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Reducing Energy Use in Multimodal Transportation System

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Outline

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- Motivation
- Preliminaries
  - Research Statement
  - Interactions between Traffic Demand and Supply
  - Intermodal Network
- Mathematical Model
- Solution Methodology
- Case Study and Preliminary Results
- Future Work
- Other Research

Transp[illegible] Dominates Total U.S. Petroleum C[illegible]on

Responsibility

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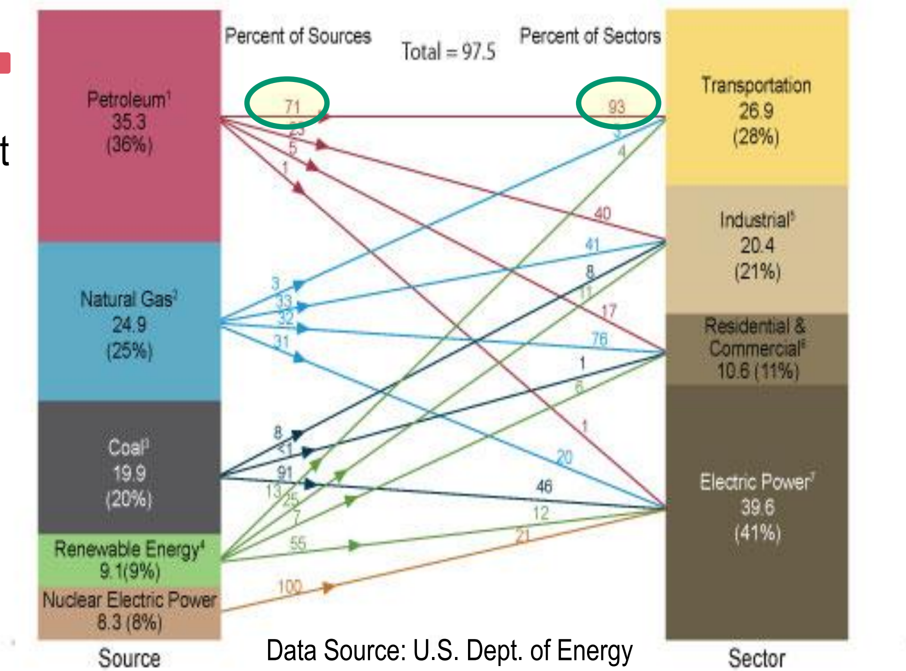
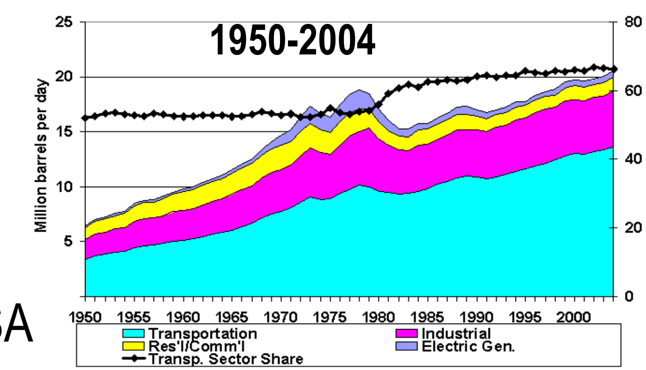
Primary Energy Consumption By Source and Sector, 2011

quadrillion Btu

Most important energy source



- "Transportation" use: the use of petroleum products as vehicle fuels
- Transportation system accounts for 65-71% of the nation's gasoline consumption



- Energy crisis becomes more and more urgent
- Non-renewable Oil provides 36% of energy sources in USA
- Transportation systems are highly oil dependent

Transportation Dominates Total U.S. Petroleum Consumption

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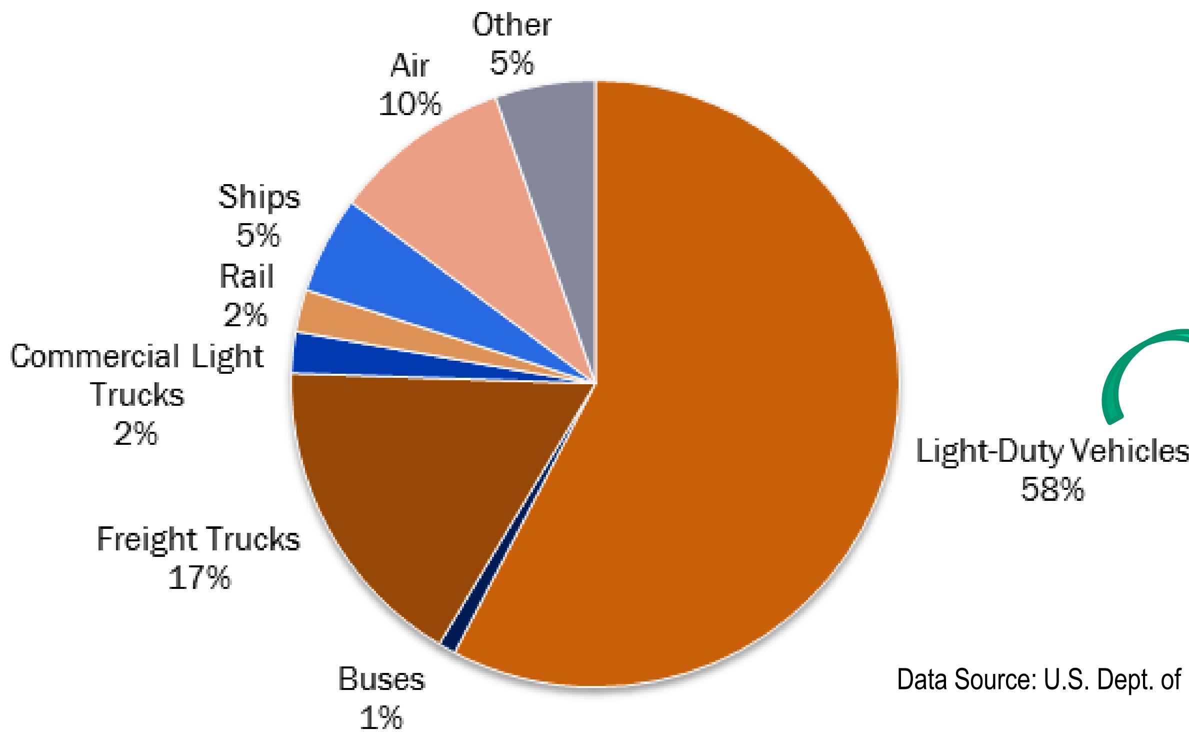
Potential

Transportation Energy Use by Mode (2008)



(passenger cars, fleet vehicles, and light truck)

Data Source: U.S. Dept. of Energy

- <u>Cars and Light Trucks</u> account for most of the share, then Truck and Aviation

Long Distance Passenger Transport Service Mode Energy Consumption Efficiency

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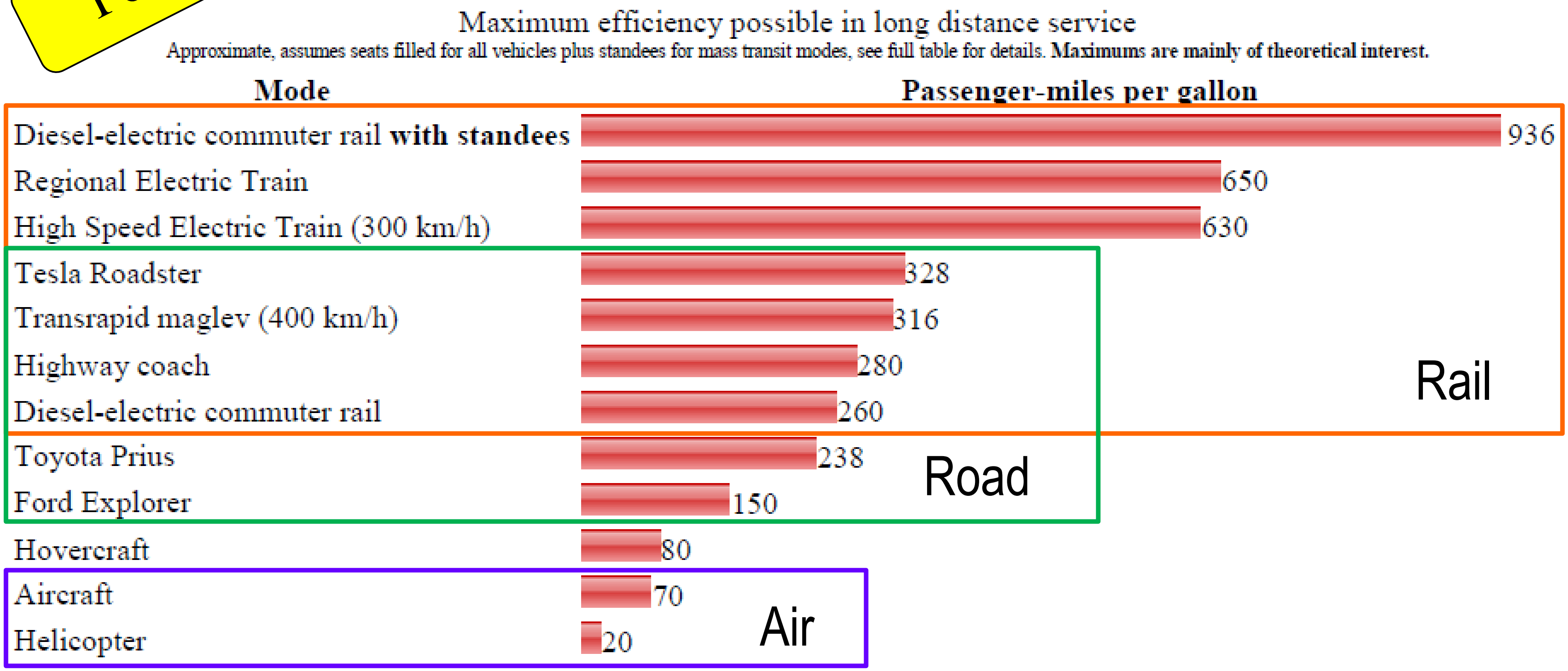
Potential

James Strickland, 2009



For passenger transportation, the order of energy efficiency is "Rail" > "Road" > "Air"

How

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Solutions for reducing energy use in transportation

1. Focus on major modes

- Cars/light trucks, freight trucks, and aviation
  - Account for nearly all passenger and freight activity—will continue to account for the lion's share for decades
- Other modes contribute very little to energy use/emissions
  - These modes may prove to be helpful as solutions

