Flight Delays, Capacity Investment and Welfare under Air Transport Supply-demand Equilibrium

Bo Zou[1], Mark Hansen[2]

[1]University of Illinois at Chicago
[2]University of California at Berkeley


GATE #
STATUS
A23
DELAYED
C72
DELAYED
B34
DELAYED
A14
DELAYED
C89
DELAYED
G12
DELAYED
C5
DELAYED
D13
DELAYED
A4
DELAYED
B22
DELAYED

Total economic impact of flight delay:

Total economic impact of flight delay:

$32 billion in 2007

Total economic impact of flight delay: $32 billion in 2007

Ball, M., Barnhart, C., Dresner, M., Hansen, M. Neels, K., Odoni, A., Peterson, E., Sherry, L., Trani, A., **Zou, B.**, 2010. *Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States. Major Participant.* Report Prepared for the US Federal Aviation Administration.

Zou, B., Hansen, M., 2012. *Impact of Operational Performance on Air Carrier Cost Structure: Evidence from US Airlines*. Transportation Research Part E: Logistics and Transportation Review, 48 (6), 1032-1048.

Hansen, M., **Zou, B.**, 2013. *Airport Operational Performance and its Impact on Airline Cost.* In: Odoni, A. and Zografos, K. (eds.), Modeling and Managing Airport Performance: Theory and Practice, John Wiley & Sons, Inc.

Means to mitigate flight delay

- Managing demand

Means to mitigate flight delay

- Managing demand
  - Congestion pricing

Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control

Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control

Swaroop, P., **Zou, B.**, Ball, M., Hansen, M., 2012. *Do More U.S. Airports Need Slot Controls? A Welfare Based Approach to Determine Slot Levels*. Transportation Research Part B: Methodological, (9), 1239-1259.

Ball, M., Hansen, M., Swaroop, P., **Zou, B.**, 2013. *Design and Justification for Market-Based Approaches to Airport Congestion Management*. In: Odoni, A. and Zografos, K. (eds.), Modeling and Managing Airport Performance: Theory and Practice, John Wiley & Sons, Inc.

Means to mitigate flight delay

- Managing demand
  - Congestion pricing
  - Slot control

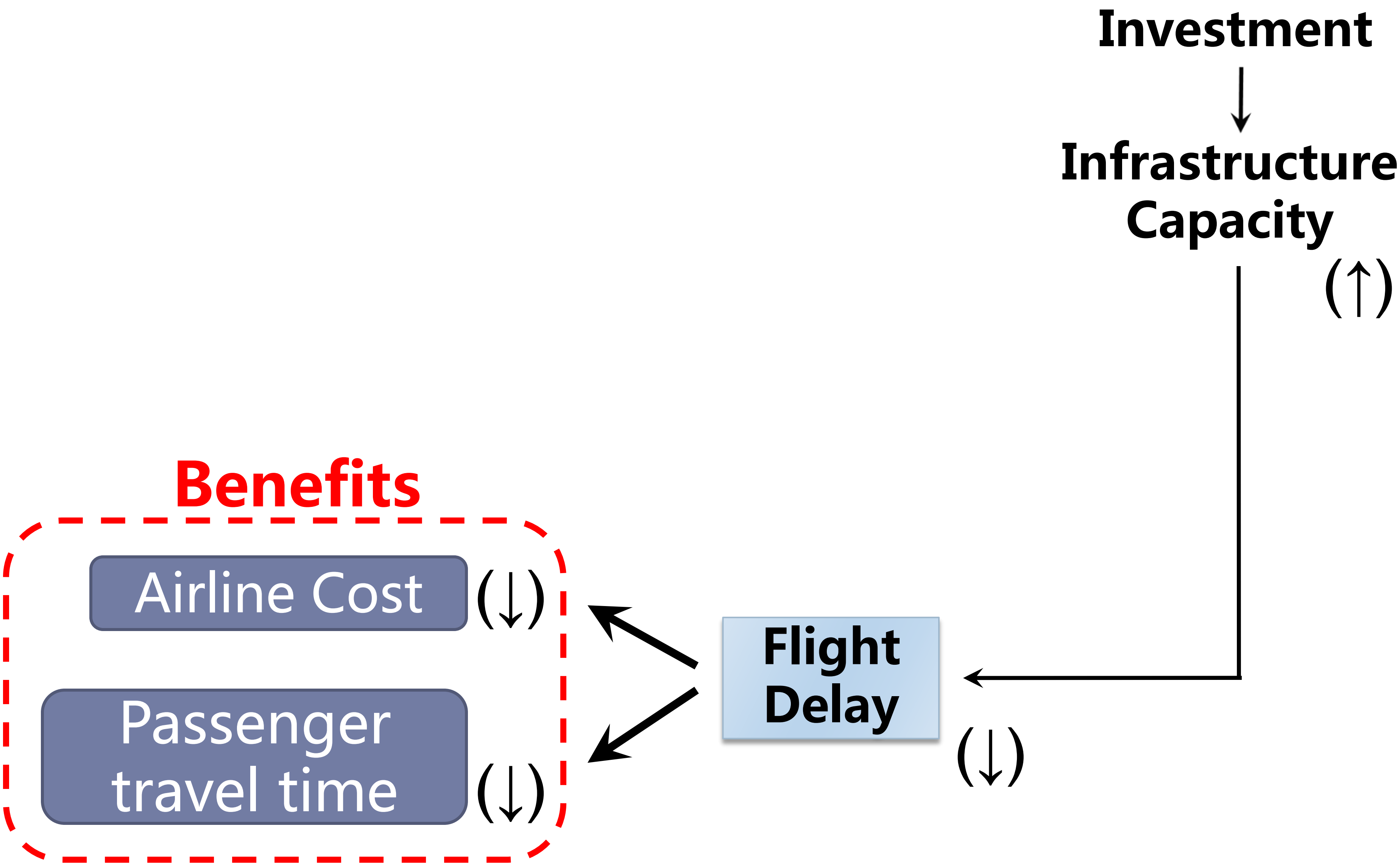
Swaroop, P., **Zou, B.**, Ball, M., Hansen, M., 2012. *Do More U.S. Airports Need Slot Controls? A Welfare Based Approach to Determine Slot Levels*. Transportation Research Part B: Methodological, (9), 1239-1259.

Ball, M., Hansen, M., Swaroop, P., **Zou, B.**, 2013. *Design and Justification for Market-Based Approaches to Airport Congestion Management*. In: Odoni, A. and Zografos, K. (eds.), Modeling and Managing Airport Performance: Theory and Practice, John Wiley & Sons, Inc.

- Increasing supply

Outline

- Background
- Research Framework
- Equilibrium Model
- Conclusion


Investment
Infrastructure Capacity
(↑)
Benefits
Airline Cost
(↓)
Passenger travel time
(↓)
Flight Delay
(↓)

Issues with the approach

***Ceteris paribus* assumption**

Predicting future

Investment

↓

Infrastructure Capacity (↑)

Flight Delay (↓)

Benefits

- Airline Cost (↓)
- Passenger travel time (↓)

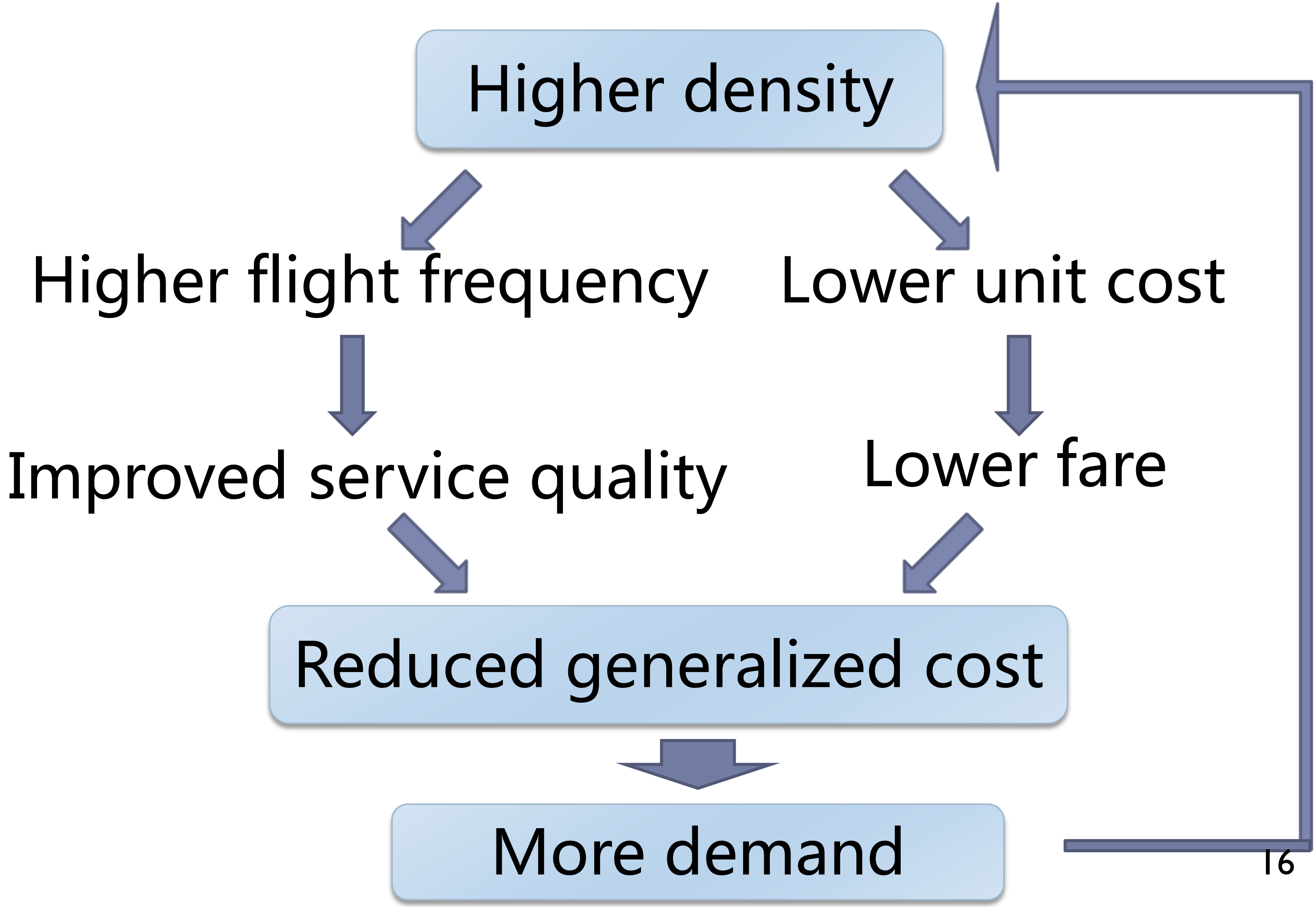
Objective of the Research

Develop an innovative methodology to systematically capture supply-demand response to investment

