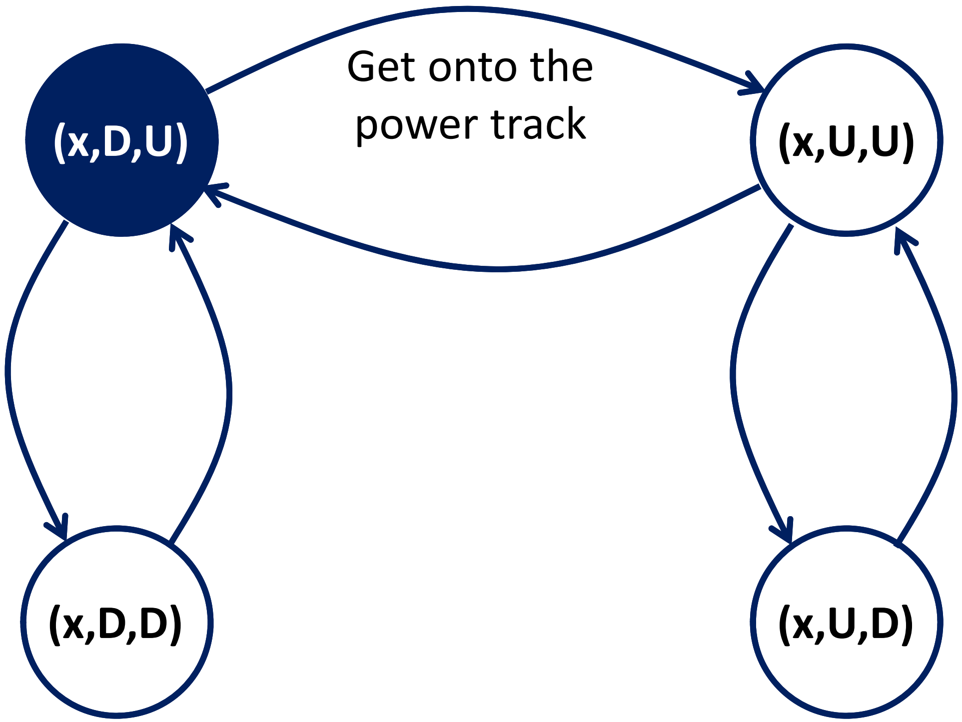


System Dynamics

- **Interior processes**

(x,D,U)

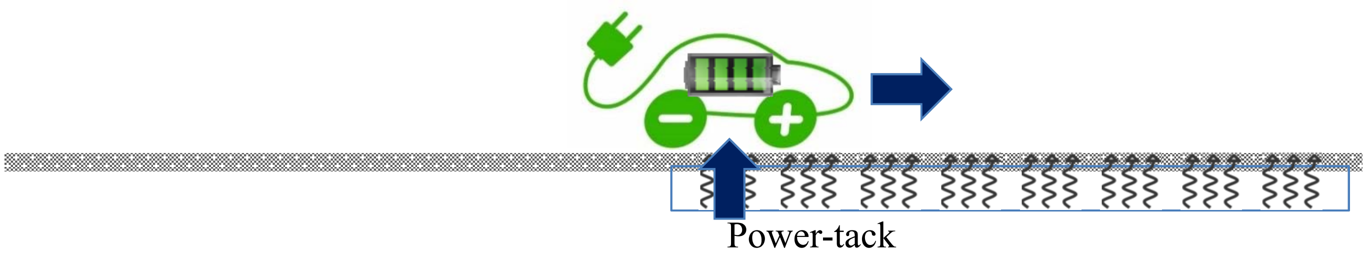


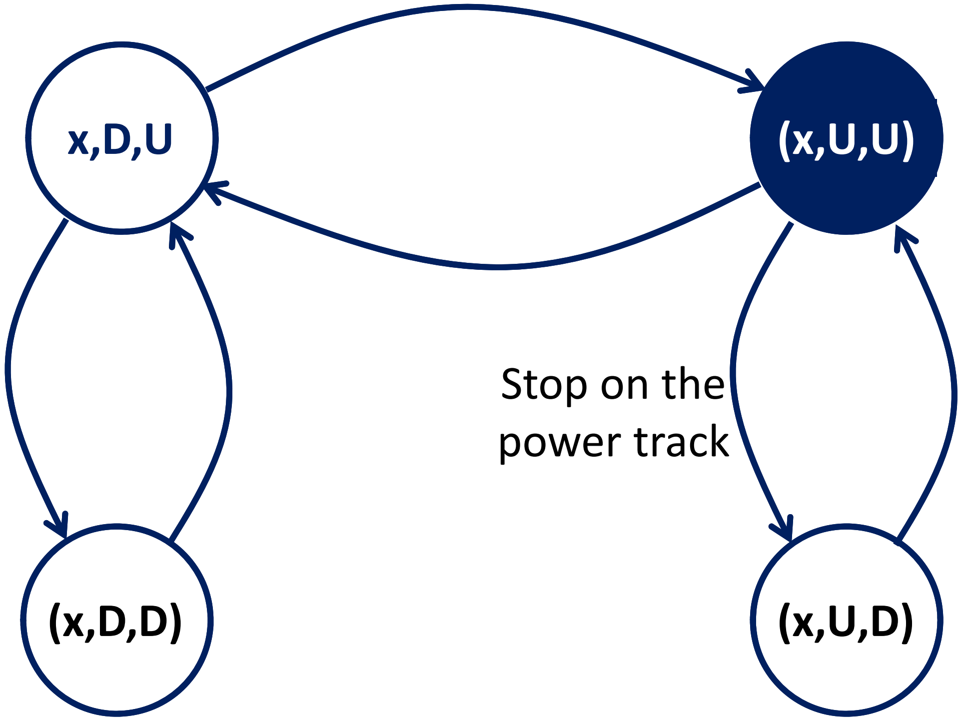


System Dynamics

- **Interior processes**

(x,U,U)