3. Develop system policy affecting both demand and supply

- Increase consumer demand for and manufacturer supply of efficient vehicles
- Enable more efficient transportation system operations
- Reduce demand for energy-intensive forms of travel

How

Policy Options

- Fuel Taxes (higher fuel prices)
  - Induces both consumer and supplier interest in vehicle efficiency
  - Motivates interest in reducing energy-intensive travel activity
  - <u>Will prompt consumer demand for more efficient systems</u>
  - Induces interest in alternative energy sources
- Vehicle Efficiency Standards
  - Compels development and supply of more efficient vehicles
- Land Use/Transportation Coordination
  - Better enables consumer reductions in energy-intensive travel activity (e.g., more travel alternatives)
- Public Investments in Infrastructure and More Efficient System Operations
  - <u>Invests more energy efficient traffic mode</u>
  - Reduces congestion to increase system energy efficiency
  - Valued by consumers when fuel prices are rising

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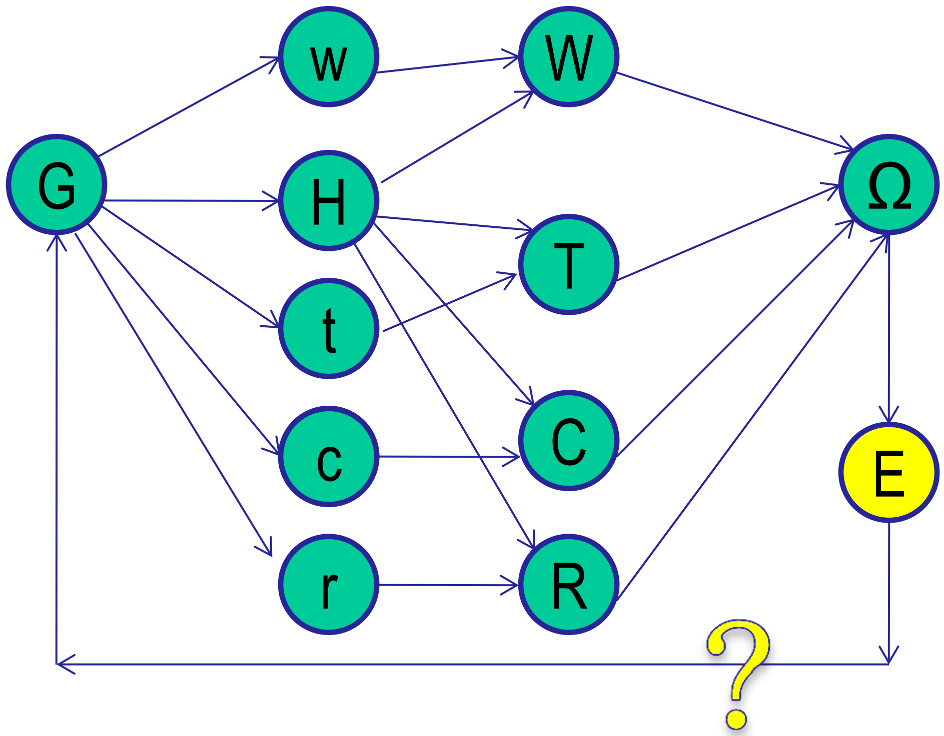
Preliminary Research

- ***Study*** **the interurban passenger trips in the multimodal transportation systems** ***aiming to*** **reduce the system energy consumption** ***considering*** **the interactions between policy makers, multimodal traffic facility suppliers, and traffic demand.**

- ***Develop*** **a mathematical model whose optimal solution provides the support/insights for the system policy makers to strengthen the energy sustainability in the multimodal transportation systems in <u>long-term planning</u>.**

Interactions between Traffic Demand and Supply

- Given a multimodal network, G
- Link traffic service described by waiting time, travel time, fare, service frequency
- Link traffic service leads to intermodal path traffic service
- Traffic supply further leads to traffic flow distribution among modes.
- Traffic flow distribution influences energy consumption



- Energy consumption should be considered as one of the most important factors which impact network design, traffic demand as well as the traffic supply in long term.

G: multimodal network; Ω: distribution of travel demand; E: energy consumption;
t/c/w/ r: travel time/fare/waiting time/service frequency;
T/C/W/R: corresponding path value; H: intermodal paths.

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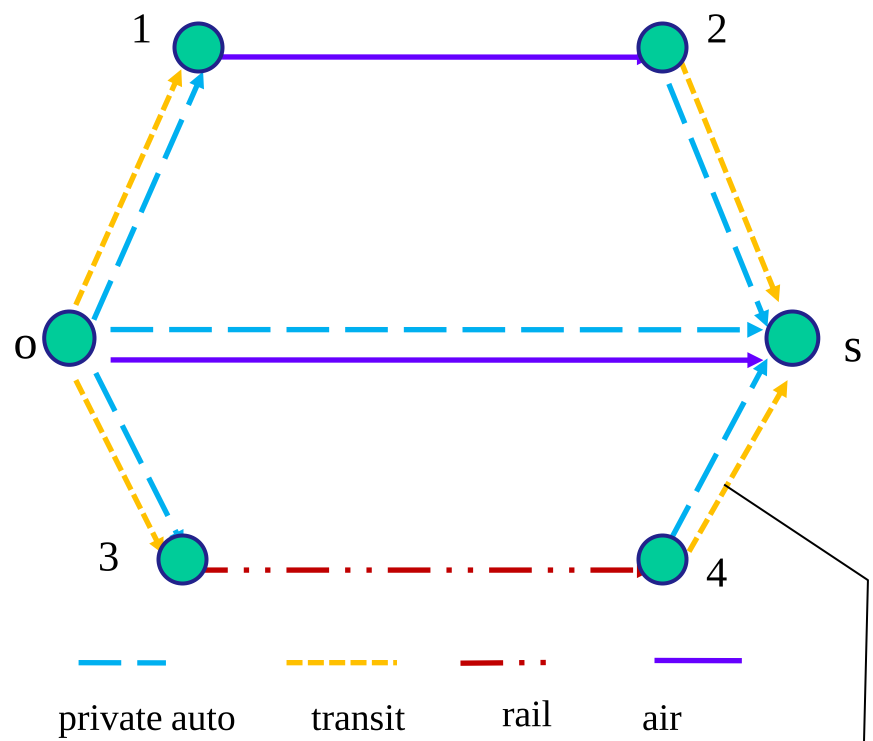
Intermodal Network

- **Nodes: cities or mode transfer ports**
- **Directed links: the connections between cities/transfer ports**
  - **Multiple modes: private auto, transit, rail, and air**
  - **Links differentiated by modes instead of physical network**
  - **Aggregated link service level**
- **Interurban traffic demand**
  - **Deterministic, single O-D**
  - **Business and non-business trip**
- **Energy consumption per link, δ**



w: waiting time; t: travel time; c: fare; r: service frequency; p: seat capacity

Methodology: Bi-Level Mathematical Programming (MP)

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Main Idea

First Level MP

Traffic flow

Second Level MP

1. Policy Maker
Make policy to minimize energy consumption

- Fuel tax
- Land use strategies
- Allowance
- Mandatory

Cost, Profit

2. Traffic Supplier (S)
Adjust service level to sustain revenue

- Service level (ticket fare, capacity, service frequency , ridership)
- Operation Cost
- Business profit

S-D: Ridership Change

3. Traffic Demand (D)
Maximize trip satisfaction

- Travel time (Waiting time)
- Service frequency
- Travel cost
- Comfort

The First Level Of Bi-Level Model

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Min Energy consumption

Supply-Demand (S-D) relation

Fa...

The objective of system policy makers

Servi... a... re... profit li... constraints in reality

More considerations to operation constraints from traffic suppliers

Other constraints of the decision variables; and the conversion from path flow (x) to link flow (y); x comes from the second level

M

s.t.

$$\text{Min } \sum_l \sum_i r_{li} \delta_{li}$$

$$\varepsilon r_{li} p_{li}^0 - y_{li} \geq -B z_{li}, i \in \{2,3,4\}, l \in L$$

$$\epsilon r_{li} p_{li}^0 - y_{li} \leq B s_{li}, i \in \{2,3,4\}, l \in L$$

$$z_{li} + s_{li} \leq 1, i \in \{2,3,4\}, l \in L$$

$$c_{l1} = c_{l1}^0, l \in L$$

$$c_{li} = (1+\alpha_{li}^{\varepsilon} z_{li} - \alpha_{li}^{\epsilon} s_{li},) c_{li}^0, i \in \{2,3,4\}, l \in L$$

$$b_{li}^c \leq c_{li} \leq u_{li}^c, i \in I, l \in L$$

$$\zeta_{li}^{\varepsilon} \alpha_{li}^{\varepsilon} z_{li} + \eta_{li}^{\epsilon} \alpha_{li}^{\epsilon} s_{li} \geq (z_{li} + s_{li}) \pi_{li}^c, i \in \{2,3,4\}, l \in L$$

$$r_{l1} = y_{l1}, l \in L$$

$$r_{li} = (1+\beta_i^{\varepsilon} z_{li} - \beta_i^{\epsilon} s_{li}) r_{li}^0, i \in \{2,3,4\}, l \in L$$

$$b_{li}^r \leq r_{li} \leq u_{li}^r, i \in I, l \in L$$

$$\theta_{li}^{\varepsilon} \beta_i^{\varepsilon} z_{li} + \vartheta_{li}^{\epsilon} \beta_i^{\epsilon} s_{li} \geq (z_{li} + s_{li}) \pi_{li}^r, i \in \{2,3,4\}, l \in L$$

$$\alpha_{li}^{\varepsilon} \geq 0, i \in I, l \in L$$

$$\alpha_{li}^{\epsilon} \geq 0, i \in I, l \in L$$

$$\beta_{li}^{\varepsilon} \geq 0, i \in I, l \in L$$

$$\beta_{li}^{\epsilon} \geq 0, i \in I, l \in L$$

$$z_{li} \in \{0,1\} \text{ and } s_{li} \in \{0,1\}, l \in L, i \in I$$

$$y = \sum_{\kappa=1}^{K} m_h x_h^{\kappa}$$

The Second Level Of Bi-Level Model

- **Mathematical Model**

	$x \in \operatorname{argmax}\{\sum_{h=1}^{H}\sum_{\kappa=1}^{K}\rho_h^\kappa x_h^\kappa\}$	Max trip satisfaction
s.t	$\sum_{h=1}^{H} x_h^\kappa = D^\kappa,\ \kappa \in K$	Flow conservation
	$\sum_{h=1}^{H}\left(m_h^{li}\sum_{\kappa=1}^{K} x_h^\kappa\right) \le r_{li}p_{li}$	Link capacity
	$x_h^\kappa \ge 0, h \in H, \kappa \in K$ $t_{li} = t_{li}^0, i \in I, l \in L$ $w_{li} = w_{li}^0, i \in I, l \in L$	Variable constraints Static travel time Static waiting time