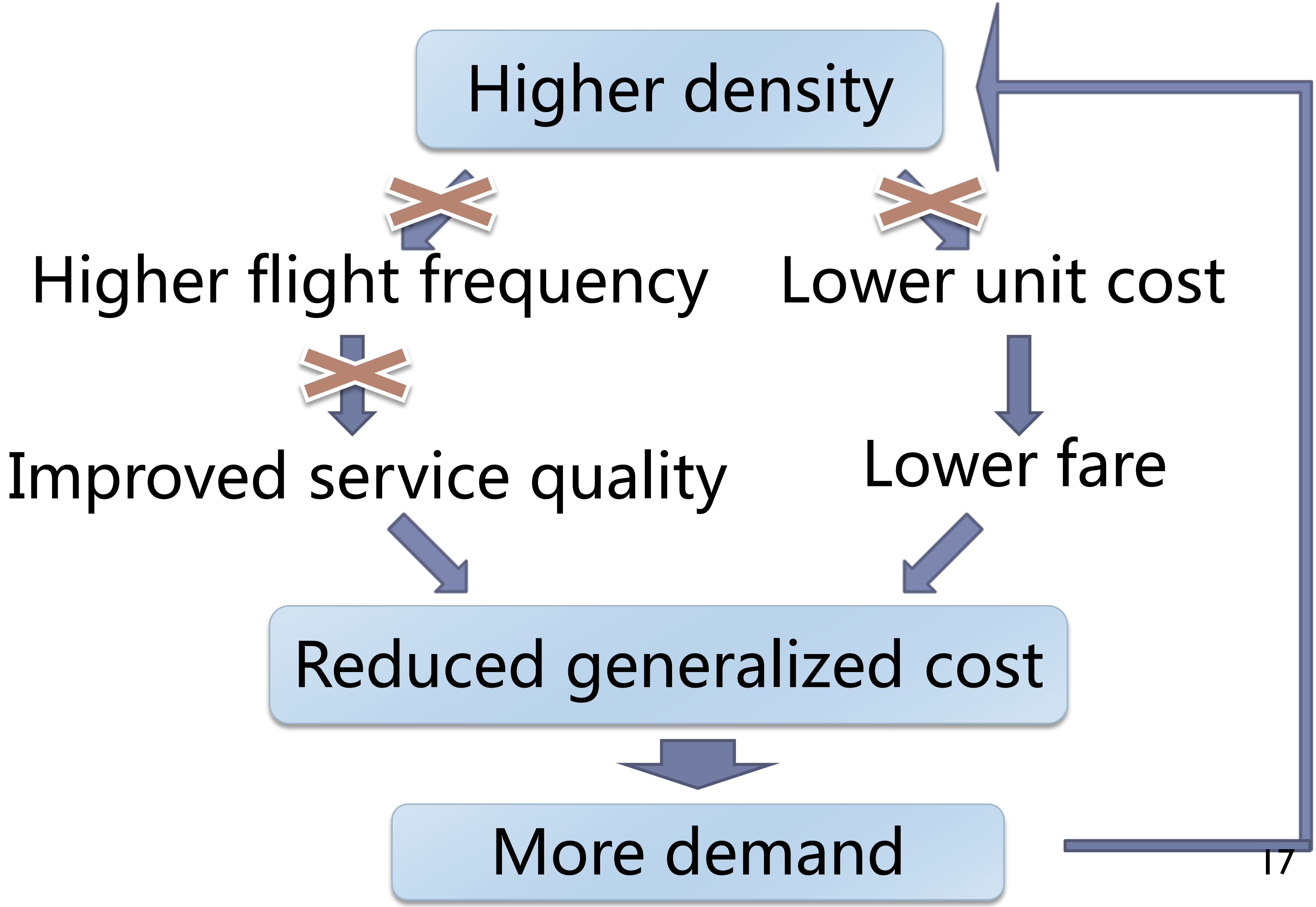
Outline

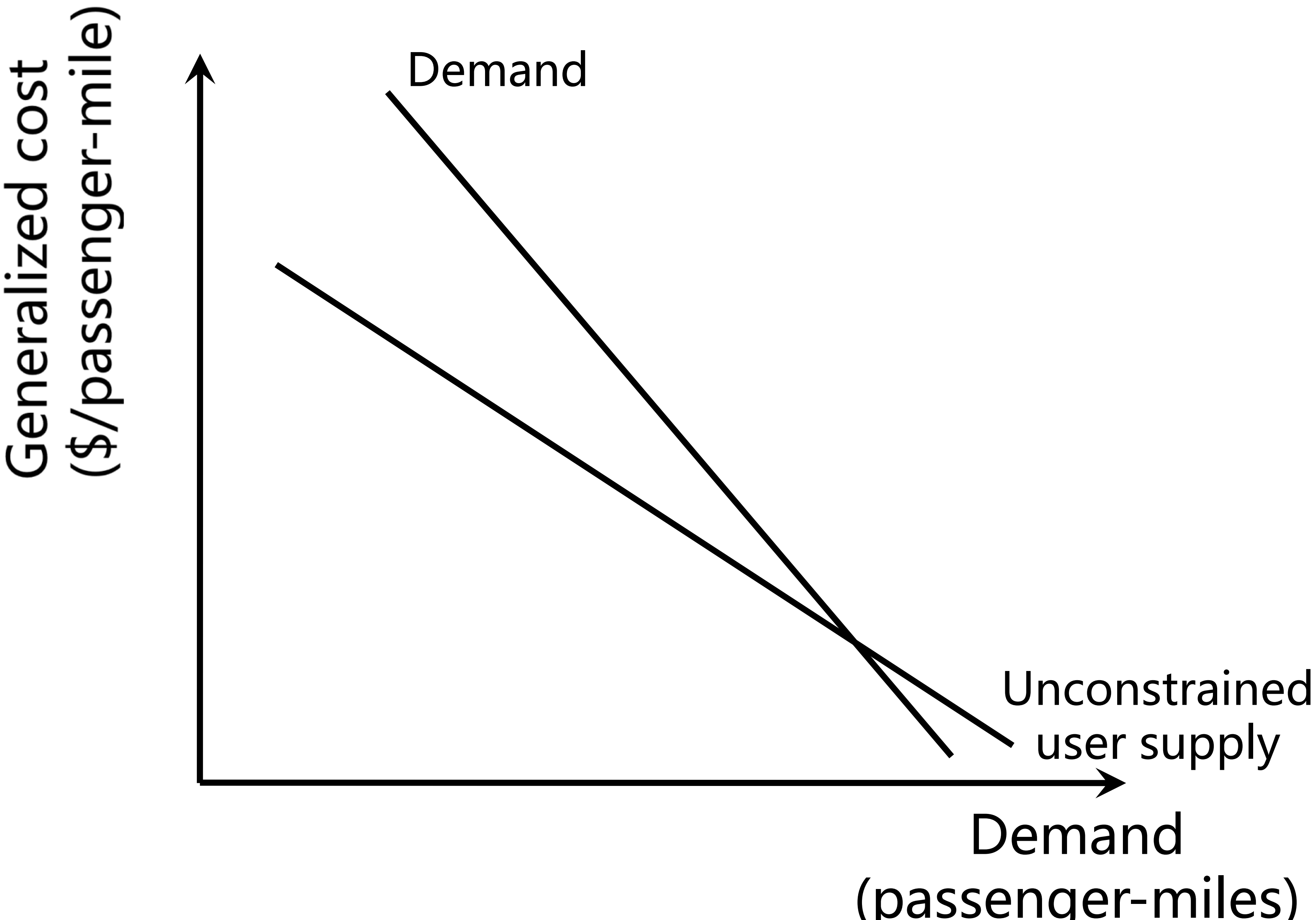
- Background
- **Research Framework**
- Equilibrium Models
  - Airline competition model
  - User equilibrium model
- Conclusion