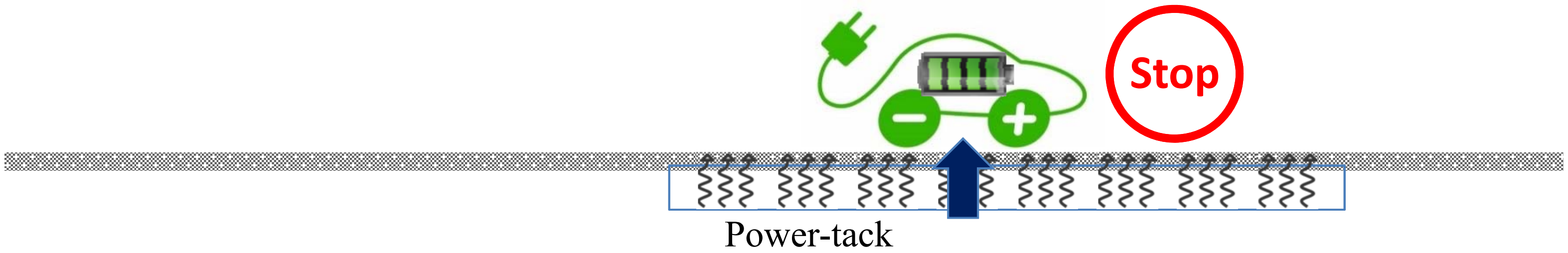


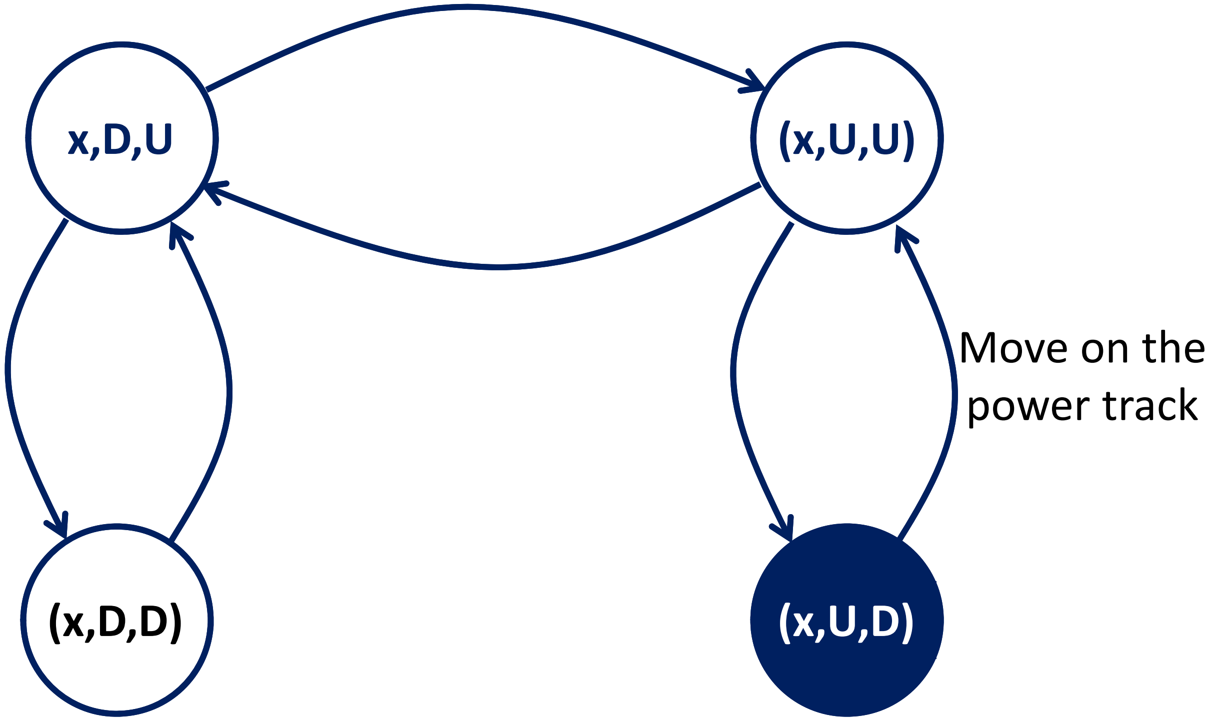


System Dynamics

- **Interior processes**

(x,U,D)