Travelers' preferences

Network related constraints

- **Two classes of traffic demand: Business (B) and non-business (NB)**
- **Linear utility function used to measure the preference of travelers to a certain intermodal path** $\rho_h^\kappa = a^{ck}C_h + a^{wk}W_h + a^{tk}T_h + a^{rk}R_h,\ h \in H, \kappa \in K$
- **Constant link travel time and waiting time, do not factor traffic congestion directly**

Solution Methodology

➢ Model Computational Complexity

- Bi-level model, NP hard
- First level, nonlinear mixed integer program
- Second level, linear program

➢ Solution Method

- Substituting the second level by its KKT conditions
- Bi-level program => one level nonlinear program (Mathematical Program with Complementarity Constraints, MPCC))
- Branch and Bound algorithms to address integer variables

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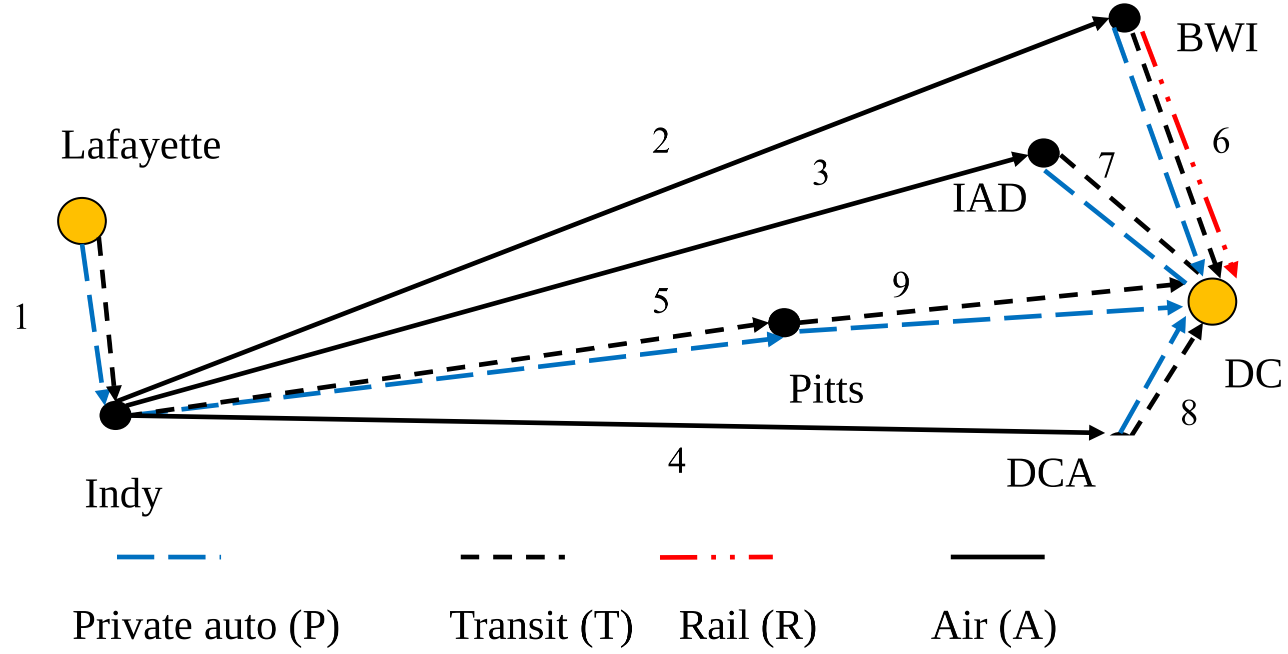
A Small Case Study

- **Study intercity trip from Lafayette to Washington D.C. with the given OD traffic demand equal to150.**
- **Investigate the system optimal traffic flow distributions considering energy consumption under different traffic demand compositions (*business trips and non-business trips).***
- **Investigate the optimal traffic flow distributions considering system energy consumption under the various *road* traffic conditions.**

Test Network



- One OD: Lafayette to Washington D.C.
- Determined total traffic demand, 150
- Four traffic modes: private auto, transit, rail, and air
- Nine links, and twenty two intermodal paths differentiated by links and modes
- Cities: Lafayette, Indianapolis, Baltimore, Pittsburg, Dallas, and Washington D.C.

System Optimal Traffic Demand Distribution among Intermodal Path

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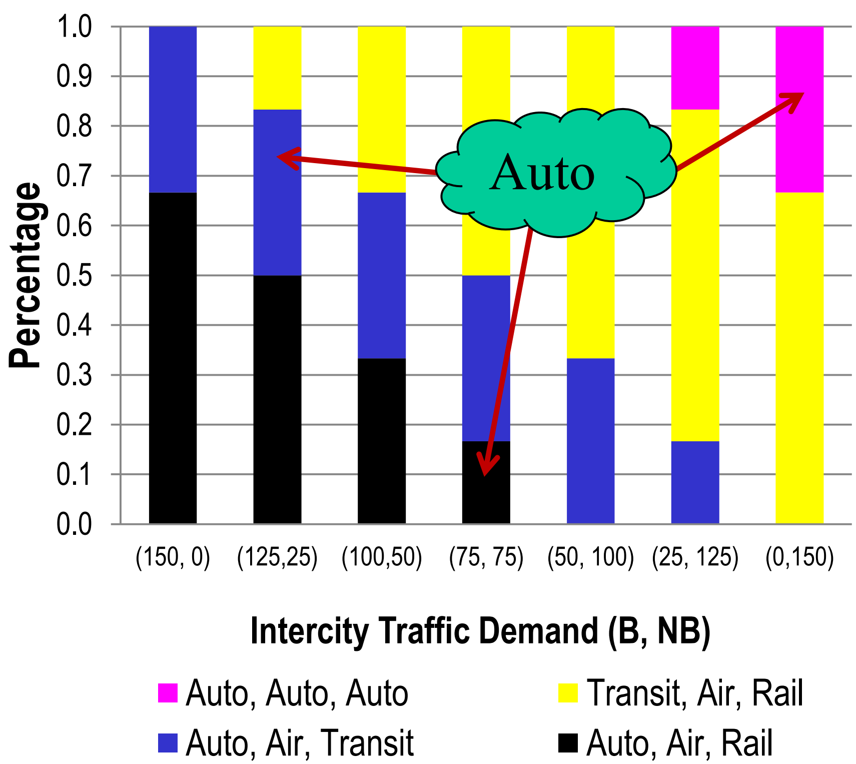
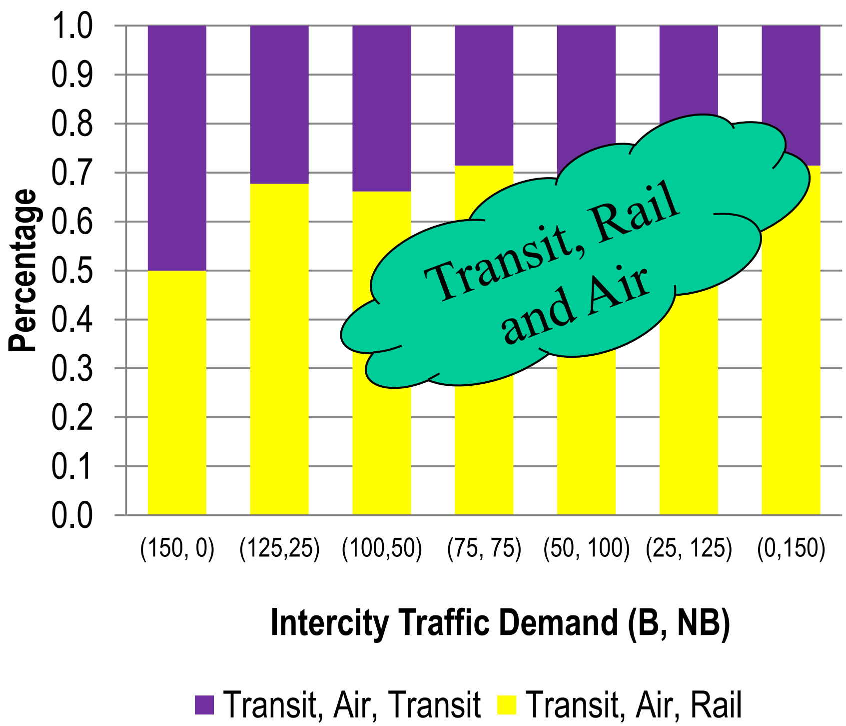
Only Considering Traveler Preference