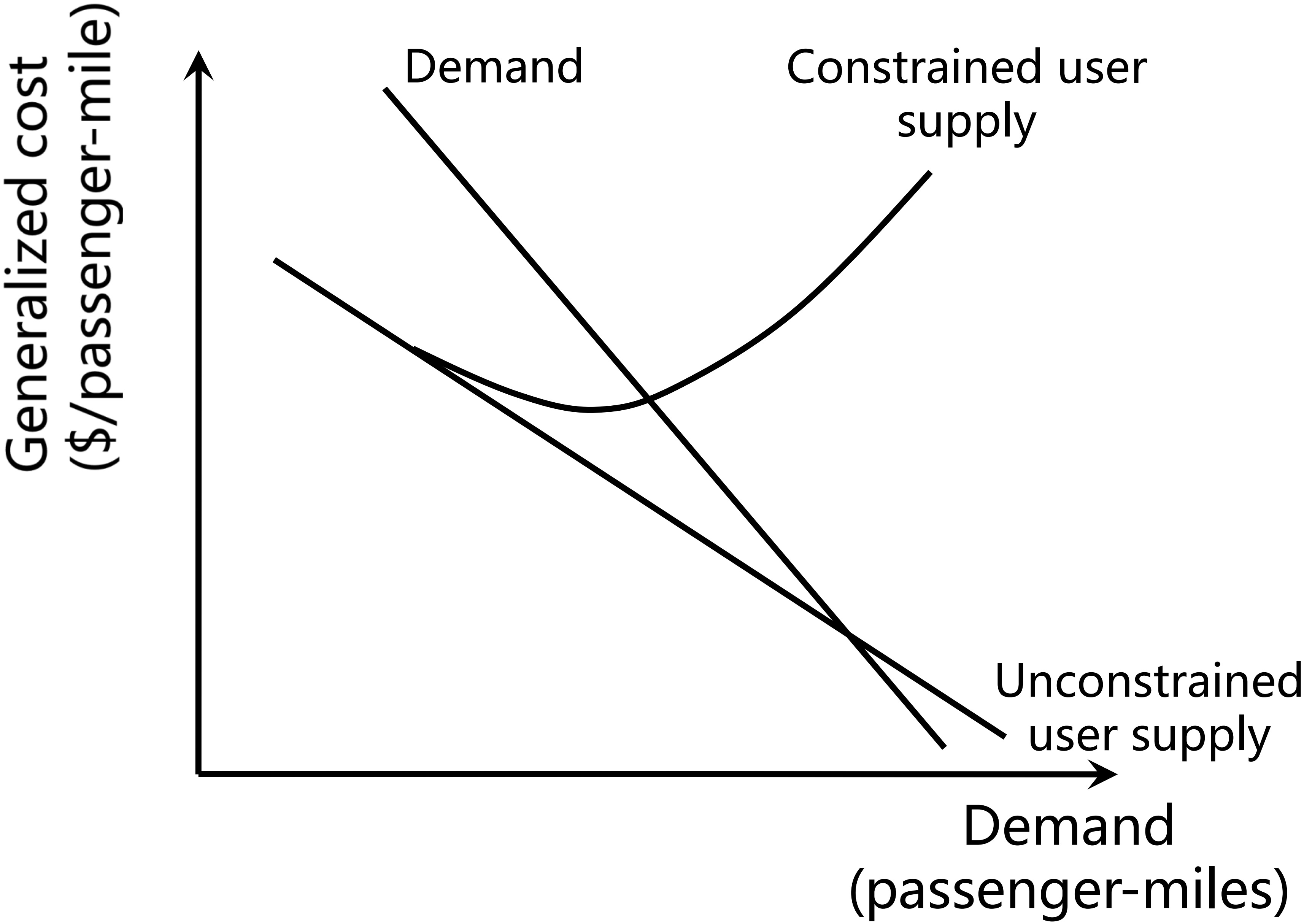
No congestion

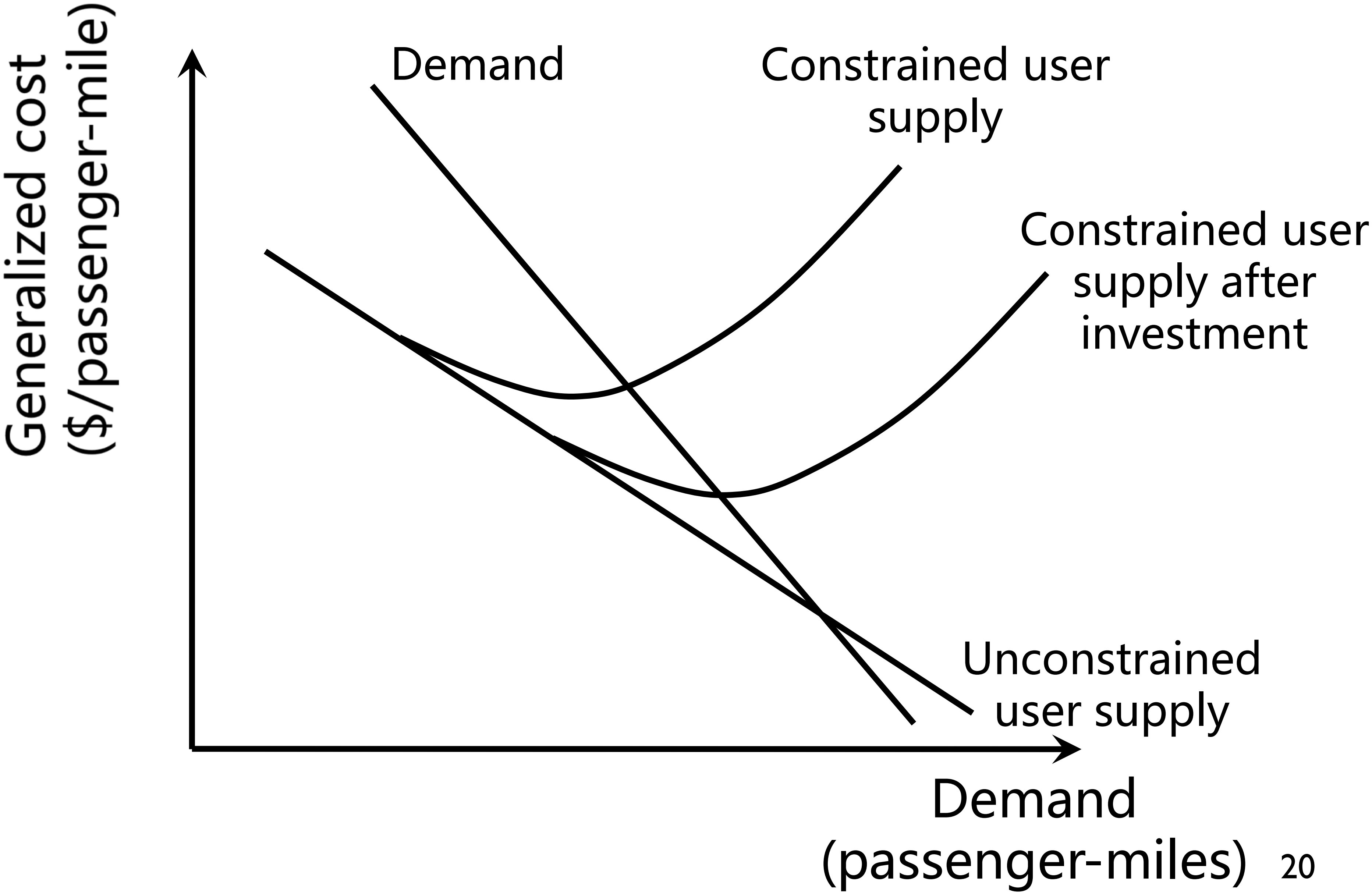


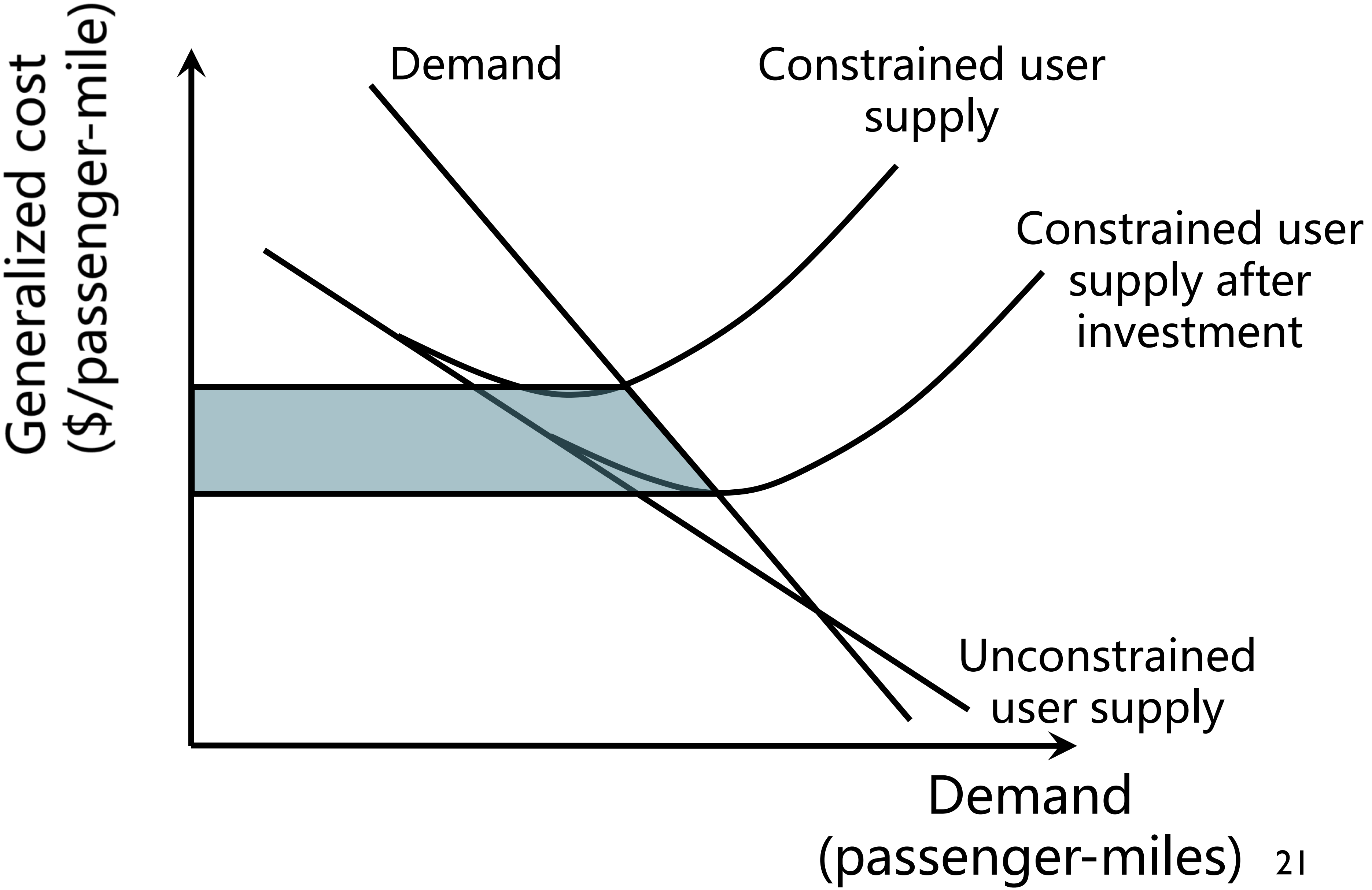
With congestion




Generalized cost
($/passenger-mile)
Demand
Unconstrained
user supply
Demand
(passenger-miles)


Generalized cost ($/passenger-mile)
Demand
Constrained user supply
Unconstrained user supply
Demand (passenger-miles)


Generalized cost ($/passenger-mile)
Demand
Constrained user supply
Constrained user supply after investment
Unconstrained user supply
Demand (passenger-miles)


Generalized cost ($/passenger-mile)
Demand
Constrained user supply
Constrained user supply after investment
Unconstrained user supply
Demand (passenger-miles)