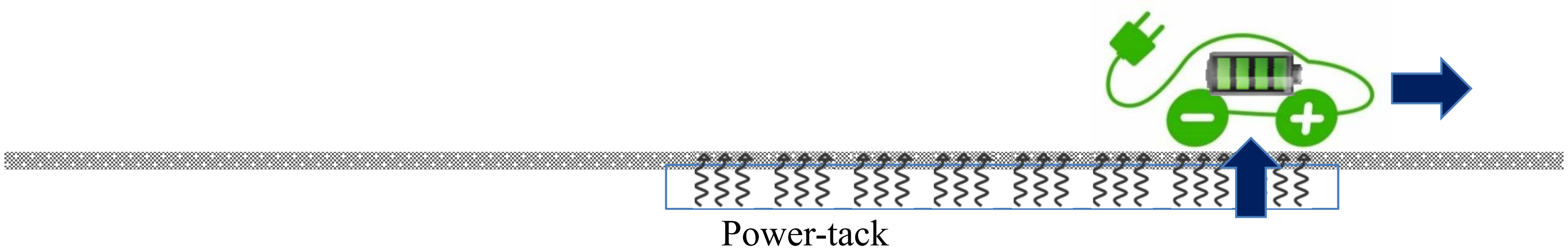


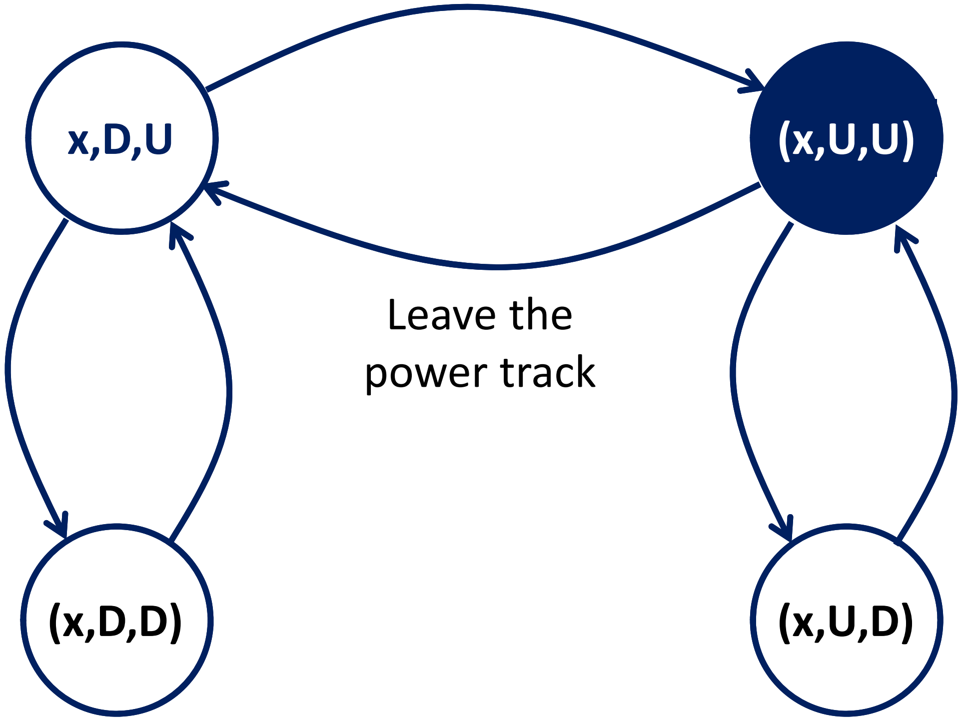


System Dynamics

- **Interior processes**

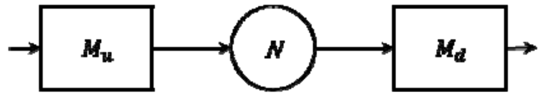
(x,U,U)