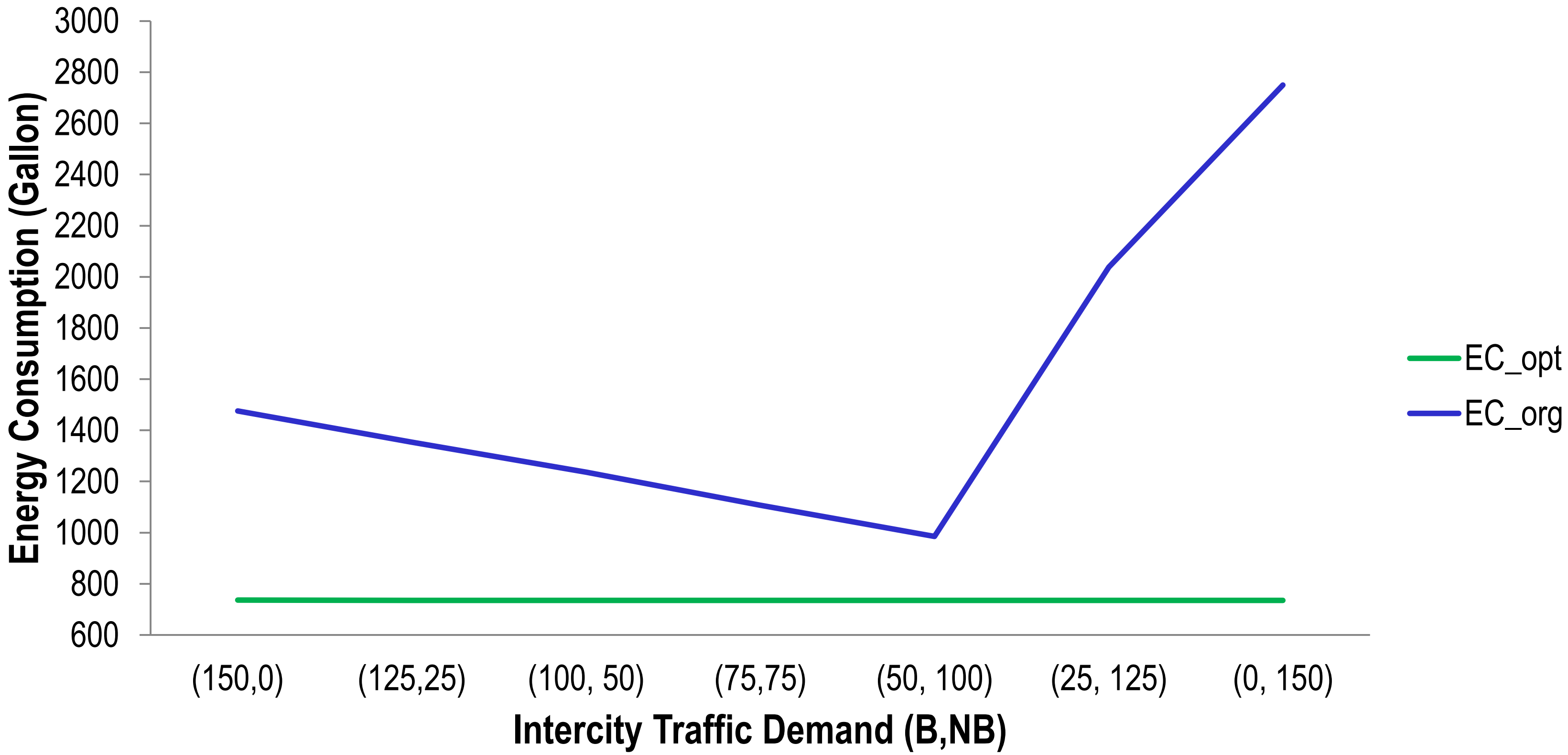


Considering Energy Consumption



- **Without considering energy, intermodal paths including auto are used very often**
- **Considering energy, intermodal paths including transit and rail are highly recommended.**

Energy Consumption



- **System energy consumption is significantly reduced by shifting travelers from the intermodal paths including Auto to the intermodal paths including transit and rail.**

Ticket Price Adjustment for Each Mode on Individual Link

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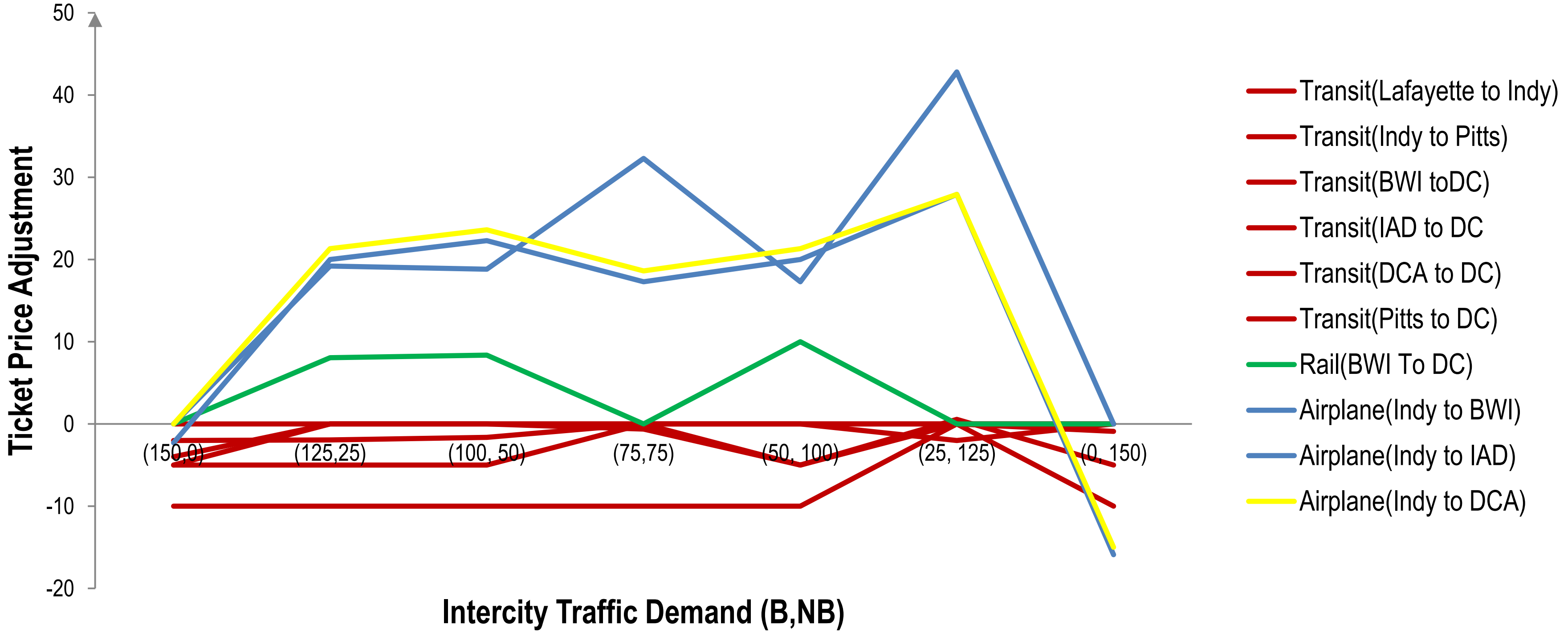
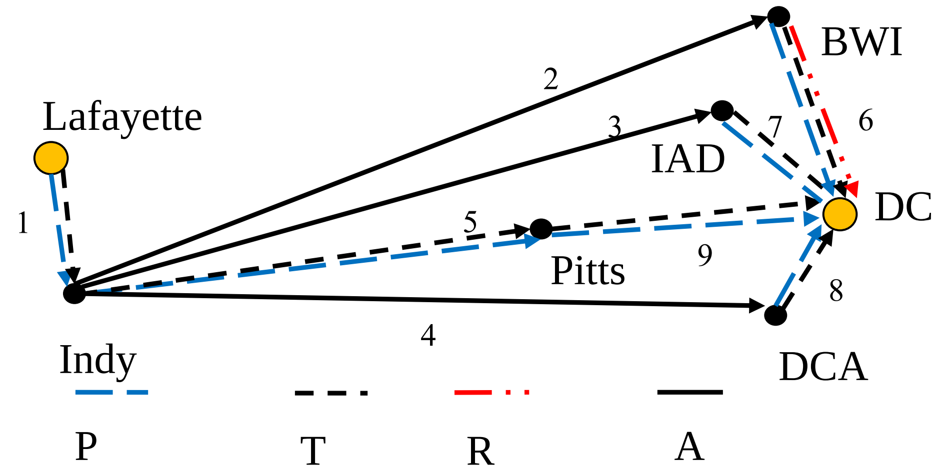


Reducing the system energy consumption leads to

- **Transit systems bring down ticket price**
- **Rail and air may increase ticket prices**
- **Customers using low energy efficiency mode need to pay more**

Preliminary Results

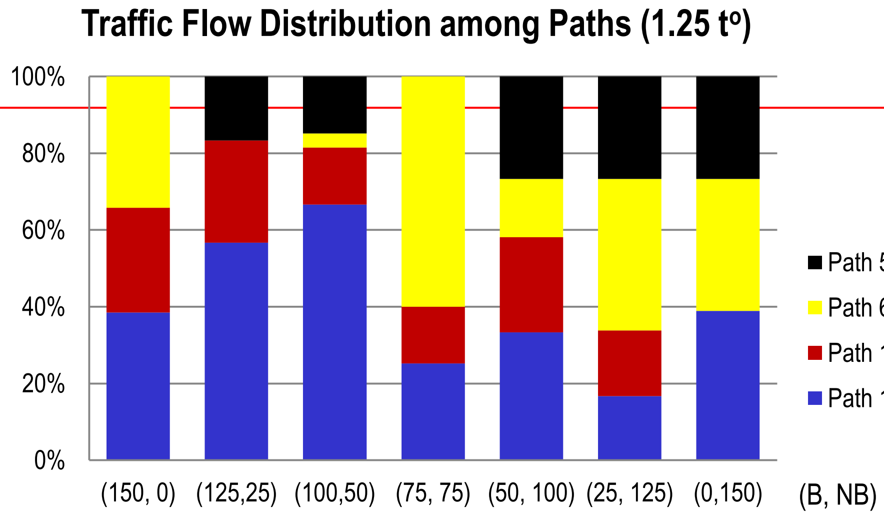
- Experiments: increase road traffic time to 1.25, 1.5, 1.75, and 2 times of the original value t^0
- Check the system optimal solution
  - 4 Paths are included
  - Paths 5(1-2-6), Path 10 (1-3-7): Path 14 (1-4-8): Path 6 (1-2-6):
  - Transit, Air, and Rail