Conventional view

Investment

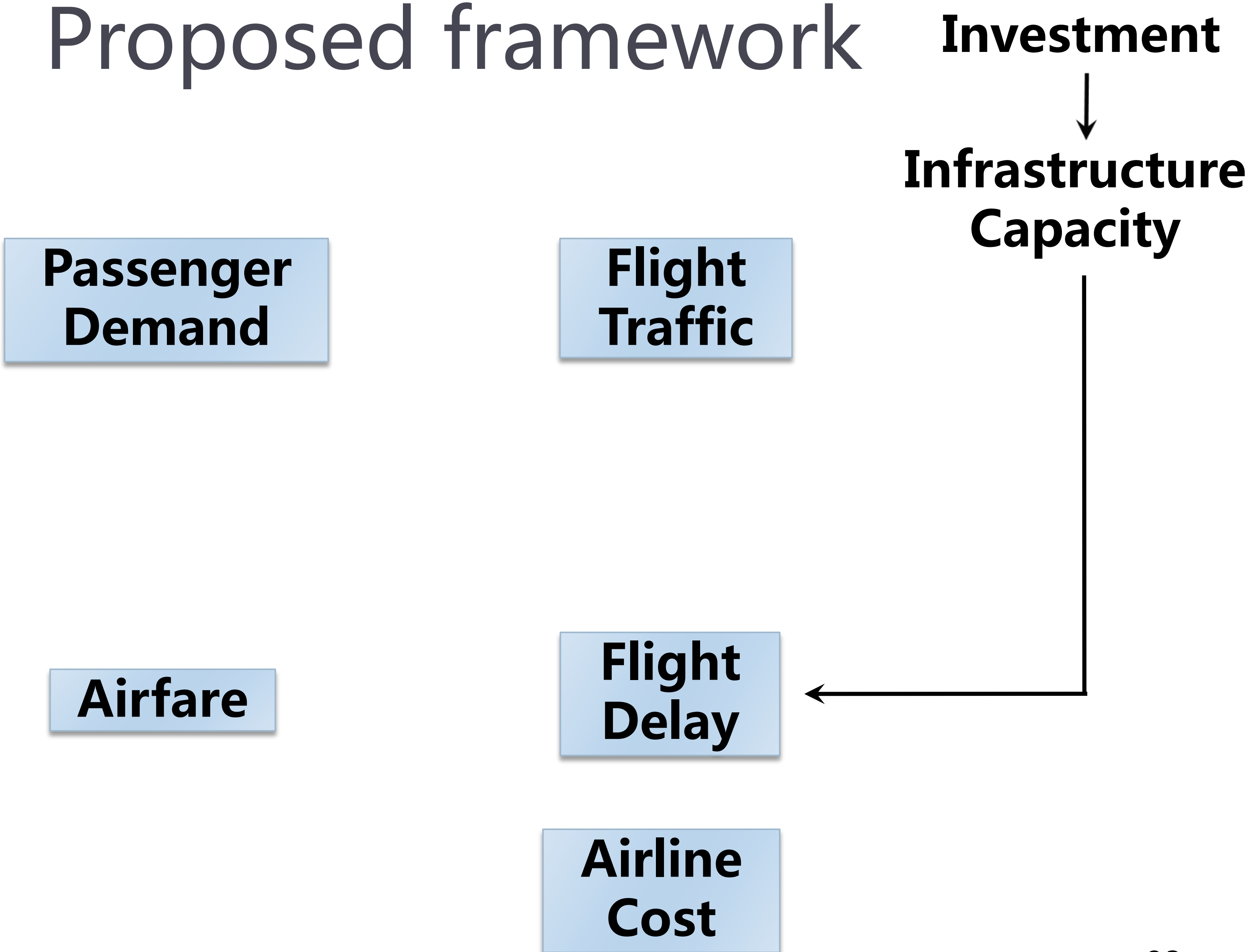
↓

Infrastructure Capacity

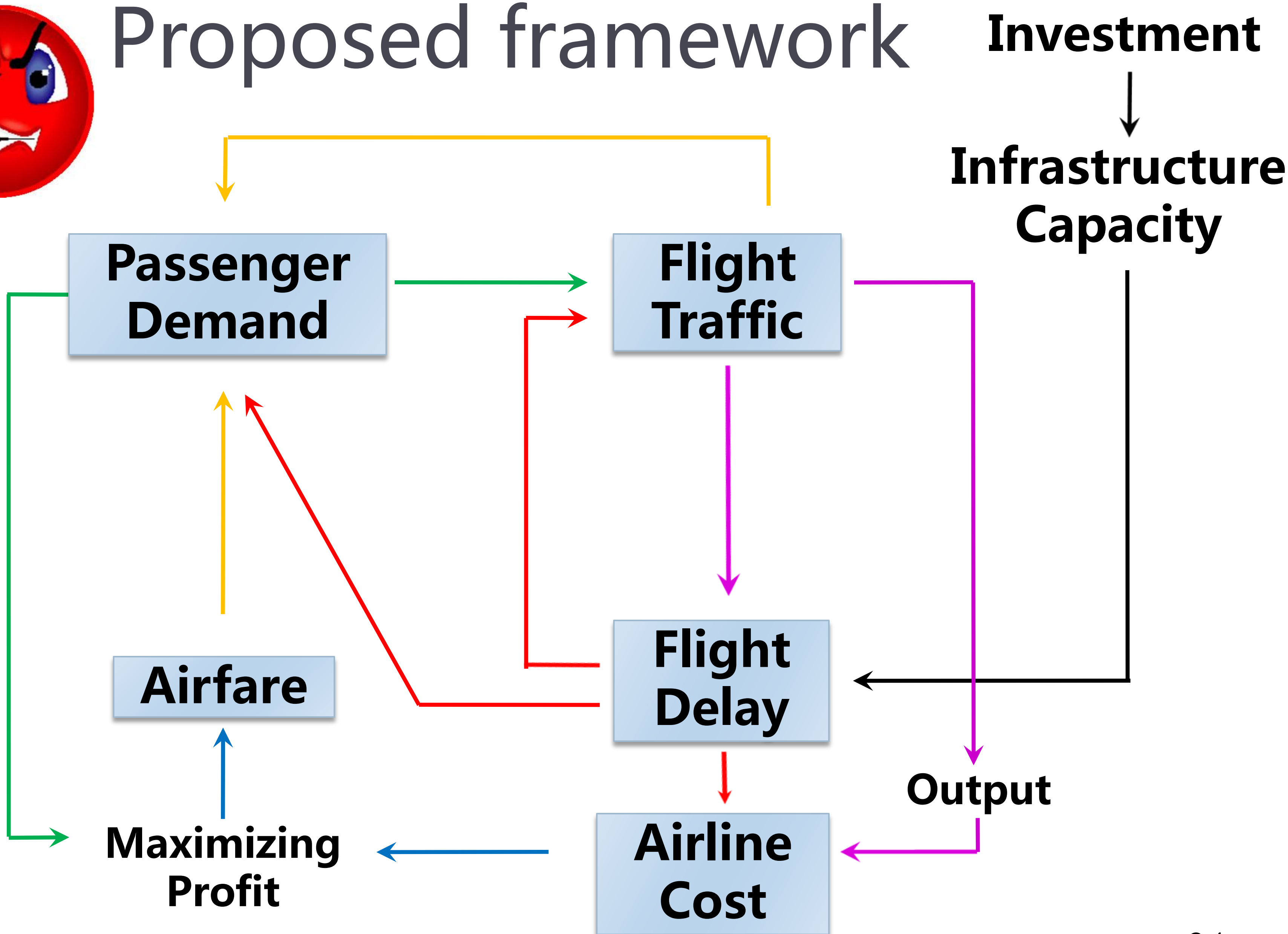
↓

Flight Delay

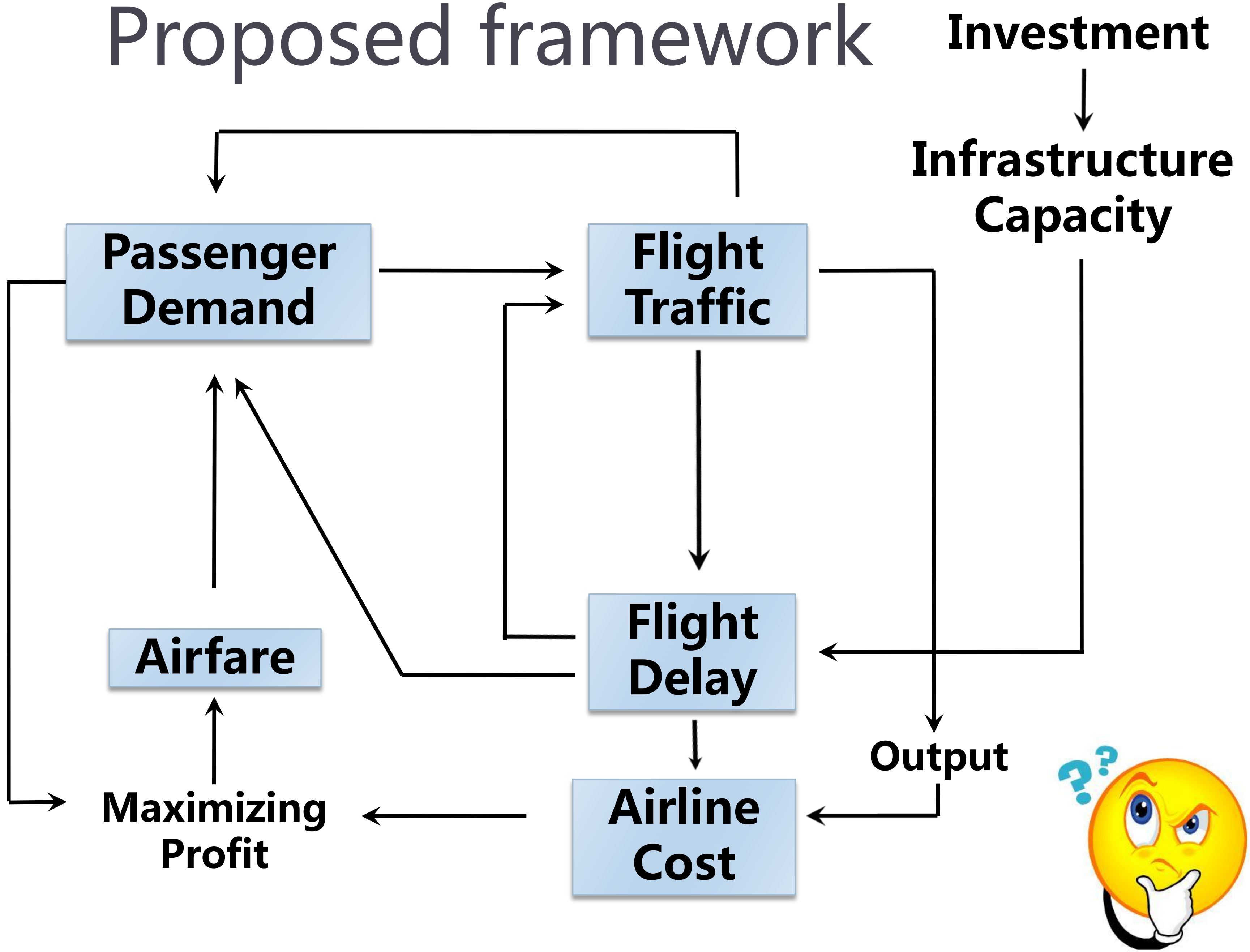
Proposed framework



Proposed framework



Proposed framework



Outline

- Background
- Research Framework
- **Equilibrium Models**
- Conclusion

Outline

- Background
- Research Framework
- **Equilibrium Models**
  - **Airline competition model**
  - User equilibrium model
- Conclusion

Zou, B., Hansen, M., 2012. Flight Delays, Capacity Investment and Social Welfare under Air Transport Supply-Demand Equilibrium. Transportation Research Part A: Policy and Practice 46 (6), 965-980.

- Consider a duopoly market

- Consider a duopoly market
- Utility of a representative individual

$$U(q_0,q_1,q_2)=q_0+\frac{\alpha_{00}}{\alpha_{01}-\alpha_{02}}(q_1+q_2)-\frac{1}{2}\frac{1}{\alpha_{01}{}^2-\alpha_{02}{}^2}(\alpha_{01}q_1^2+2\alpha_{02}q_1q_2+\alpha_{01}q_2^2)$$

- Consider a duopoly market
- Utility of a representative individual

$$U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}}(q_1 + q_2) - \frac{1}{2}\frac{1}{\alpha_{01}{}^2 - \alpha_{02}{}^2}(\alpha_{01} q_1^2 + 2\alpha_{02} q_1 q_2 + \alpha_{01} q_2^2)$$

Consumption of numeraire goods

- Consider a duopoly market
- Utility of a representative individual

$$U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}}(q_1 + q_2) - \frac{1}{2}\frac{1}{\alpha_{01}^2 - \alpha_{02}^2}(\alpha_{01} q_1^2 + 2\alpha_{02} q_1 q_2 + \alpha_{01} q_2^2)$$

Consumption of airline 1's service

- Consider a duopoly market
- Utility of a representative individual

$$U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}}(q_1 + q_2) - \frac{1}{2}\frac{1}{\alpha_{01}^2 - \alpha_{02}^2}(\alpha_{01} q_1^2 + 2\alpha_{02} q_1 q_2 + \alpha_{01} q_2^2)$$

Consumption of airline 2's service

- Consider a duopoly market
- Utility of a representative individual

$$U(q_0, q_1, q_2) = q_0 + \frac{\alpha_{00}}{\alpha_{01} - \alpha_{02}}(q_1 + q_2) - \frac{1}{2}\frac{1}{\alpha_{01}^2 - \alpha_{02}^2}(\alpha_{01} q_1^2 + 2\alpha_{02} q_1 q_2 + \alpha_{01} q_2^2)$$

$\alpha_{00}, \alpha_{01}, \alpha_{02}$: parameters ($\alpha_{01} \geq \alpha_{02}$)

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

Generalized cost for choosing airline 1

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

Generalized cost for choosing airline 2

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

$$\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \qquad i = 1,2$$

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

$$\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \qquad i = 1,2$$

Airfare

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \leq I$$

$$\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \qquad i = 1,2$$

Airfare

Schedule delay

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \le I$$

$$\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \qquad i = 1,2$$

Airfare | Schedule delay | Delay

$$\max U(q_0, q_1, q_2)$$

$$s.t. \quad q_0 + \overline{P}_1 q_1 + \overline{P}_2 q_2 \le I$$

Composite of income and travel time constraints

$$\overline{P}_i = P_i + \frac{\gamma}{f_i} + kL \qquad i = 1,2$$

Airfare

Schedule delay

Delay

- Individual demand

$$q_i = \alpha_{00} - \alpha_{01} P_i + \alpha_{02} P_{-i} - \frac{\alpha_{01}\gamma}{f_i} + \frac{\alpha_{02}\gamma}{f_{-i}} - (\alpha_{01} - \alpha_{02})kL, \quad i = 1,2$$

$$(\alpha_{01} \geq \alpha_{02})$$

- Individual demand

$$q_i = \alpha_{00} - \alpha_{01}P_i + \alpha_{02}P_{-i} - \frac{\alpha_{01}\gamma}{f_i} + \frac{\alpha_{02}\gamma}{f_{-i}} - (\alpha_{01} - \alpha_{02})kL, \quad i = 1,2$$

$$(\alpha_{01} \geq \alpha_{02})$$

- Market demand

$$Q_i = \alpha_0 - \alpha_1 P_i + \alpha_2 P_{-i} - \frac{\alpha_1\gamma}{f_i} + \frac{\alpha_2\gamma}{f_{-i}} - \mu L, \quad i = 1,2$$

$$(\alpha_1 \geq \alpha_2)$$

- Flight operating cost for trip *i*

$$C_i = c_0 + \tau s_i + \eta s_i L$$

- Flight operating cost for trip *i*

$$C_i = c_0 + \tau s_i + \eta s_i L$$

Fixed cost

- Flight operating cost for trip *i*

$$C_i = c_0 + \tau s_i + \eta s_i L$$

Fixed cost

Variable cost as a function of aircraft size ***s***

- Flight operating cost for trip *i*

$$C_i = c_0 + \tau s_i + \eta s_i L$$

Fixed cost

Variable cost as a function of aircraft size ***s***

Delay cost as a function of aircraft size ***s*** and delay ***L***

- Flight operating cost for trip *i*

$$C_i = c_0 + \tau s_i + \eta s_i L$$

Fixed cost

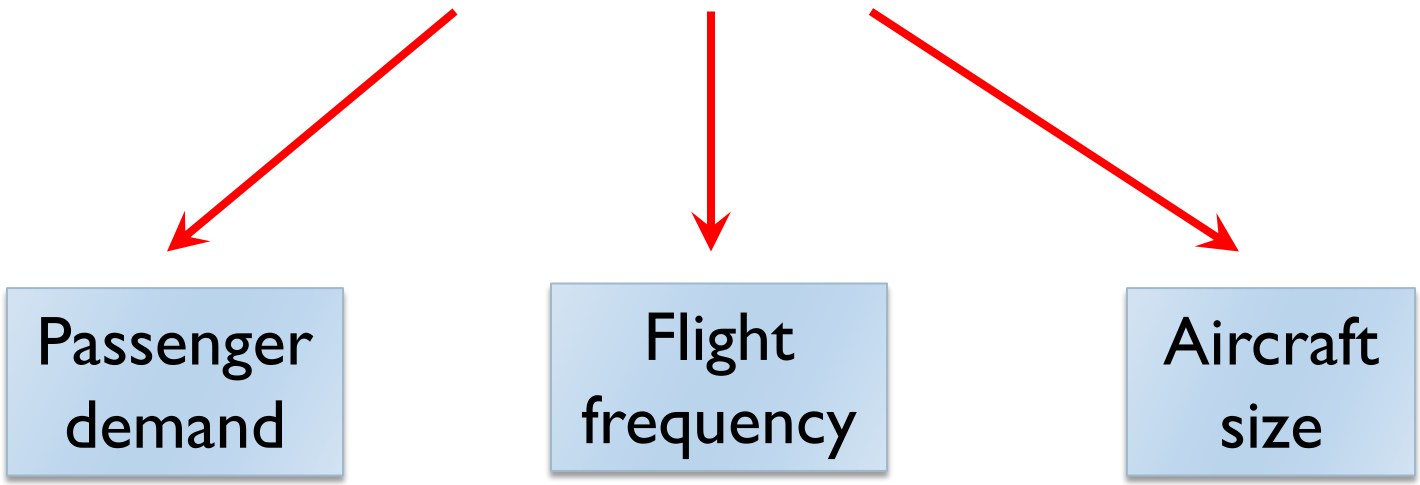
Variable cost as a function of aircraft size ***s***

Delay cost as a function of aircraft size ***s*** and delay ***L***

- Assumption: each flight is full

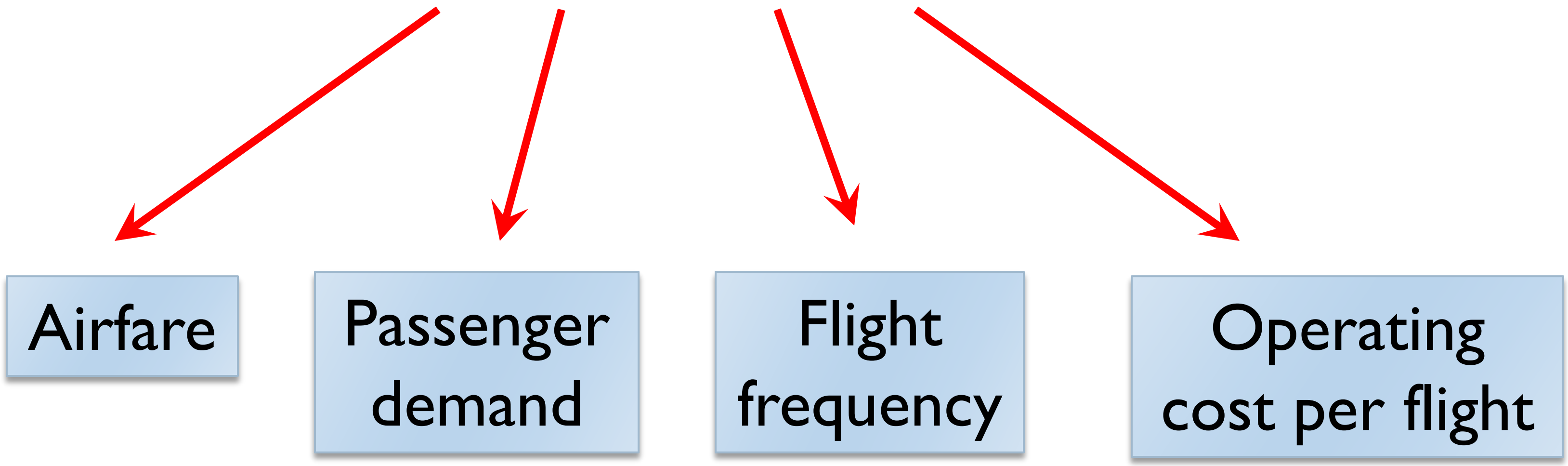
- Assumption: each flight is full

$$Q_i = f_i \cdot s_i$$



$$\max \pi_i = P_i \cdot Q_i - f_i \cdot C_i \quad \text{for } i = 1,2$$

$$\max \pi_i = P_i \cdot Q_i - f_i \cdot C_i \quad \text{for } i = 1,2$$



- Assume
  - airlines compete on fare and frequency **simultaneously** in a Nash fashion

$$\frac{\partial \pi_i}{\partial P_i} = 0 \quad \frac{\partial \pi_i}{\partial f_i} = 0 \quad i = 1,2$$

- Assume
  - airlines compete on fare and frequency **simultaneously** in a Nash fashion

$$\frac{\partial \pi_i}{\partial P_i} = 0 \quad \frac{\partial \pi_i}{\partial f_i} = 0 \quad i = 1,2$$

  - Symmetric airlines

$$P_1 = P_2 = P \qquad f_1 = f_2 = f$$

- Price response

$$P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{\frac{(\alpha_1 - \alpha_2)\gamma}{f}}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}$$

- Price response

$$P=\frac{\alpha_0+\alpha_1\tau}{2\alpha_1-\alpha_2}-\frac{\dfrac{(\alpha_1-\alpha_2)\gamma}{f}}{2\alpha_1-\alpha_2}-\frac{\mu L}{2\alpha_1-\alpha_2}+\frac{\alpha_1\eta L}{2\alpha_1-\alpha_2}$$

Constant

- Price response

$$P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{\frac{(\alpha_1 - \alpha_2)\gamma}{f}}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}$$

Constant

Frequency effect on WTP

Price response

$$P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{\frac{(\alpha_1 - \alpha_2)\gamma}{f}}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}$$

Constant

Frequency effect on WTP

Delay effect on WTP

- Price response

$$P = \frac{\alpha_0 + \alpha_1 \tau}{2\alpha_1 - \alpha_2} - \frac{\frac{(\alpha_1 - \alpha_2)\gamma}{f}}{2\alpha_1 - \alpha_2} - \frac{\mu L}{2\alpha_1 - \alpha_2} + \frac{\alpha_1 \eta L}{2\alpha_1 - \alpha_2}$$

Constant

Frequency effect on WTP

Delay effect on WTP

Airline delay cost passed onto passengers

Compare equilibrium with and without congestion

Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)

Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)
  - Passenger generalized cost (↑)

Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)
  - Passenger generalized cost (↑)
  - Passenger demand (↓)

Compare equilibrium with and without congestion

- With congestion
  - Frequency (↓)
  - Passenger generalized cost (↑)
  - Passenger demand (↓)

  - Fare (?)
  - Aircraft size (?)
  - Unit operating cost per passenger (?)