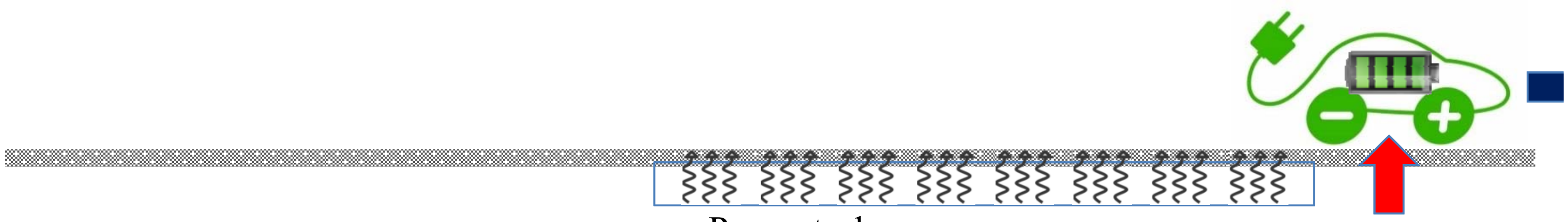


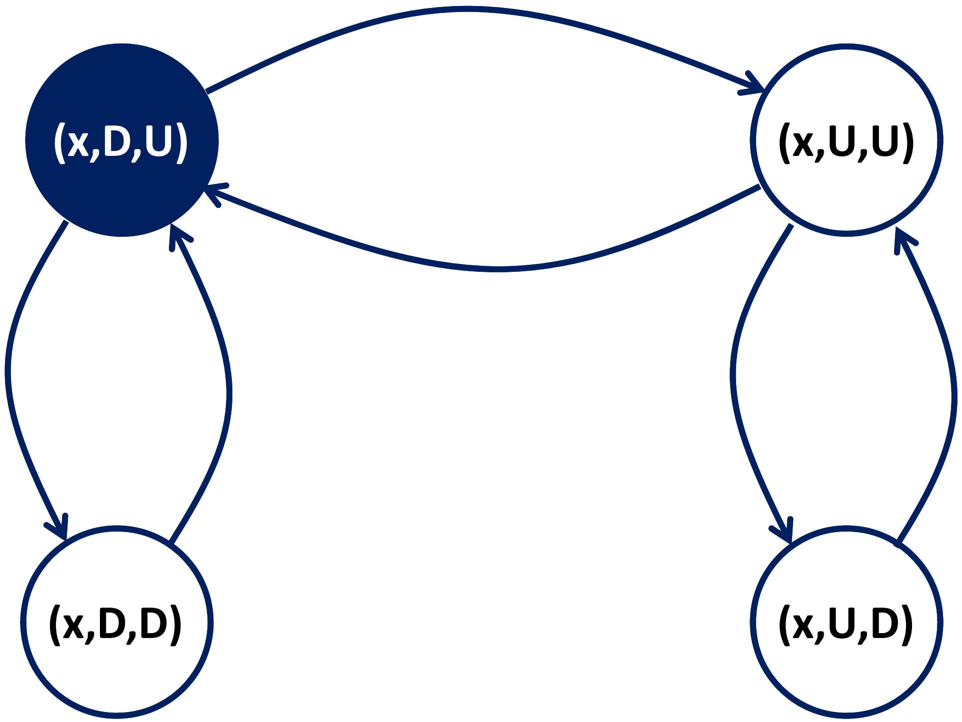
System Dynamics

- **Interior processes**



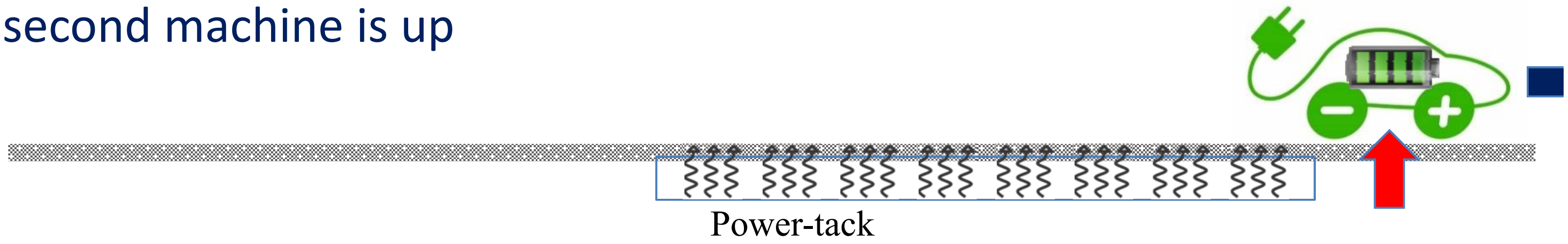
(x,D,U)

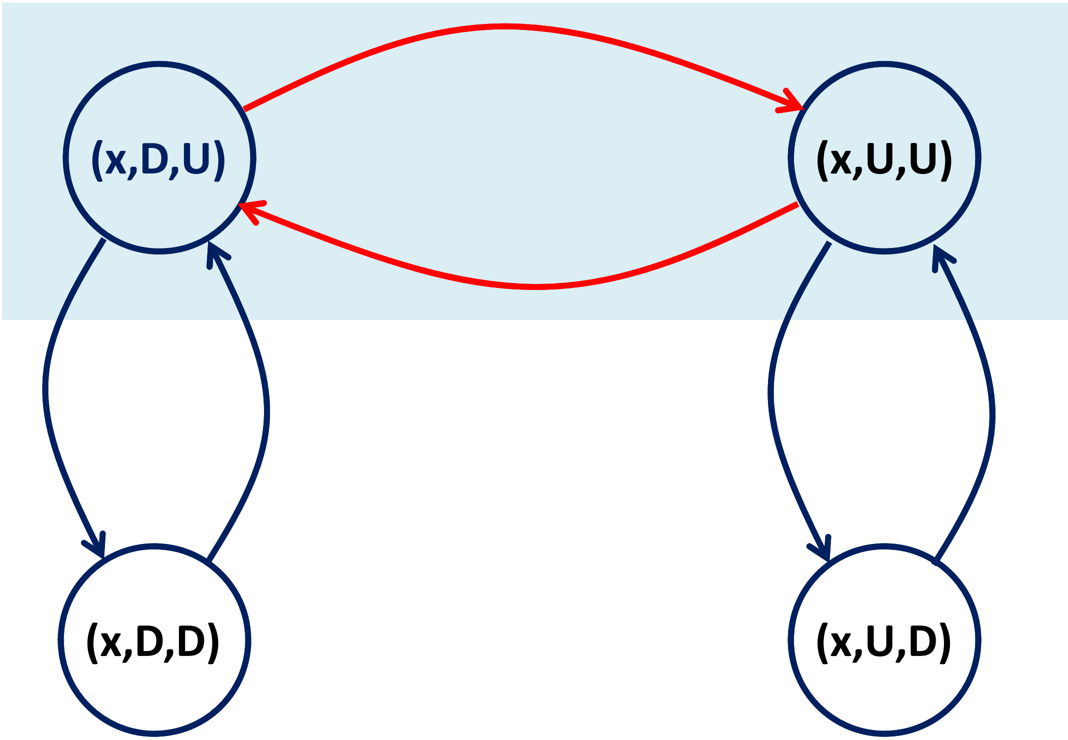




System Dynamics

- **Note**
  - State of the first machine is allowed to change when the second machine is up