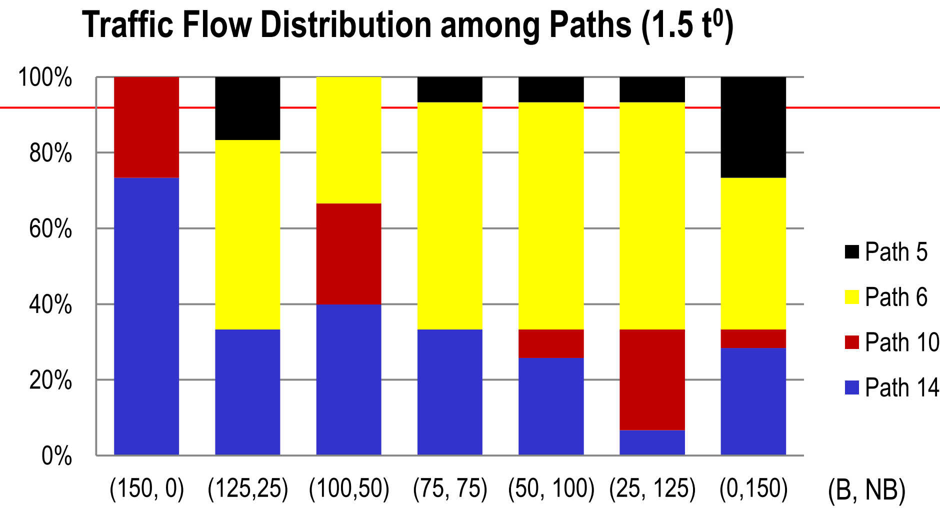


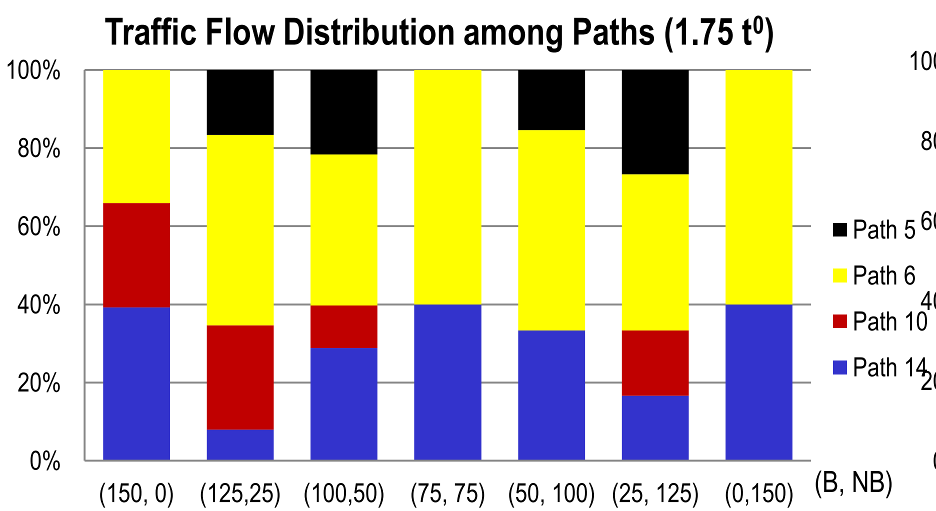
Path \Ranking	Energy Computation	Travel Time	Fare
Path 5 (cheaper but not efficient)	1	1	3
Path 6 (cheaper and efficient)	2	2→3	4
Path 10 (expensive and efficient)	4	3 →2	1
Path 14 (expensive and efficient)	3	4	1
Score 4: best one → 1: worst one			

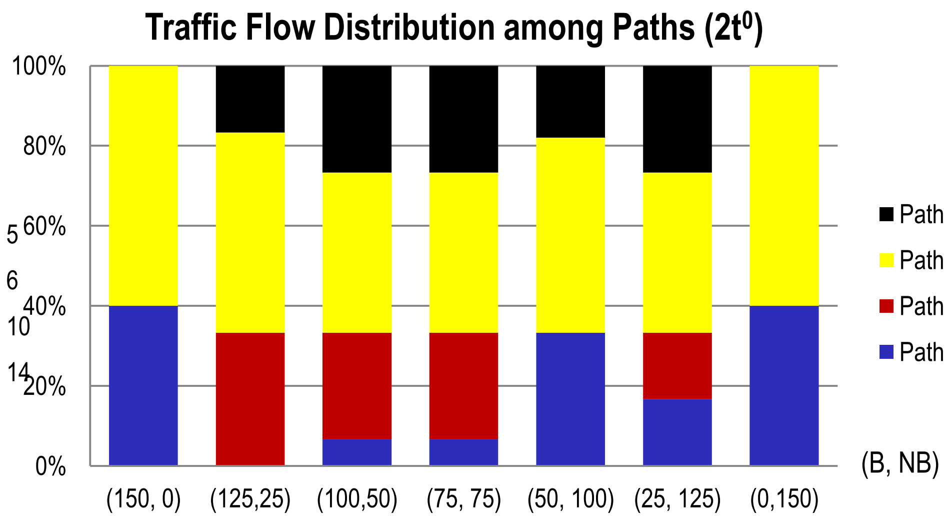
- **Path 14 has the smallest travel time; Path 10 consumes the least fuel; Path 5 and Path 6 are relative cheap; the trade-off exists between Path 5, 6, 10, and14.**

Preliminary Results









- **As traffic become more congested, the advantage of path 14 in travel time become smaller; traffic demand shifts from path 14 (most energy efficient) to other paths such as path 6 (cheaper and relatively efficient).**
- **Need to consider traveler's preference and multimodal network structures, even though energy consumption is the main concern.**

Summary

- Build a rigorous mathematical model which provides technical support for system policy makers to reduce energy consumption in multimodal transportation systems in long-term.
- Case study indicates that system energy consumption can be significantly reduced by shifting traffic demand to the more energy efficient intermodal paths.
- It is possible that air, combined with other traffic modes such as transit and rail, results in energy efficient intermodal paths. The collaboration between different traffic modes will benefit energy consumption reduction.
- System policy affecting both demand and supply is needed to reduce energy consumption in multimodal transportation systems
- Systematically considering the mode energy efficiency, traveler preference, and network structure is needed to reduce energy consumption in multimodal transportation systems

Future Work

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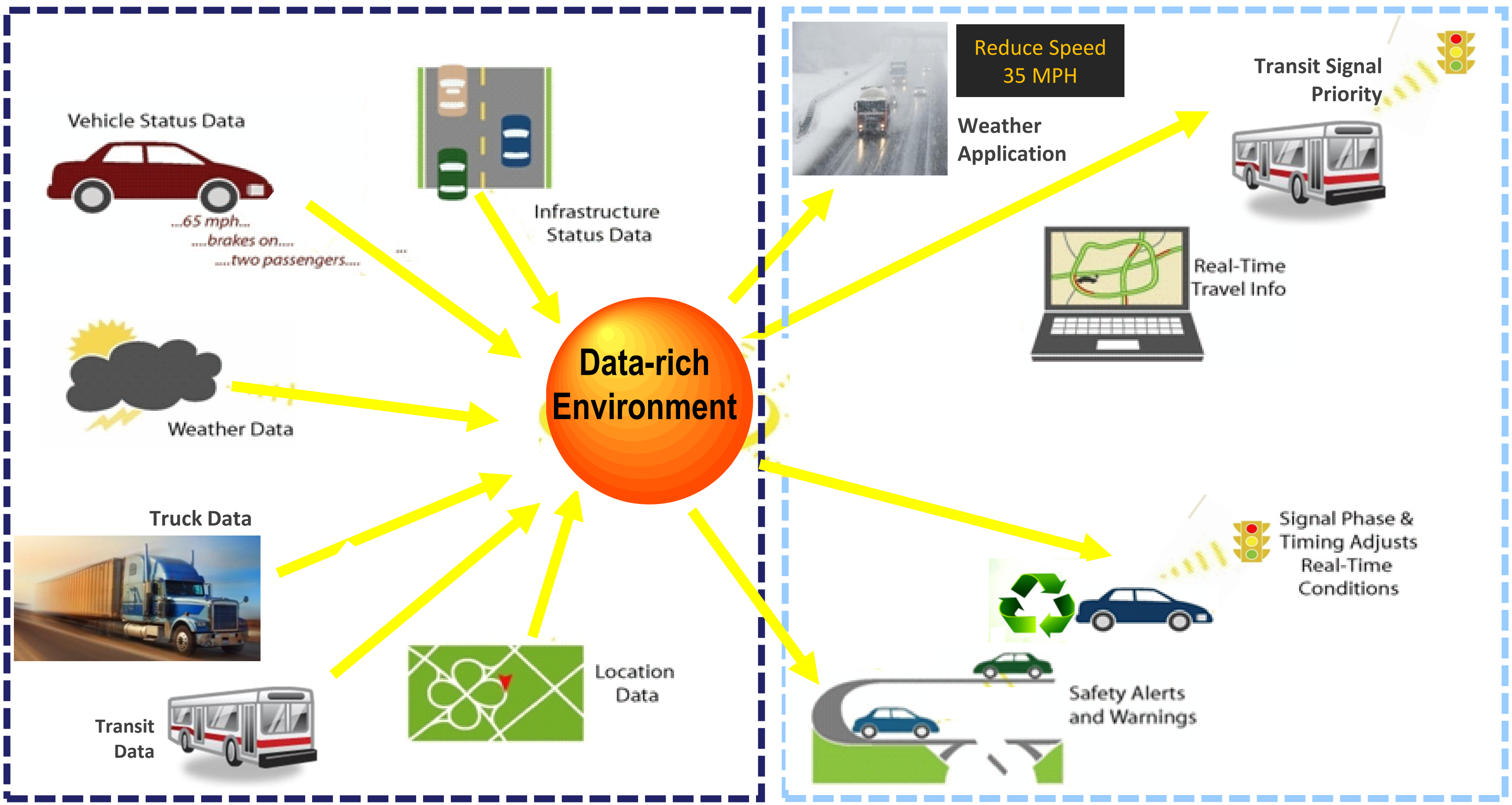
- The emission and energy consumption issues in metropolitan multimodal transportation systems, such as Chicago
- Traffic modes
  - Transit, private auto, metro, rail
  - Need data supports from the supply side
- Clarify the applicable policy options
  - Need the input from policy maker side
- Interaction between policy options taking and traffic supply
  - Need necessary data support
- Traffic demand
  - Traffic demand distribution
  - Traffic mode choice model