Simulation analysis

- Simulation analysis
  - Assumption about airport delay L
    - Delay on a market is determined by the more congested airport
    - N independent and identical markets into that airport

- Simulation analysis
  - Assumption about airport delay *L*

$$L = \delta[N(f_1 + f_2)/K]^{\theta}, \ \theta > 1$$

$N(f_1 + f_2)$ → Total airport traffic

K → Airport capacity

Simulation analysis

- Assumption about airport delay *L*

$$L = \delta[N(f_1 + f_2)/K]^{\theta}, \ \theta > 1$$

- All other parameters derived from empirical evidence

Scenarios	Fare	Aircraft size	Unit operating cost ($/passenger)
Infinite capacity (no delay)	98.9	63.6	91.4
Finite capacity (720 operations per day, with delay)	96.0	71.9	91.5

Scenarios	Fare	Aircraft size	Unit operating cost ($/passenger)
Infinite capacity (no delay)	98.9	63.6	91.4
Finite capacity (720 operations per day, with delay)	96.0	71.9	91.5

Decreased WTP dominates airlines' tendency to pass part of the delay cost to passengers

Scenarios	Fare	Aircraft size	Unit operating cost ($/passenger)
Infinite capacity (no delay)	98.9	63.6	91.4
Finite capacity (720 operations per day, with delay)	96.0	71.9	91.5

Use larger planes to avoid high delays

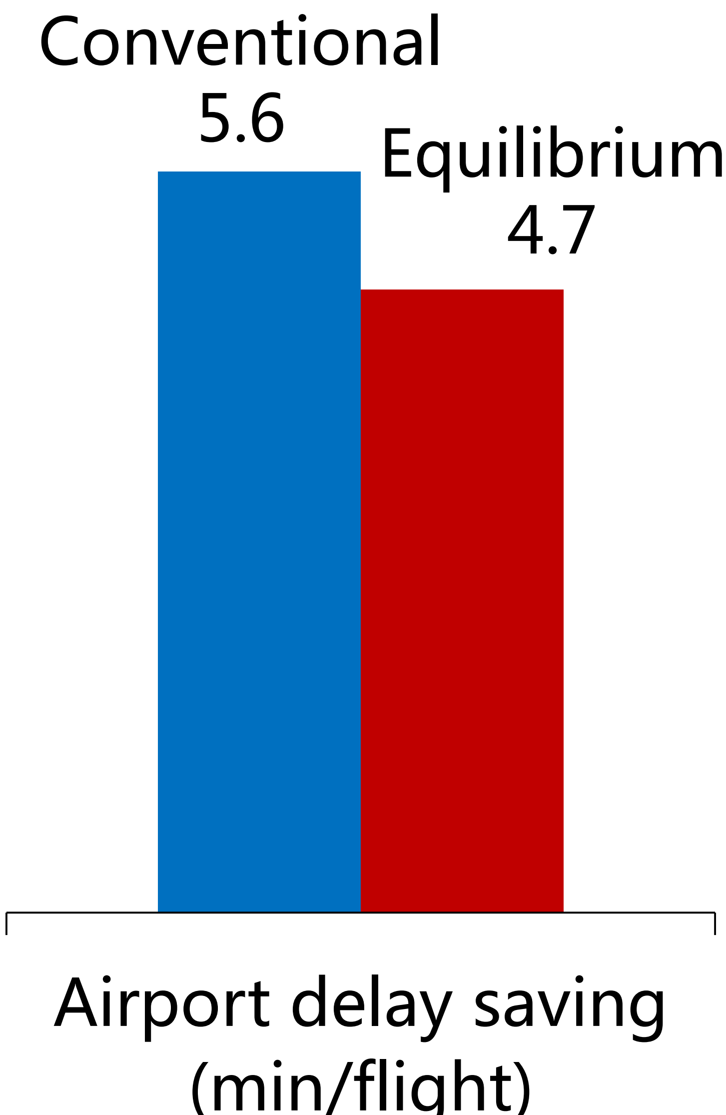
Scenarios	Fare	Aircraft size	Unit operating cost ($/passenger)
Infinite capacity (no delay)	98.9	63.6	91.4
Finite capacity (720 operations per day, with delay)	96.0	71.9	91.5

Delay cost partially offset by economies of aircraft size

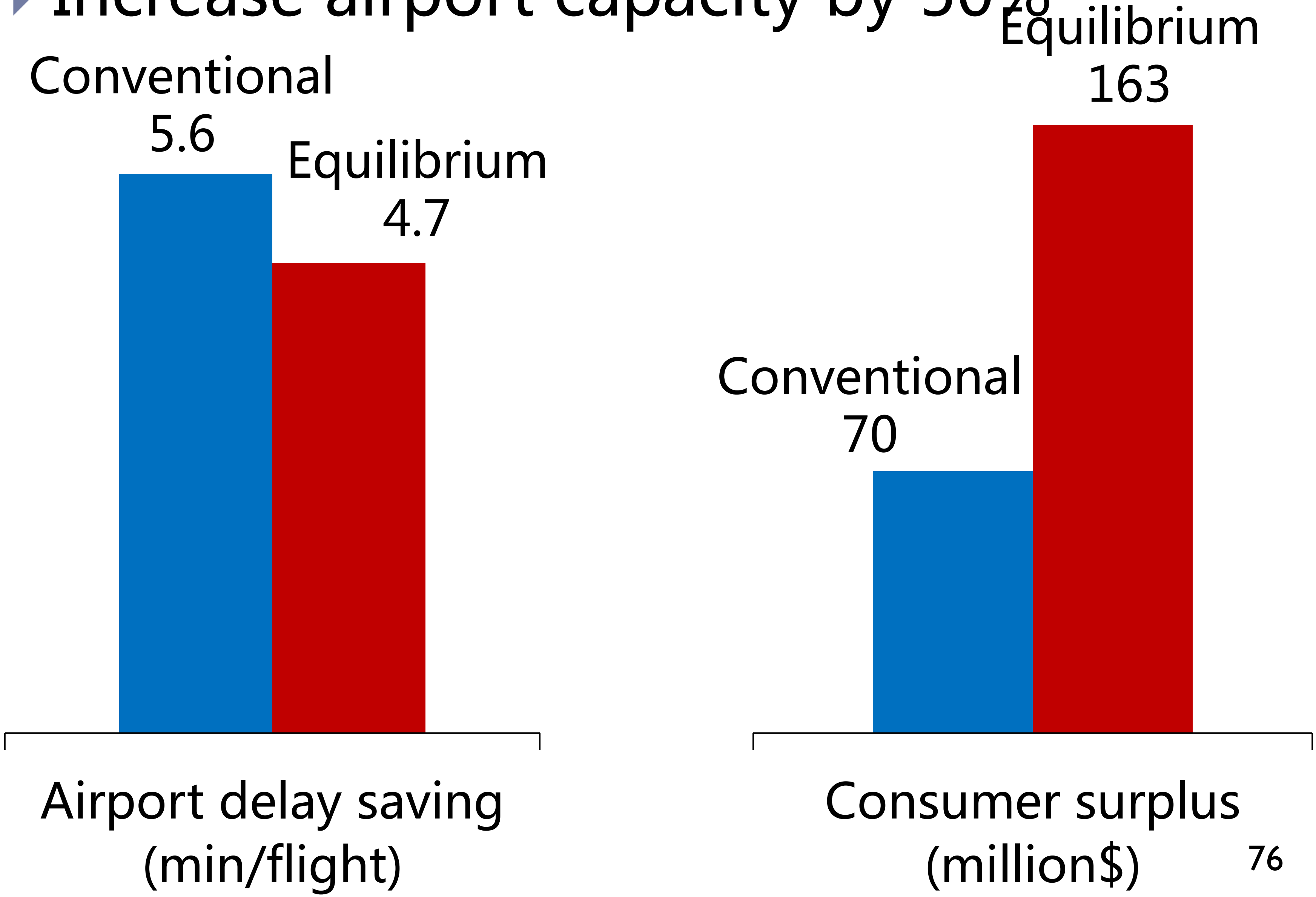
Comparison between equilibrium and conventional approaches

- Increase airport capacity by 50%

- Increase airport capacity by 50%



- Increase airport capacity by 50%



Outline

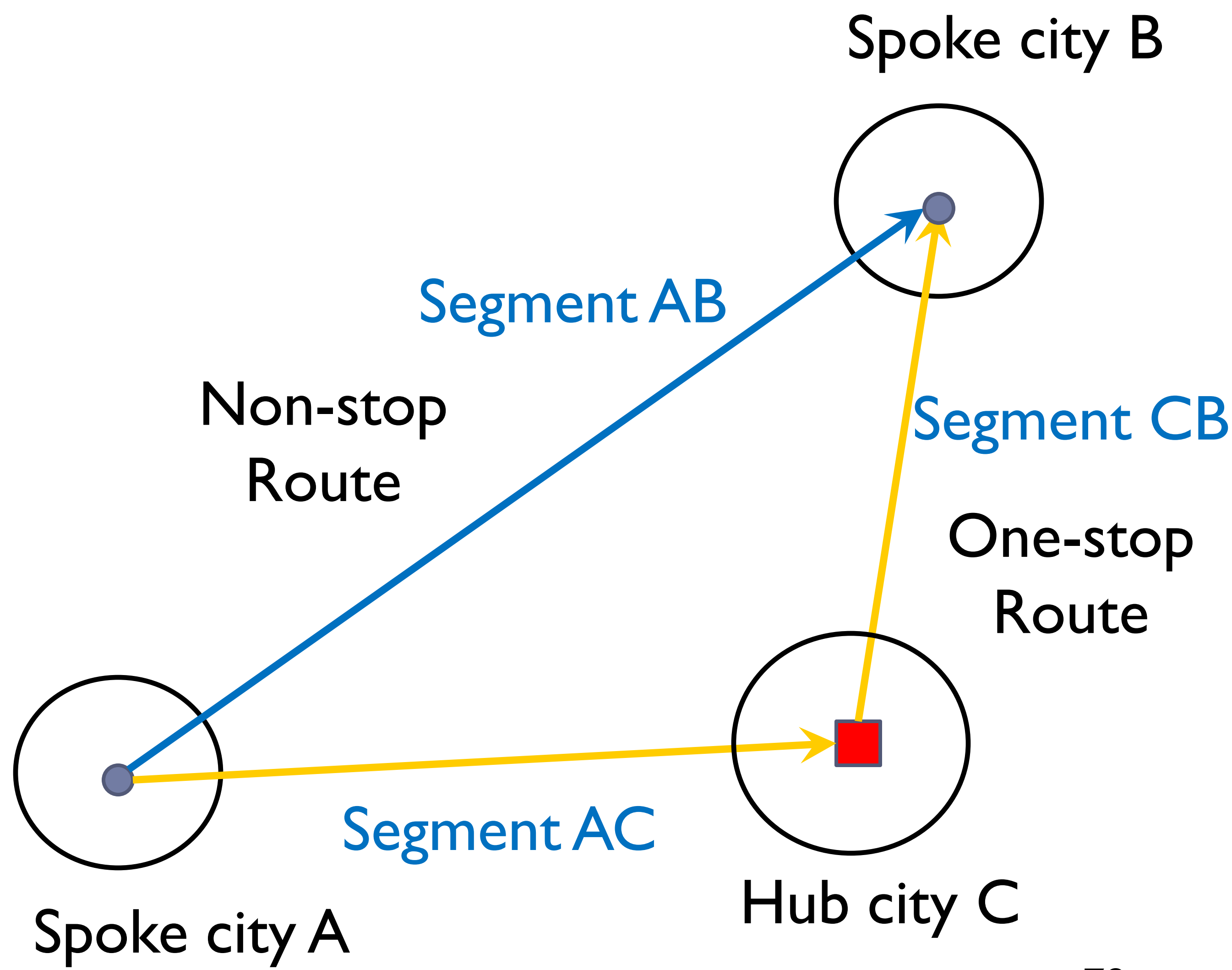
- Background
- Research Framework
- **Equilibrium Models**
  - Airline competition model
  - **User equilibrium model**
- Conclusion