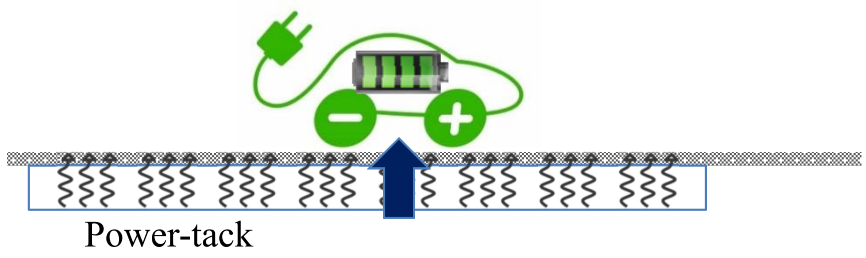


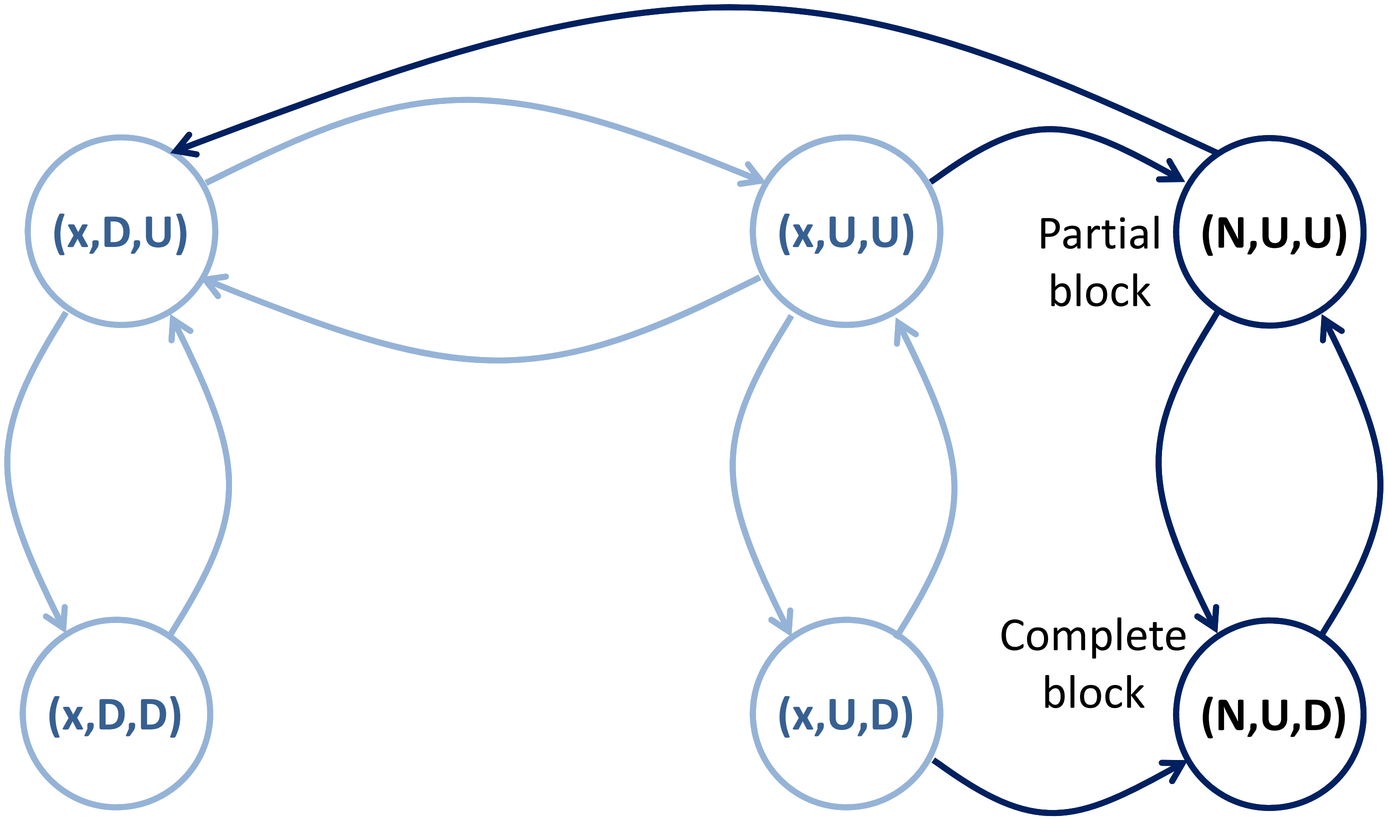


Driving state (Upstream machine is up)

System Dynamics

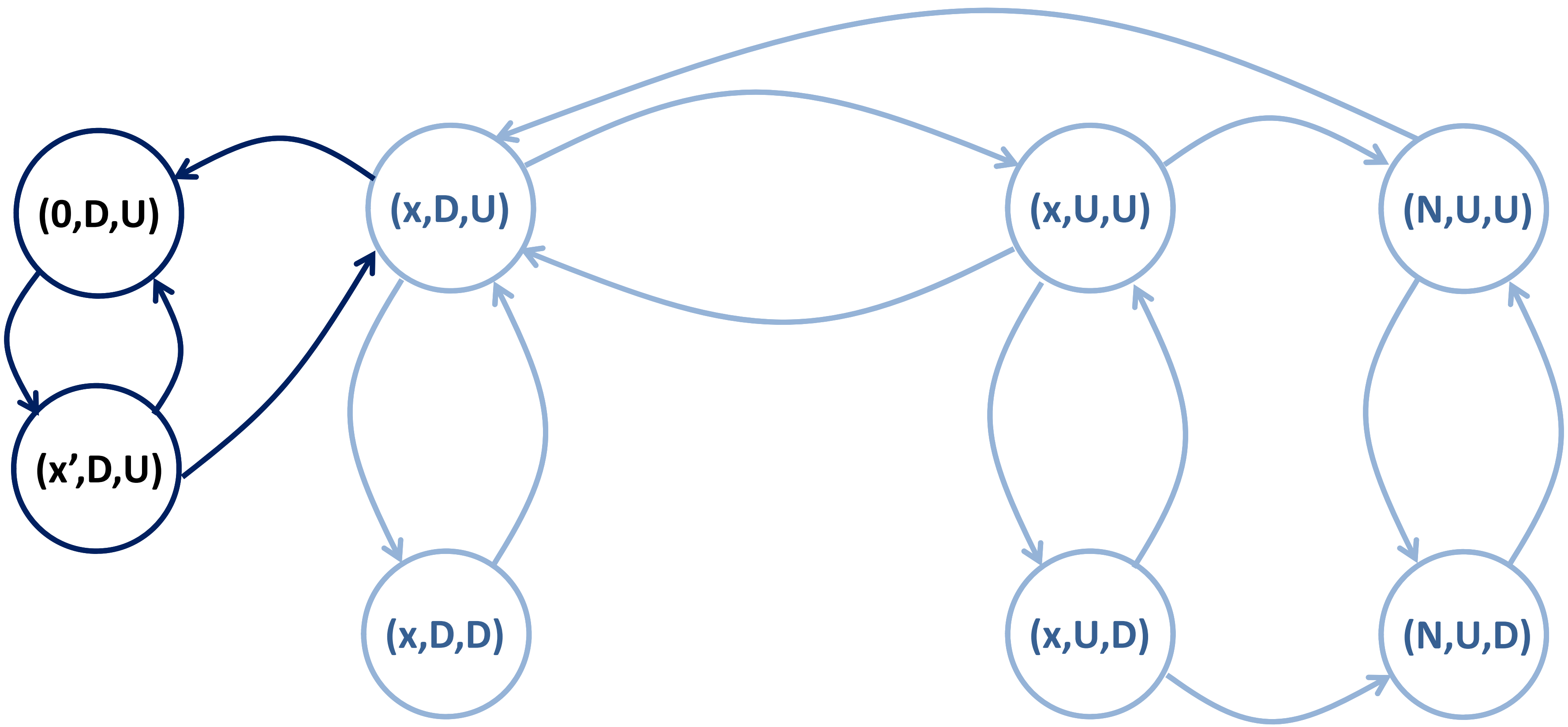
- **Boundary states – blockage**
  - Partial-block & complete-block
  - Charging rate > discharging rate
  - No failure of the first machine during the complete-block