OTHER MAJOR INITIATIVE

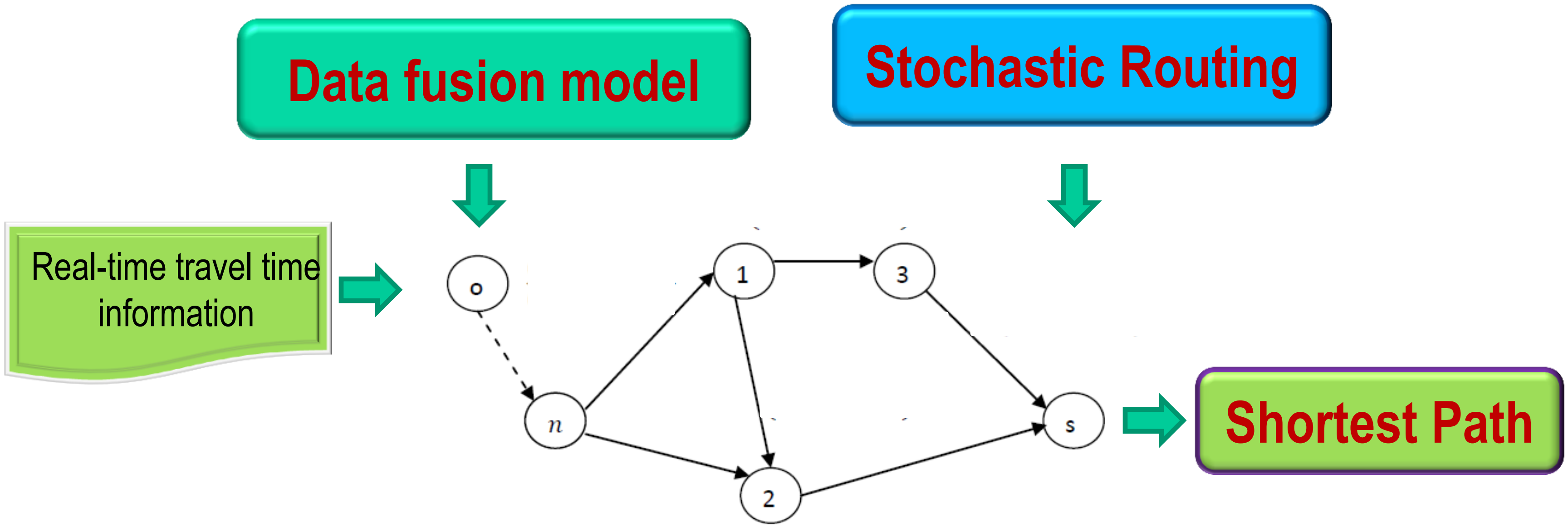
IntelliDrive with Vehicle-Infrastructure (and Driver-Data) Integration

- Real-time Data Capture and Management
- Many Applications



Source: USDOT

MAJOR INITIATIVE
Information Fusion and Reliable Route Guidance



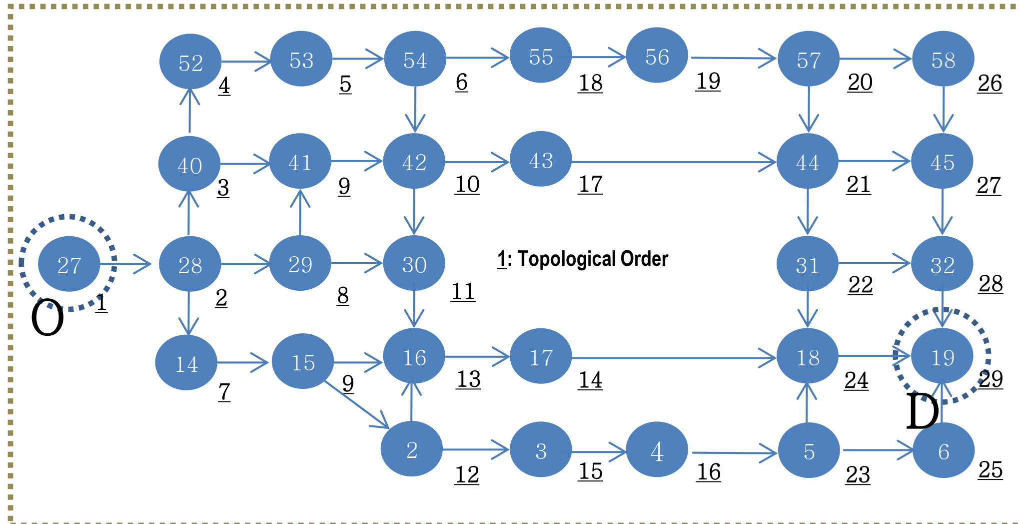
Available Link Travel Time Information: Short-term link travel time distribution

Routing Policy I (II): At each intersection n, this policy helps drivers find a link a* among all the available links so that the expected travel time (variance) from current link to destination is minimized.

MAJOR INITIATIVE

IntelliDrive: Reliable Route Guidance Experiments

- **Borman Sub-network as Test-bed**
  - Origin node (27), Destination node (19)
  - 29 nodes and 46 links
  - Running experiments in 30 days
  - Providing daily guidance for traveler to go through the O-D



- **Findings of Routing Policy I**
  - Employing the short-term arc travel time distribution, always leads to a path with a smaller average travel time than, applying long-term historical arc travel time distribution
  - With the same real-time information accuracy, routing policy I will result in a better path than pre-defined shortest path
  - With high real-time information accuracy, online routing following policy I will significantly improve the chance to find out the best path on the ground

- **Findings of Routing Policy II**
  - Paths under the guidance of Policy I and Policy II integrating short-term travel time distribution have less variance than the path using long-term historic travel time distribution
  - The path under the guidance of Policy II has less variance than the route under Policy I
  - Hence, the Routing Policy II can efficiently find the most reliable path en-route; in addition it benefits from the embedded information fusion model

Thank you!
Comments and Questions?

Preliminary Results

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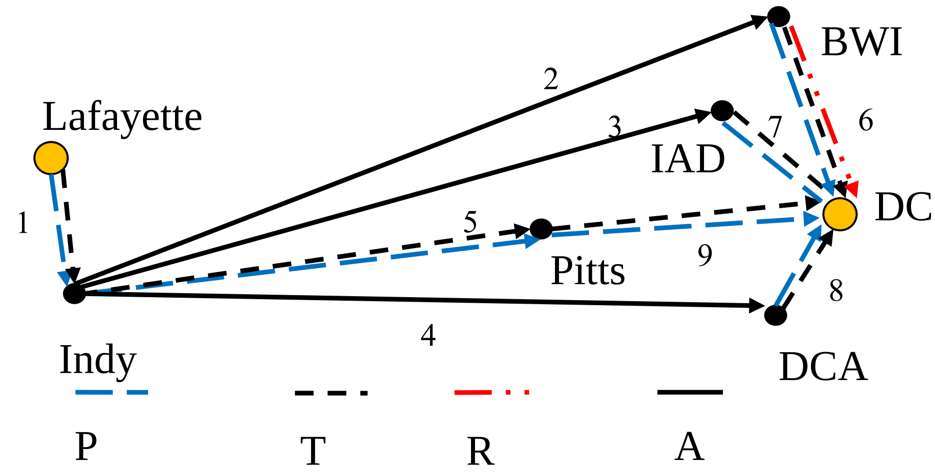
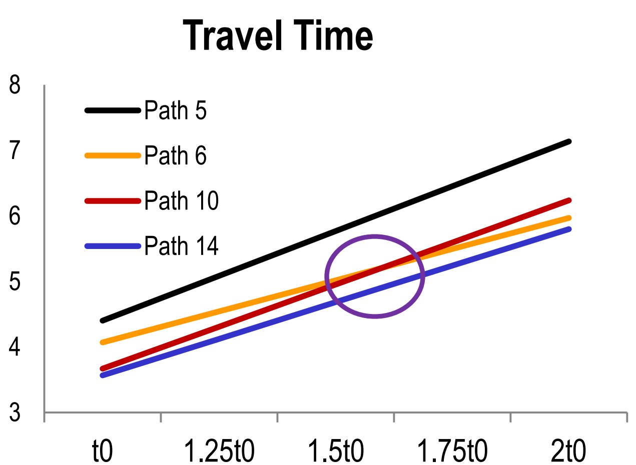
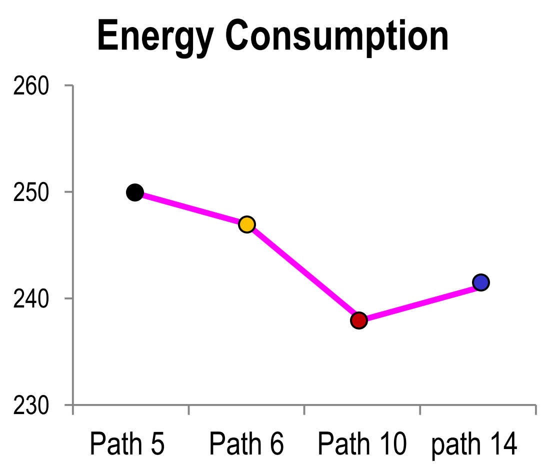
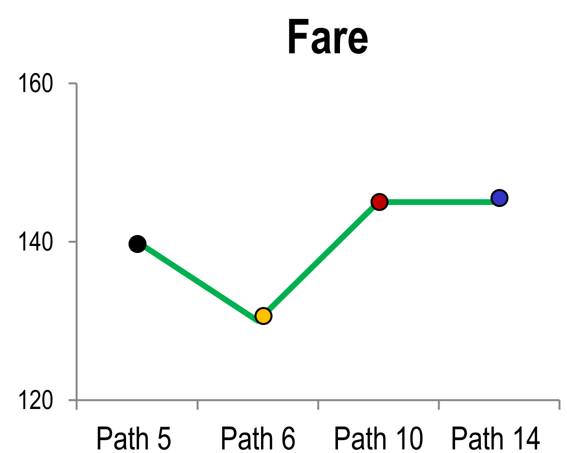
- Experiments: increase road traffic time to 1.25, 1.5, 1.75, and 2 times of the original value t^0
- Check the system optimal solution
- 4 Paths are included
- Paths 5 (1-2-6), 10 (1-3-7), and 14 (1-4-8): Transit, Air, and Transit
- Path 6 (1-2-6): Transit, Air, and Rail









- **Path 14 has the smallest travel time; Path 10 consumes the least fuel; Path 5 and Path 6 are relative cheap; the trade-off exists between Path 5, 6, 10, and14.**