Introduction of basic concepts

Route

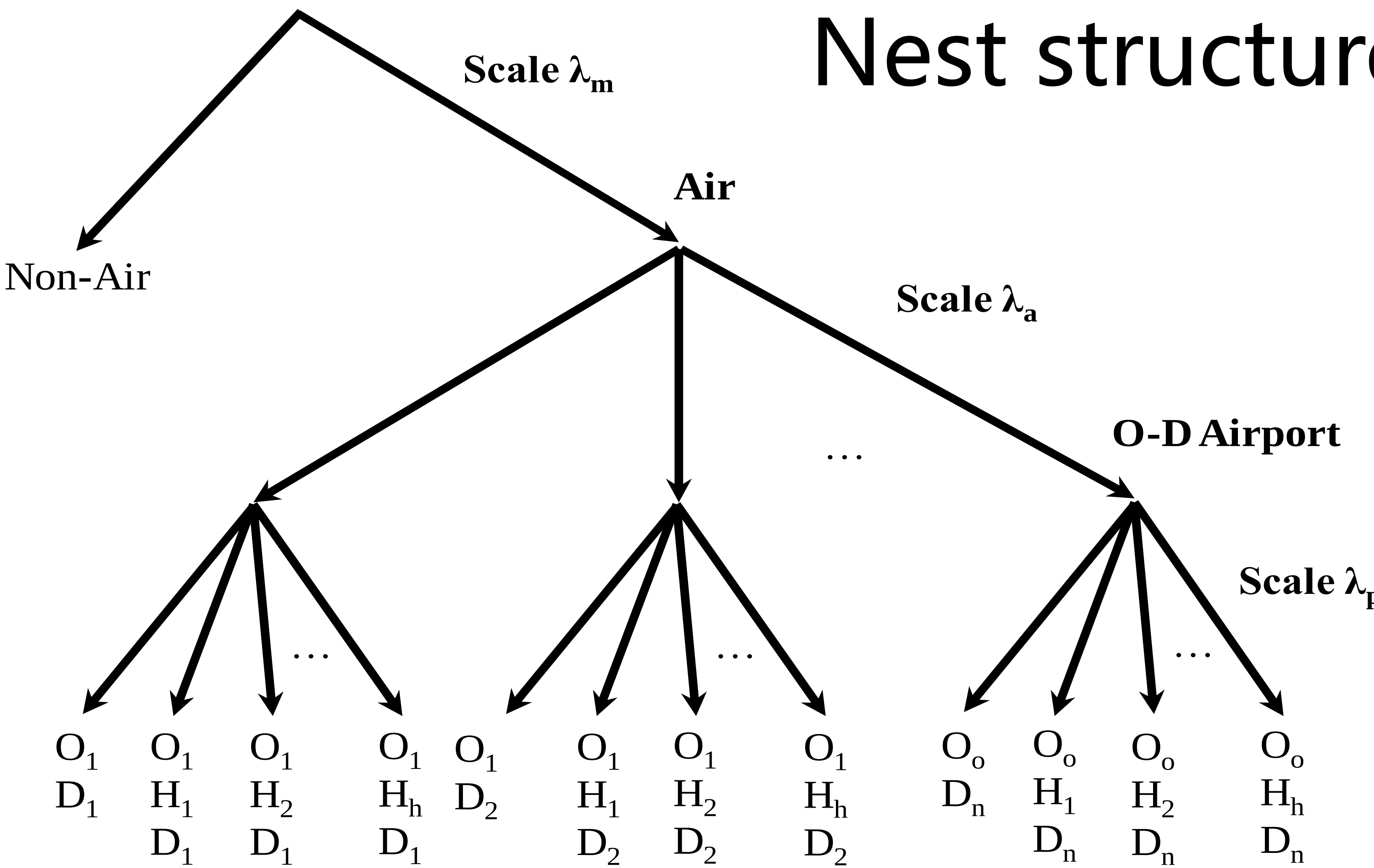
Segment

Market



Demand estimation

Nest structure

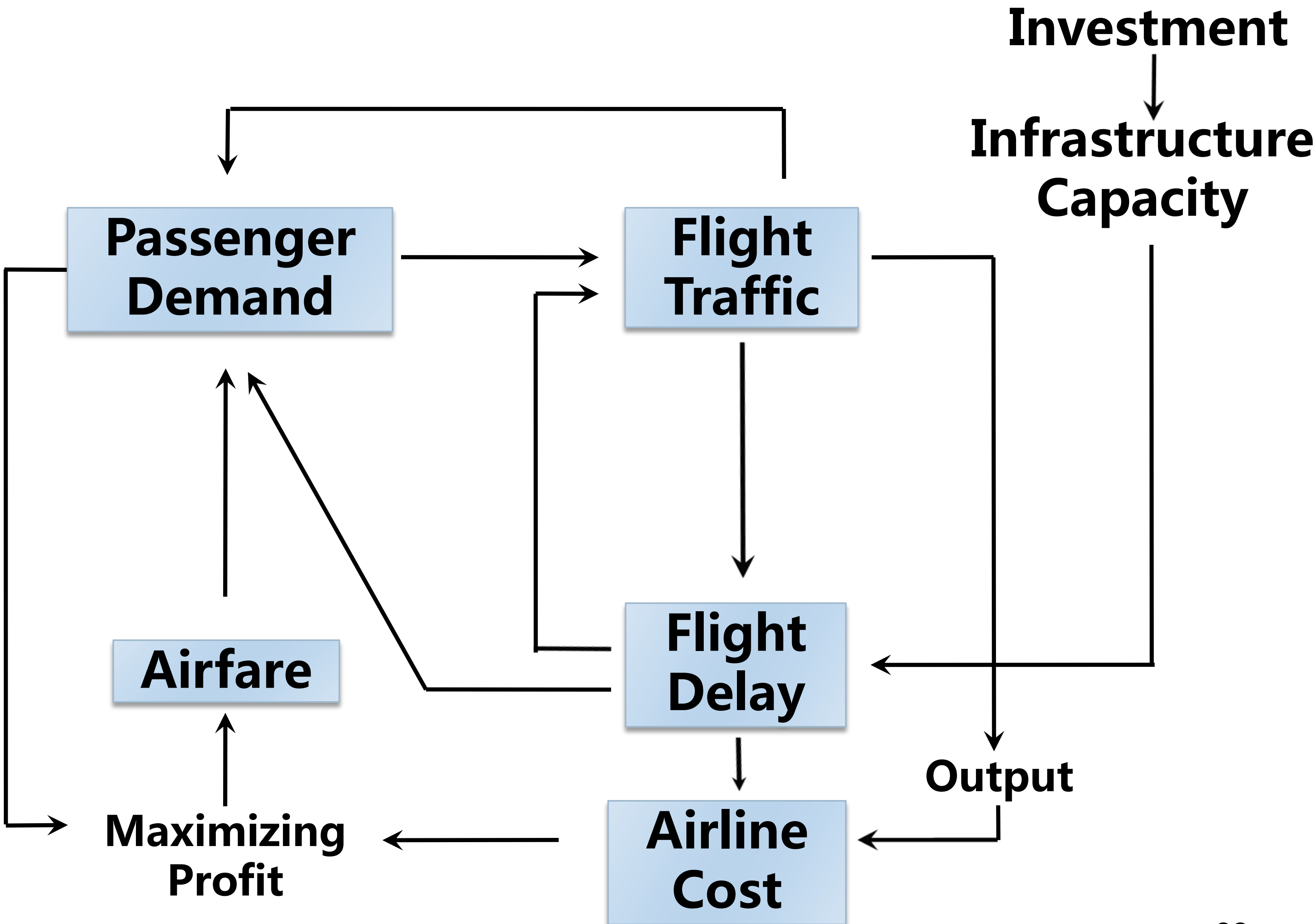


Source: Hsiao, C. and Hansen, M., 2011. *A passenger demand model for air transportation in a hub-and-spoke network*. Transportation Research Part E: Logistics and Transportation Review, Vol. 47, 1112-1125.

User equilibrium formulation

Demand = G_1(Fare, Flight Traffic, Airport delay)

s.t. Constraints


Investment
Infrastructure Capacity
Passenger Demand
Flight Traffic
Flight Delay
Airfare
Output
Maximizing Profit
Airline Cost

Flight traffic = G_2(Demand, Airport Delay)

Fare = G_3(Demand, Airport delay)

Airport delay= G_4(Flight traffic)

Zou, B., Hansen, M. *Flight Delay Impact on Airfare and Flight Frequency: A Comprehensive Assessment*. Paper to be submitted to Transportation Research Part A.

$$\text{Flight traffic} = G_2(\overset{(++)}{\text{Demand}}, \overset{(-)}{\text{Airport delay}})$$

$$\text{Fare} = G_3(\overset{(+/-)}{\text{Demand}}, \overset{(+)}{\text{Airport delay}})$$

$$\text{Airport delay} = G_4(\overset{(++)}{\text{Flight traffic}})$$

User equilibrium formulation

Demand = G_1(Fare, Flight Traffic, Airport delay)

s.t. Flight traffic = G_2(Demand, Airport delay)

Fare = G_3(Demand, Airport delay)

Airport delay= G_4(Flight traffic)

Simultaneous equation system

Demand = G_1(Fare, Flight Traffic, Airport delay)

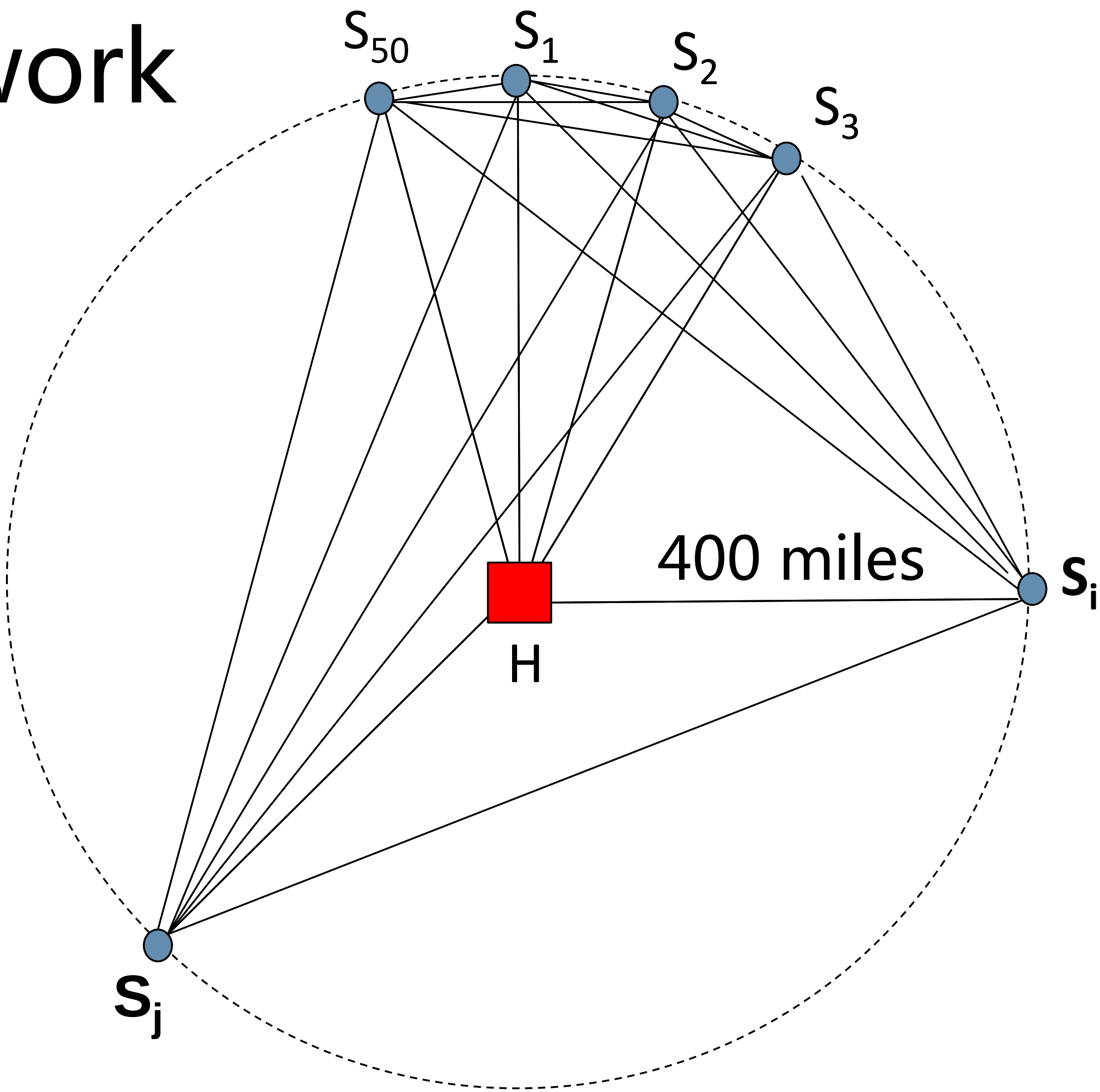
Flight traffic = G_2(Demand, Airport delay)

Fare = G_3(Demand, Airport delay)