System Dynamics

- **Boundary states – starvation**
  - Emergency charging



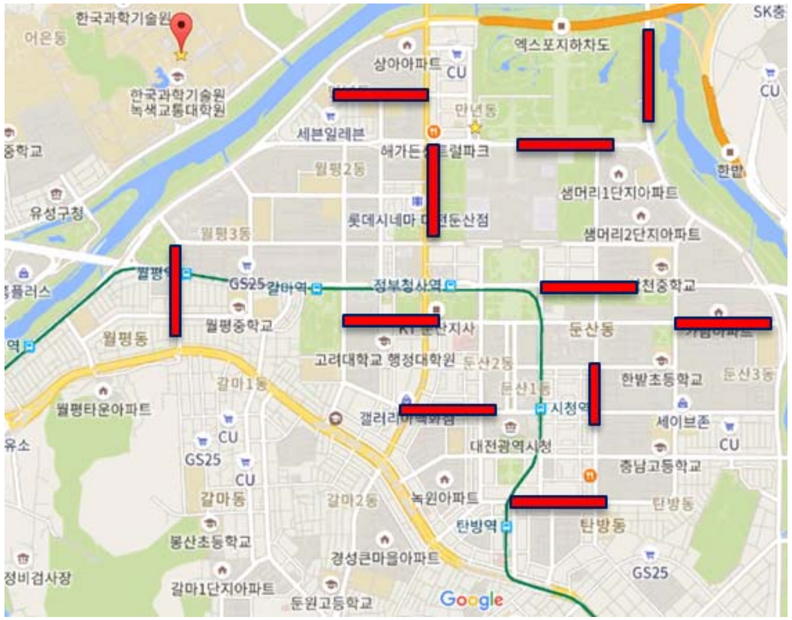
Analysis Method

- **Tan and Gershwin (2011)** provide **the general tool for the analysis**
- **Inputs = the processing rate vectors** μ^u **and** μ^d**,**

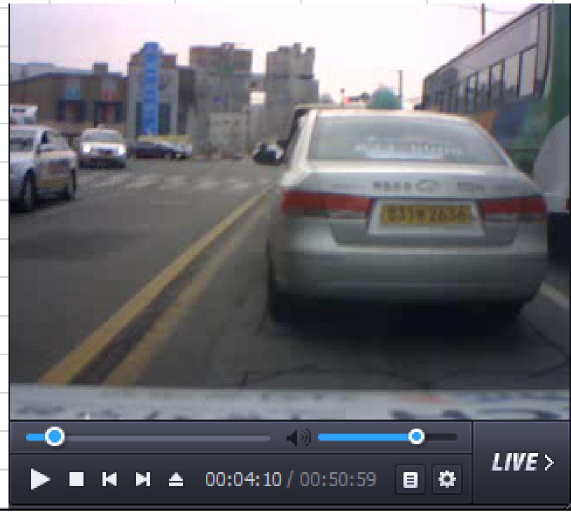
  the transition matrices λ^u **and** λ^d**,** and **the buffer size N**
- **Outputs = the steady-state probabilities** of the system by solving the differential equations describing the system dynamics, including
  1. Interior processes
  2. Boundary processes
  3. Material conservation
  4. Normalization

Preliminary Numerical Analysis

- **Daejeon City**
- **Data collection for Time to Stop and Time to Move**



TTR	time		
183	216	3.6	intersection
159	2938	49.0	intersection
129	1205	20.1	intersection
119	2178	36.3	intersection
101	2494	41.6	intersection
99	1700	28.3	intersection
94	1521	25.4	intersection
87	1412	23.5	intersection
85	2770	46.2	intersection
80	2339	39.0	intersection
75	924	15.4	intersection
67	10	0.2	intersection
60	608	10.1	intersection