Mathematical Program with Complementarity Constraints (MPCC)

$$Min \sum_l \sum_i r_{li}\, \delta_{li}$$

s.t. $\quad M^1$

The same as previous model

$$0 \le z_{li} \le 1, l \in L, i \in I$$

$$0 \le s_{li} \le 1, l \in L, i \in I$$

Linear relaxation

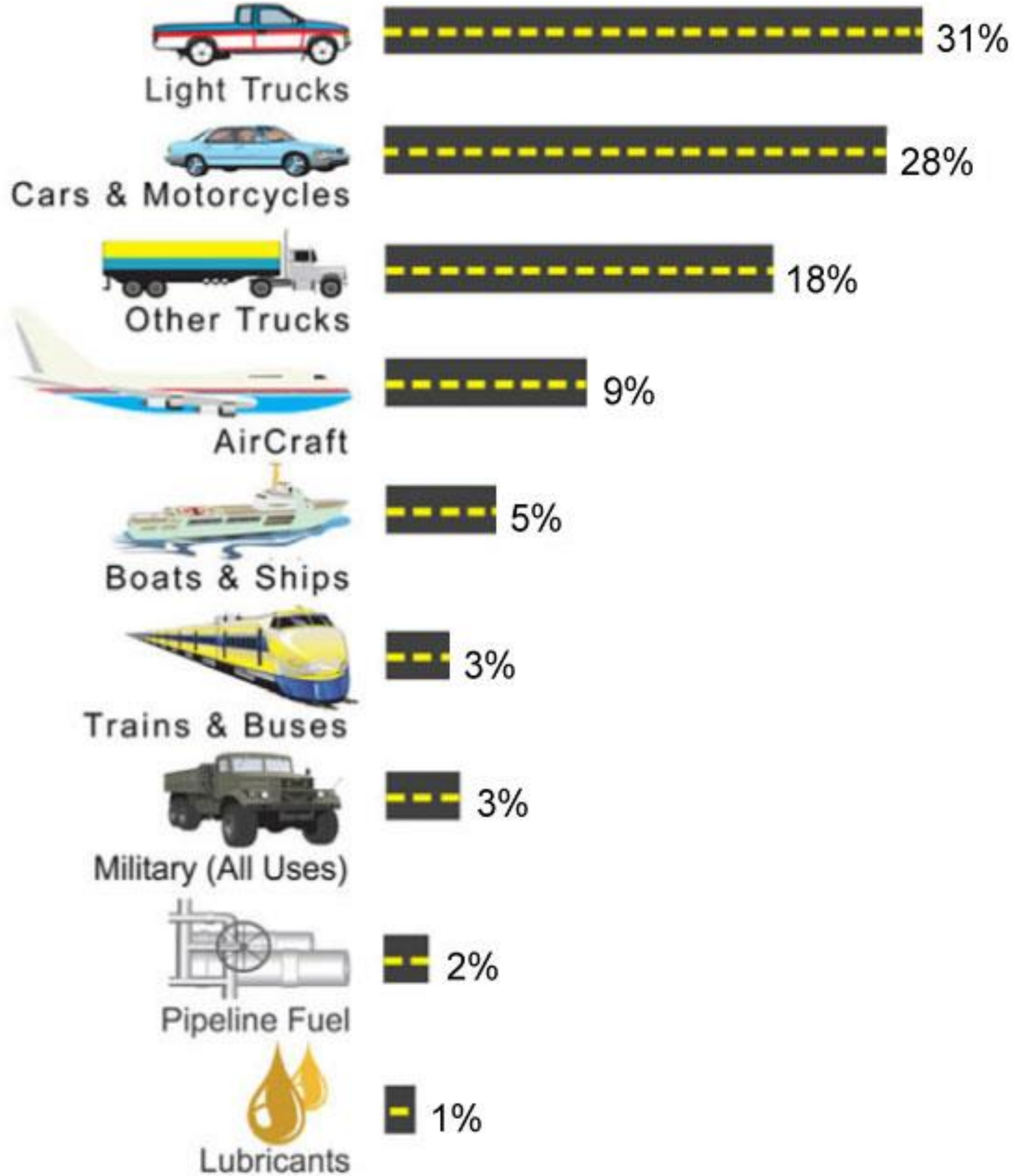
$$\rho_h^\kappa - \lambda^k - \sum_{l=1}^{L} \sum_{i=1}^{I} \mu_i^l\, m_h^{li} + \gamma_h^\kappa = 0,\ \ h \in H, \kappa \in K$$

$$\sum_{h=1}^{H} x_h^\kappa = D_k, \kappa \in K$$

KKT conditions

$$0 \le \gamma_h^\kappa \perp x_h^\kappa \ge 0, h \in H, \kappa \in K$$

$$0 \le \mu_i^l \perp r_{li} p_{li} - \sum_{h=1}^{H} \left(m_h^{li} \sum_{\kappa=1}^{K} x_h^\kappa \right) \ge 0, i \in I, l \in L$$



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2010, Reference Case*, Table 45, estimates for 2010.

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Future Work

- Perform more comprehensive case study over a large network
- Test the impact of gasoline price on the system energy consumption
- Test the interactions between different modes including network structure changes

The end

Thank you!

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Input Data Based on Survey (1/2)

Link	Mode	p^0	δ	c^0($)	t^0(h)	r^0	w^0(h)
1	1	1	5	15	1	N	0
1	2	40	3	20	1.9	6	0.333
2	4	100	240	100	1.667	1	1.5
3	4	120	230	110	1.1	2	1.5
4	4	120	235	120	1.333	2	1.5
5	1	1	25	70	8.333	N	0
5	2	80	18	100	11.667	1	0.5
6	1	1	8	35	0.667	N	0
6	2	40	7	20	0.833	10	0.25
6	3	90	4	10	0.5	12	0.333
7	1	1	6	25	0.583	N	0
7	2	40	5	15	0.667	8	0.25
8	1	1	5	10	0.333	N	0
8	2	60	3	5	0.333	8	0.333
9	1	1	20	35	5	N	0
9	2	60	10	50	6.667	1	0.333

Input Data Based on Survey (1/2)

Link	Mode	ϑ	ζ	η	b^r	u^r	b^c	u^c
1	1	N	N	N	0.001	N	10	40
1	2	0.4	0.2	0.2	1	8	15	35
2	4	0.4	0.9	0.9	1	2	80	150
3	4	0.4	0.9	0.9	1	3	90	150
4	4	0.4	0.9	0.9	1	3	100	160
5	1	N	N	N	0	N	40	90
5	2	0.6	0.2	0.2	0	2	90	150
6	1	N	N	N	0	N	30	40
6	2	0.4	0.2	0.2	1	12	18	35
6	3	0.5	0.5	0.5	1	16	5	20
7	1	N	N	N	0	N	20	35
7	2	0.2	0.2	0.2	1	10	10	20
8	1	N	N	N	0	N	5	20
8	2	0.2	0.2	0.2	1	12	1	10
9	1	N	N	N	0	N	30	60
9	2	0.6	0.2	0.2	0	2	45	60

Lagrangian, KKT Conditions

- **Lagrangian function**

$$L(x,\lambda,\mu,\gamma) = \sum_{h=1}^{H}\sum_{\kappa=1}^{K}\rho_h^\kappa x_h^\kappa - \sum_{k=1}^{K}\lambda^k\left(\sum_{h=1}^{H}x_h^\kappa - D^k\right) -$$

$$\sum_{l=1}^{L}\sum_{i=1}^{I}\mu_{li}\left(\sum_{h=1}^{H}\left(m_h^{li}\sum_{\kappa=1}^{K}x_h^\kappa\right) - r_{li}p_{li}\right) + \sum_{h=1}^{H}\sum_{\kappa=1}^{K}\gamma_h^\kappa x_h^\kappa$$

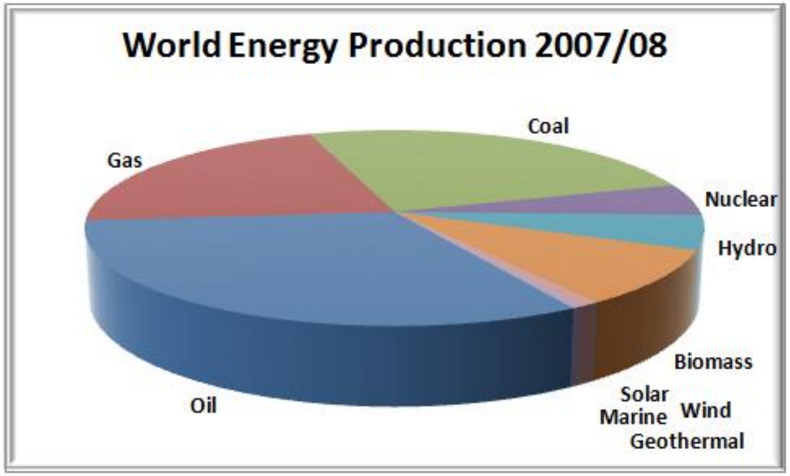
- **KKT Conditions**

$$\rho_h^\kappa - \lambda_k - \sum_{l=1}^{L}\sum_{i=1}^{I}\mu_{li}\, m_h^{li} + \gamma_h^\kappa = 0,\ \ h \in H, \kappa \in K$$

$$\sum_{h=1}^{H}\sum_{\kappa=1}^{K}x_h^\kappa = D_k$$

$$0 \le \gamma_h^\kappa \perp x_h^\kappa \ge 0, h \in H, \kappa \in K$$

$$0 \le \mu_i^l \perp r_{li}p_{li} - \sum_{h=1}^{H}\left(m_h^{li}\sum_{\kappa=1}^{K}x_h^\kappa\right) \ge 0, i \in I, l \in L$$


World Energy Production 2007/08
Coal
Gas
Nuclear
Hydro
Biomass
Oil
Solar
Marine
Wind
Geothermal

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Methodology

Variables

Supplier side

c, r

$\alpha^{\varepsilon}, \alpha^{\epsilon}$

$\beta^{\varepsilon}, \beta^{\epsilon}$

S-D: z, s

Demand side

x, y

Parameters

Policy maker side

Allowance, tax impact c^0

Supplier side

$r^0, c^0, t^0, w^0, p^0, \delta$

$[b^r, u^r], [b^c, u^c]$

$(\pi^r, \pi^c), (\varepsilon, \epsilon)$

$(\theta, \vartheta), (\zeta, \eta)$

Demand side

$(a^c, a^w, a^t, a^r), D$

Main Idea

Policy Maker
Make policy to minimize energy consumption

Traffic Supplier
Adjust fare and service frequency to guarantee profit for most modes