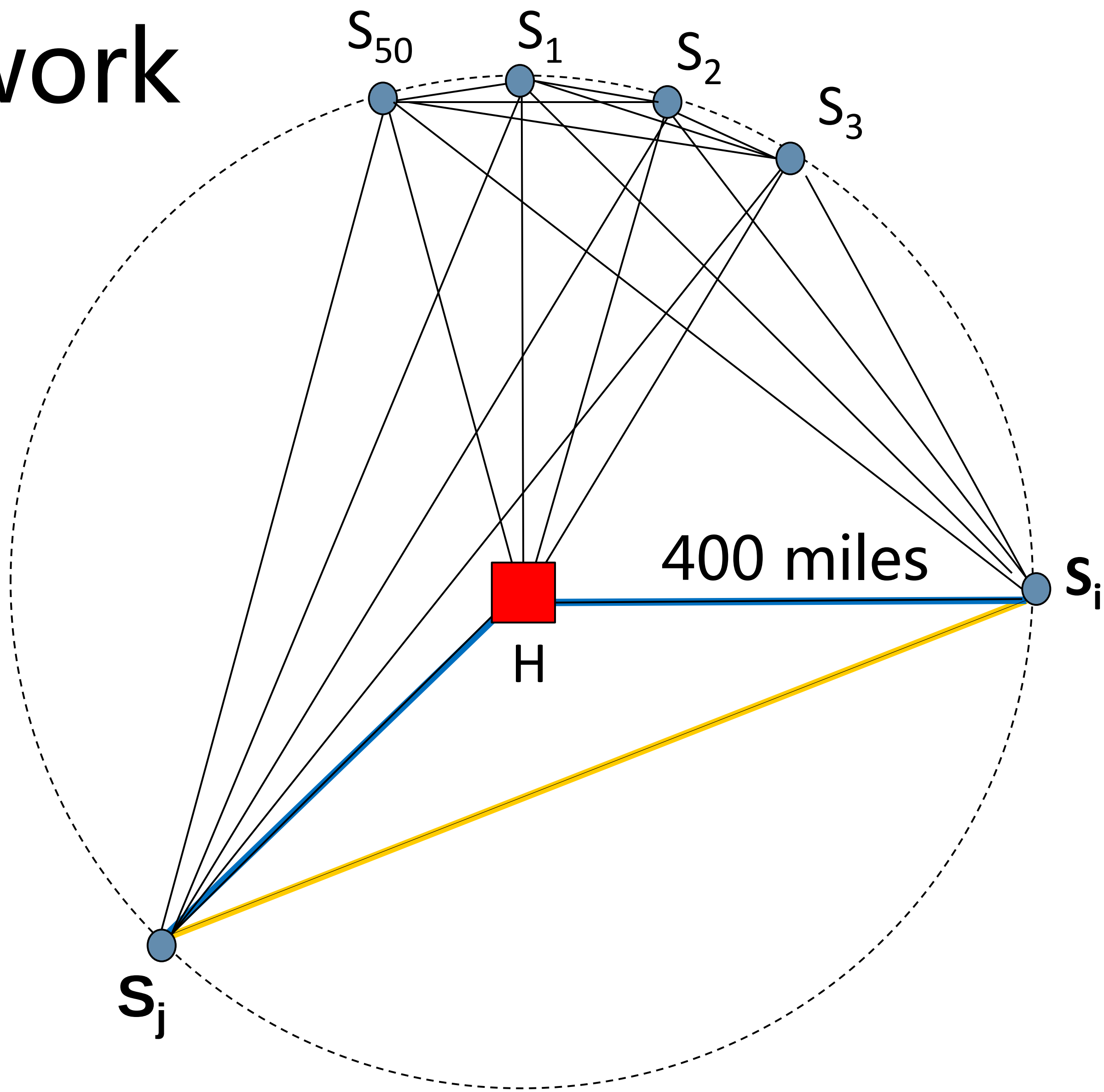
Airport delay= G_4(Flight traffic)