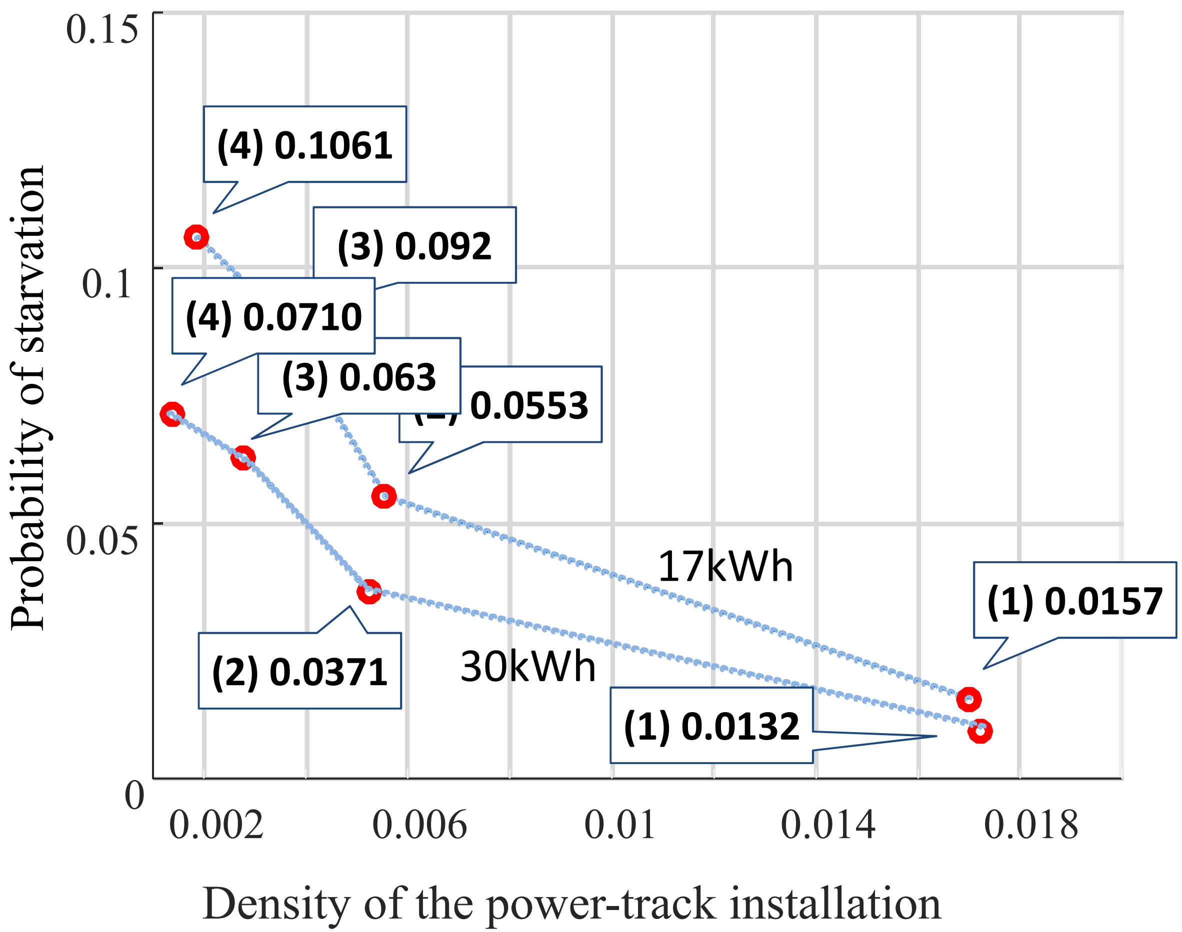
Preliminary Numerical Analysis

- **We investigated three scenarios:**
  1) Installing the charging facilities at **all (100%)** intersections
  2) Installing the charging facilities at **half** (**50%)** of intersections
  3) Installing the charging facilities at **1/3** (**33%)** of intersections
  4) Installing the charging facilities at **1/5** (**20%)** of intersections

- Battery capacity: N = 17 kWh and 30kWh

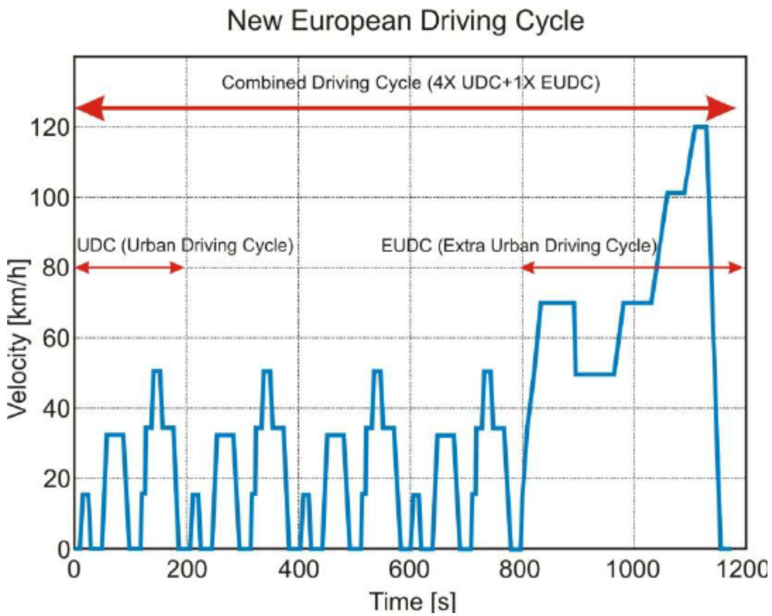
Preliminary Numerical Analysis

- **We investigated three scenarios: (1) 100% (2) 50% (3) 33% (4) 20%**

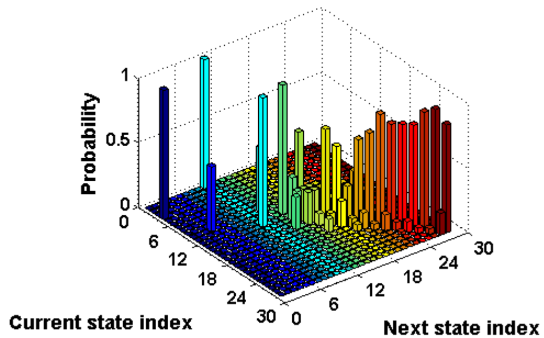


Issues in Macro Model

- **Trip based model**
- **Using standard driving cycle**
- **Human driving behavior**



Extract the driving characteristics and create Markov model



Future state $t+1$

Present state t	(0, +)	(0, -)	(0, 0)	(1, +)	…
(0, +)	0	0	0	0.0667	…
(0, -)	0	0	0.6250	0.0143	…
(0, 0)	0	0	0.5789	0.1250	…
(1, +)	0.1667	0.1667	0	0.3333	…
⋮	⋮	⋮	⋮	⋮	⋱