S-D: Ridership Elasticity

Traffic Demand
Maximize trip satisfaction

Branch and Bound Algorithm

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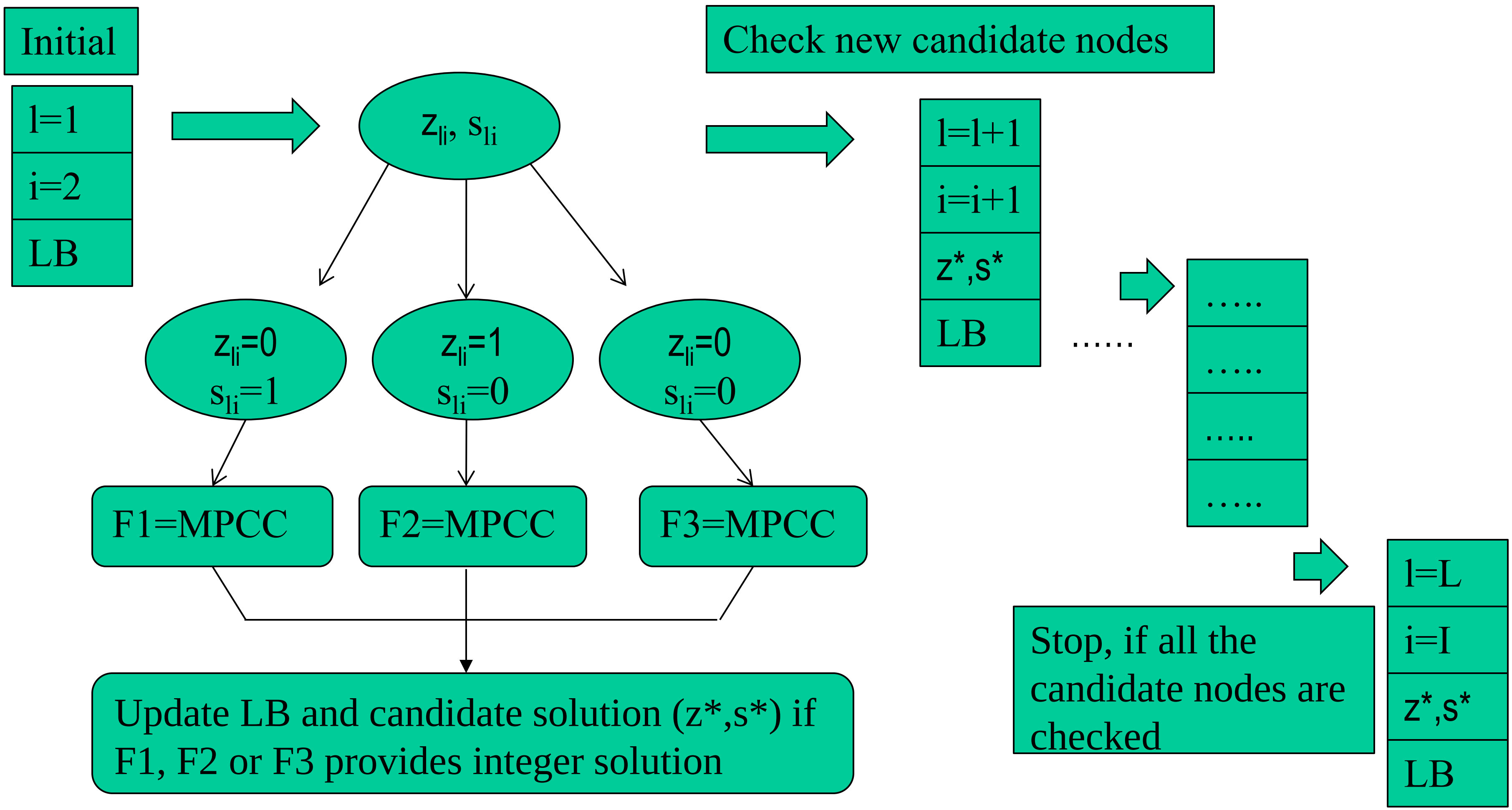
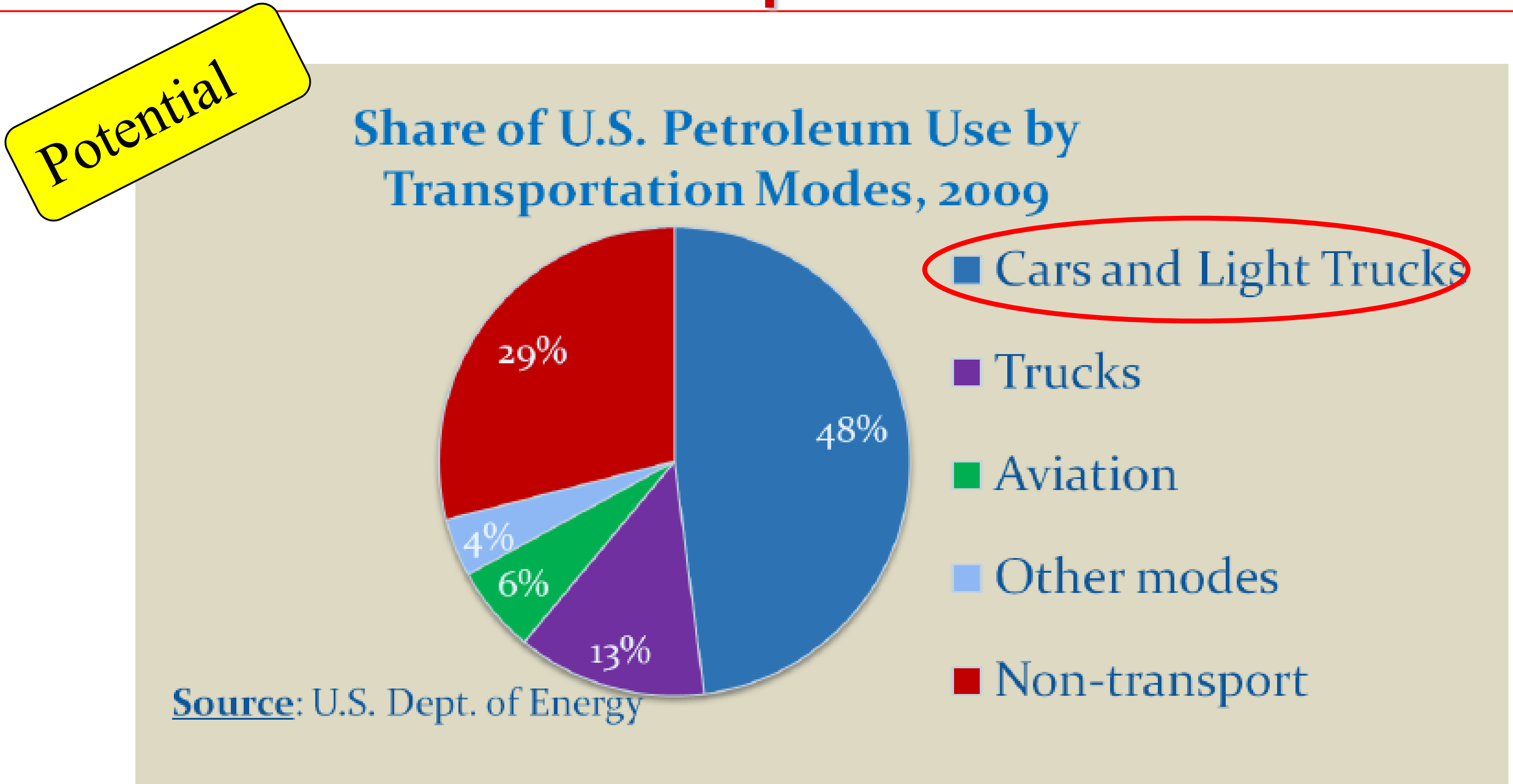


$$z_{li}+s_{li}\leq 1,\ i=\{2,3,4\},\ l=1\ldots L;\ z_{li}\epsilon\{0,1\};\ s_{li}\epsilon\{0,1\};$$

Transportation Dominates Total U.S. Petroleum Consumption

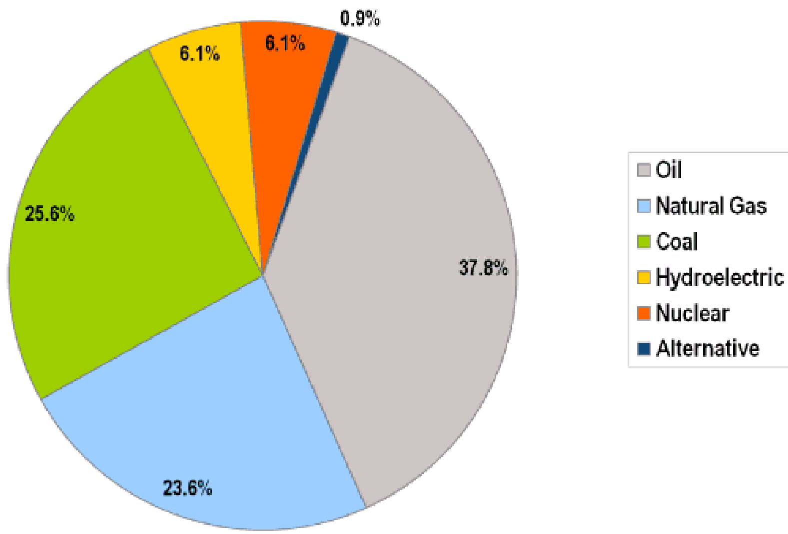


- Car and Light Trucks account for most of the share, then Truck and Aviation

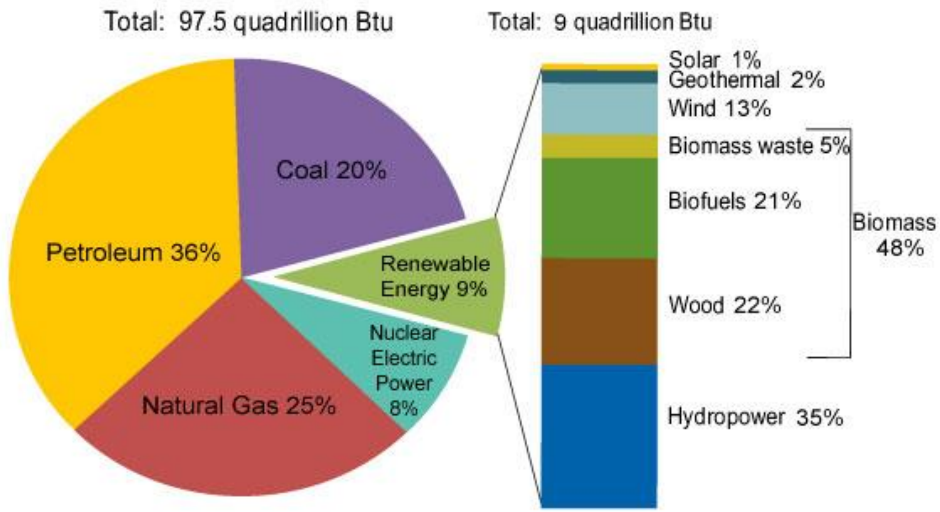
Motivations

Urgent

Worl… y Production, 2006



U.S. Energy Consumption by Energy Source, 2011



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 10.1 (March 2012), preliminary 2011 data.

- **Oil provides 36% of energy sources in USA**
- **Non-renewable energy source, limited storage on earth**
- **Energy crisis has gained attention around the world**