Topics

- Dynamic wireless charging EV
- On-Line Electric Vehicle (OLEV) at KAIST
- System issues
- Micro model
- Macro model
- Summary & conclusion

Conclusion

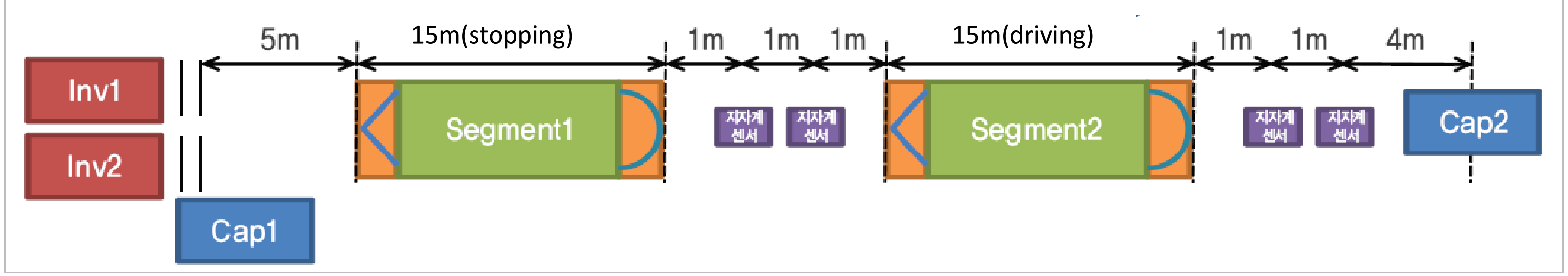
- **Micro Model**
  - tested and validated
  - effectively used for actual system designs
  - variations (robust optimization, multiple route, SOH) are under investigation
- **Macro Model**
  - far from complete
  - promising preliminary model
  - optimal decisions – Markov decision model or reinforcement learning

Future Research: Wireless Power Train

Osong Train Test Site(60kHz)

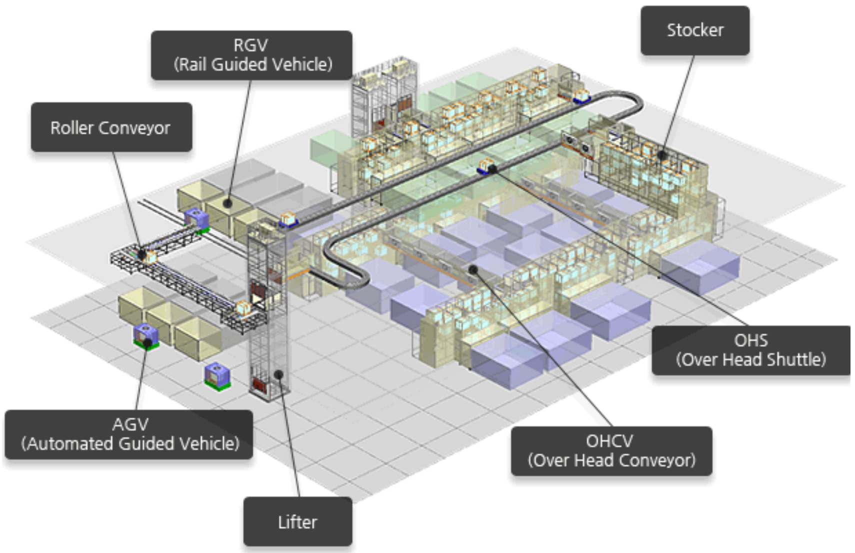
◈ **Held a demonstration of 60kHz wireless power transfer technology at the Osong Train Test Site with its application to catenary-free trams(Jun. 4, 2013)**

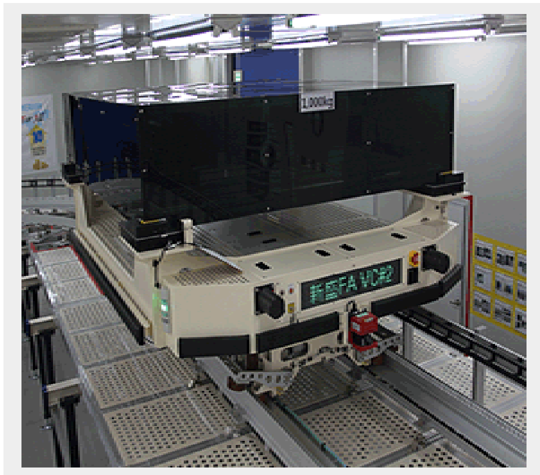
<Pick up>



AMHS in Semiconductor and LCD

- **Research topics**
  - Power track allocation issues
  - Re-charging policy
  - Optimal velocity profiles





Future Research: Self-Driving EVs

- **Autonomous EV with Wireless Charging**

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- **Young Dae Ko and Young Jae Jang, "The Optimal System Design of the Online Electric Vehicle Utilizing Wireless Power Transmission Technology," IEEE Transactions on Intelligent Transportation Systems, Vol. 14, No. 3, pp. 1255-1265, 2013.**
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- **Young Dae Ko, Young Jae Jang, and Min Seok Lee, "The Optimal Economic Design of the Wireless Powered Intelligent Transportation System using Genetic Algorithm considering Nonlinear Cost Function," Computers & Industrial Engineering, 89, pp. 67-79, November, 2015.**
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Thank you!

- **Contact Info:**
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- **Google “KAIST OLEV”**

BACKUP SLIDES

Emergency Charging Vehicle

- **Emergency charging vehicle**

AAA Is Now Providing Emergency Electric-Vehicle Charging Services To Stranded Drivers

If your EV stutters to a halt while you're cruising down the highway, call the same people who fix flats on your regular car. And more mobile charging options may soon be coming to your street.

BY ARIEL SCHWARTZ 1 MINUTE READ