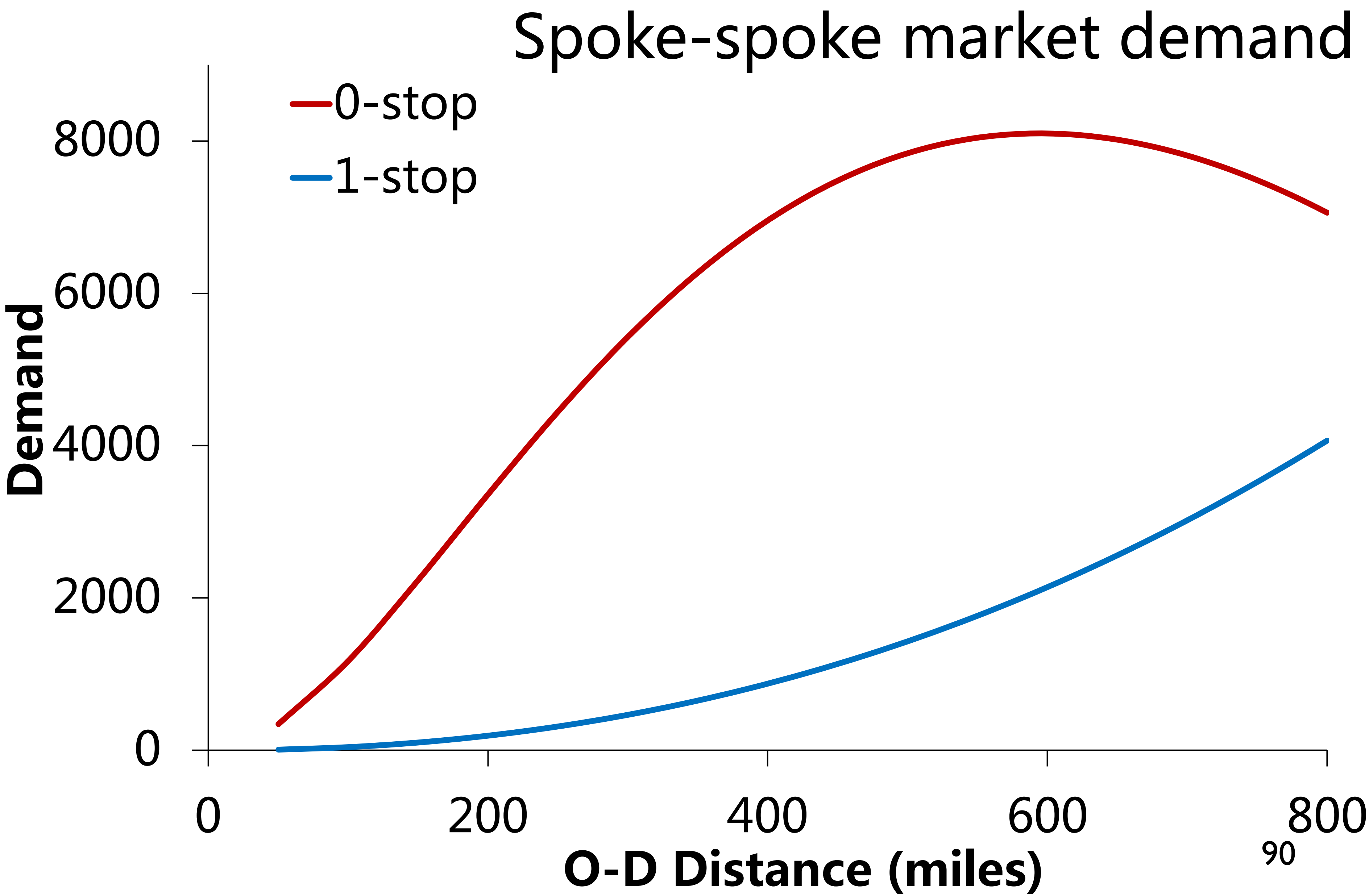
Simulation analysis

Network

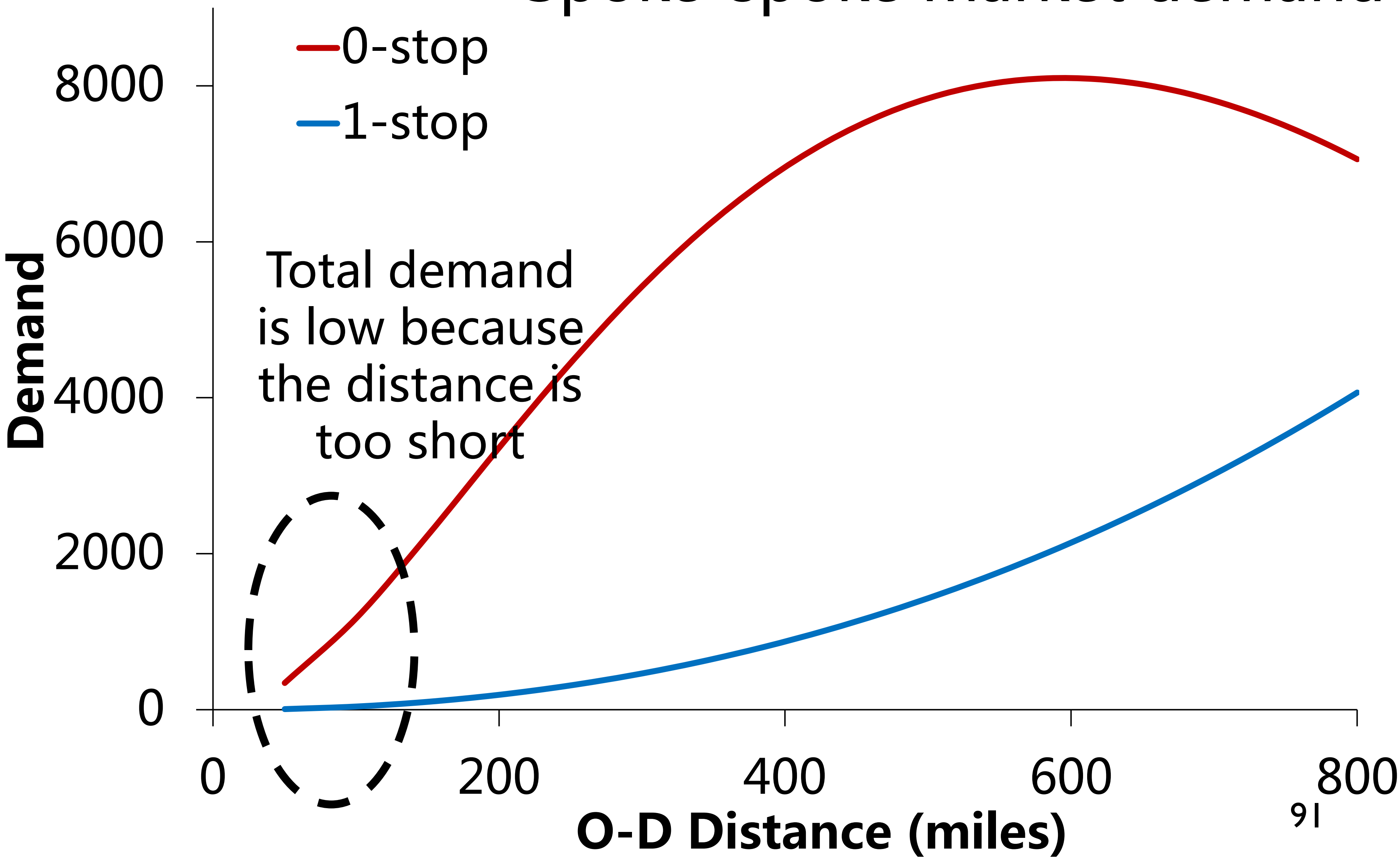


Network

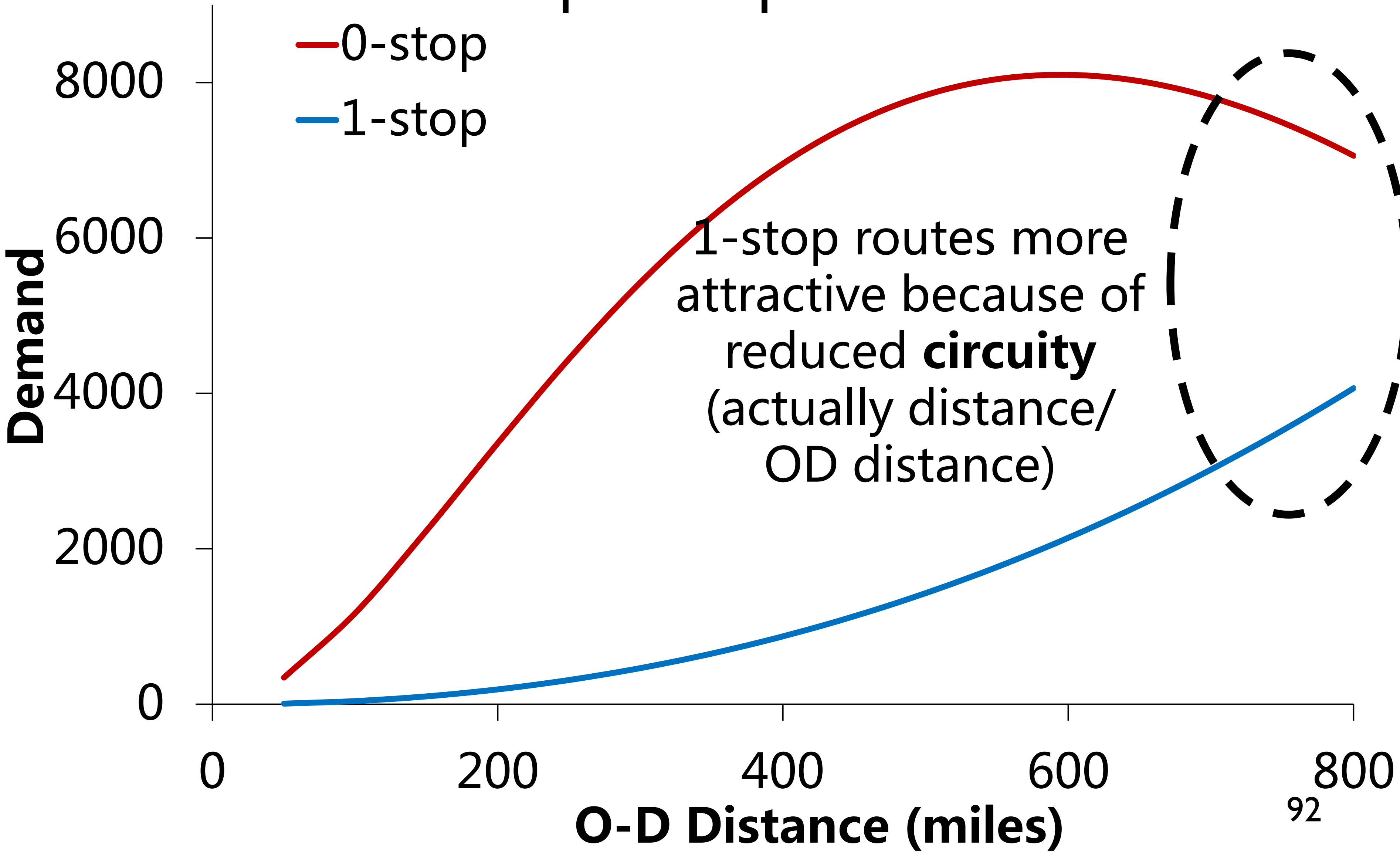


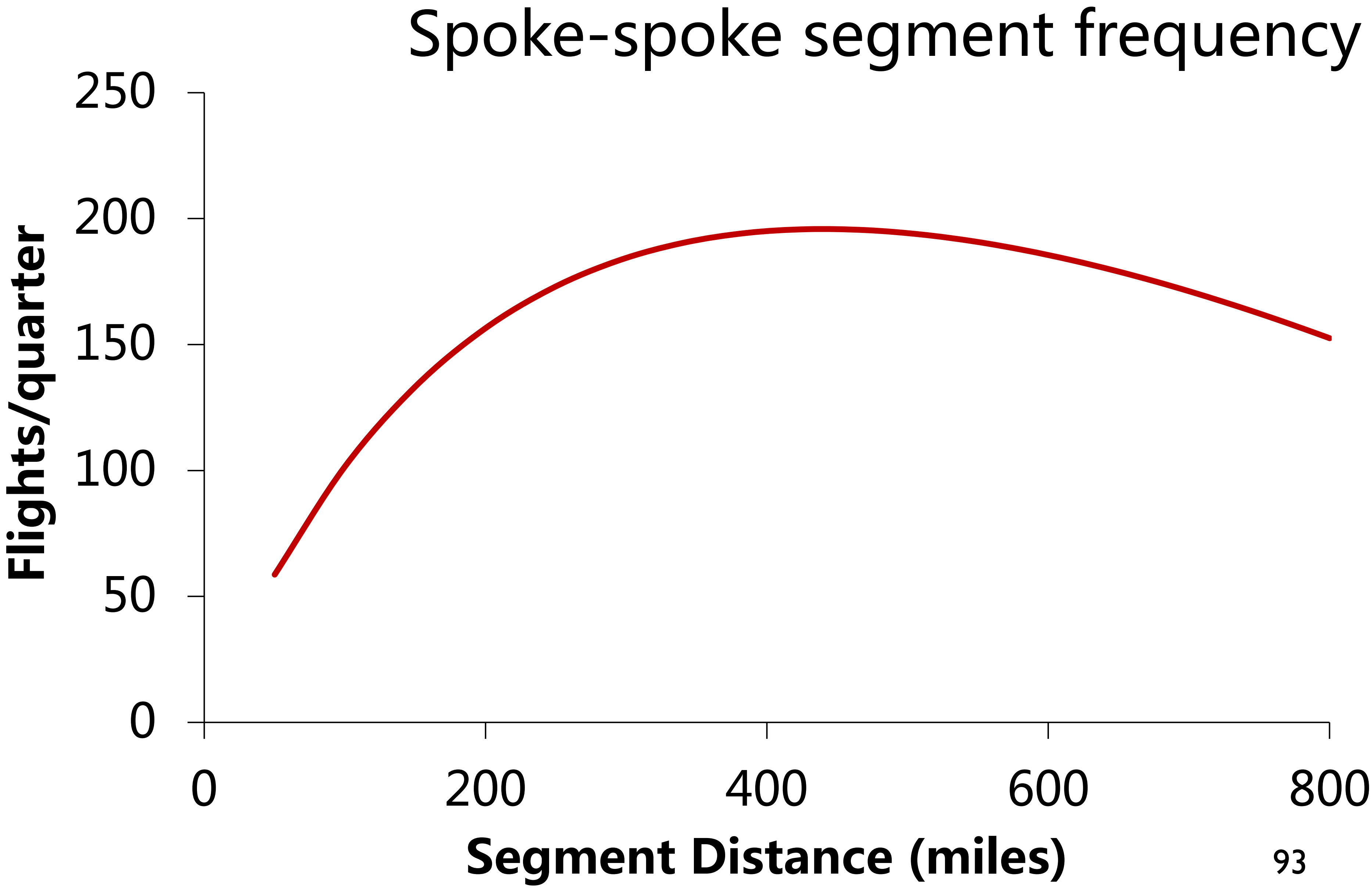

Spoke-spoke market demand
0-stop
1-stop
8000
6000
4000
2000
0
Demand
0
200
400
600
800
O-D Distance (miles)

Spoke-spoke market demand



Spoke-spoke market demand




Spoke-spoke segment frequency
Flights/quarter
250
200
150
100
50
0
0
200
400
600
800
Segment Distance (miles)

Delay (min/flight)	Hub	Spoke
Before	26.5	11.6

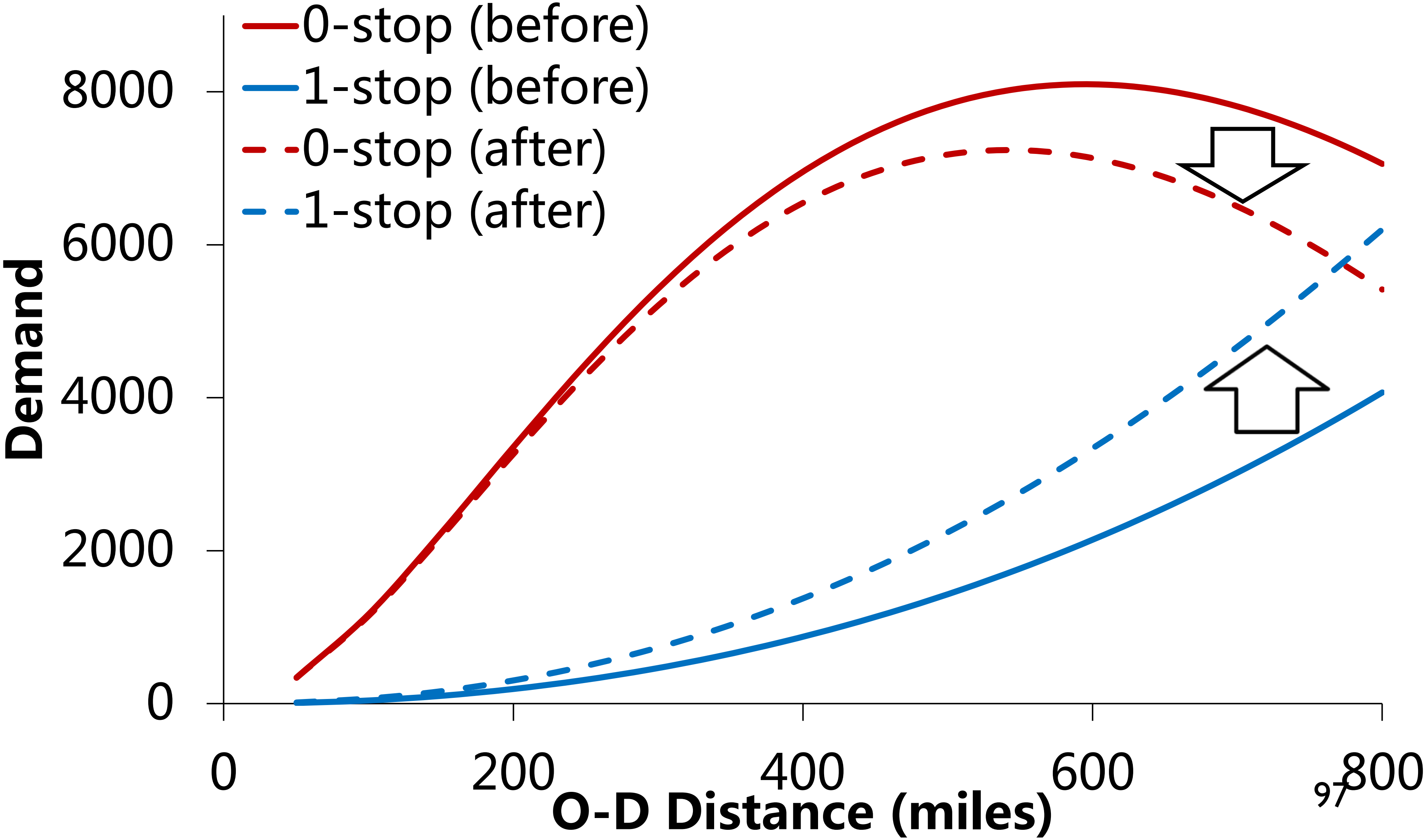
Increase hub capacity by 50%

Delay (min/flight)	Hub	Spoke
Before	26.5	11.6

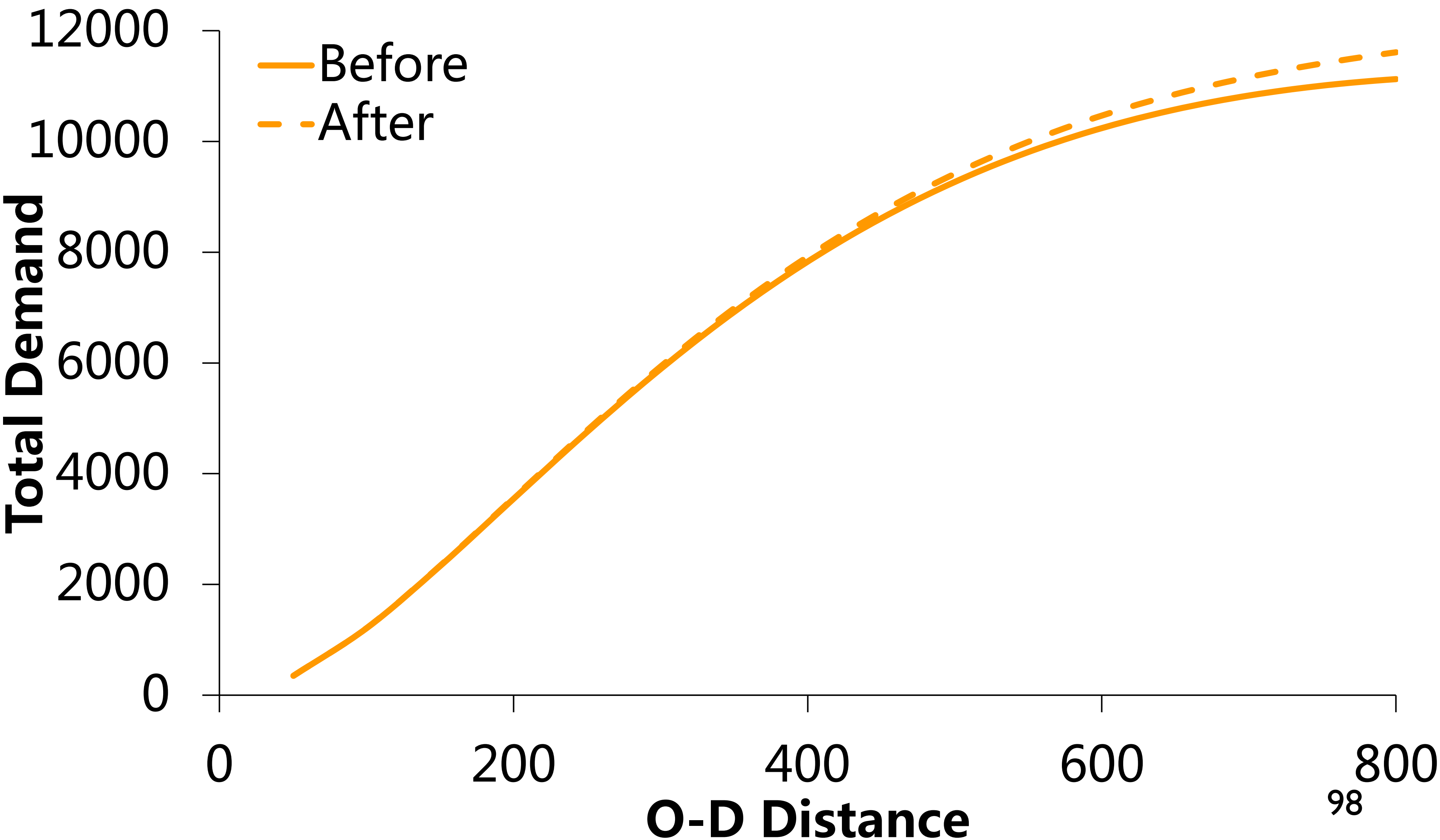
Increase hub capacity by 50%

Delay (min/flight)	Hub	Spoke
Before	26.5	11.6
After	17.5	11.4

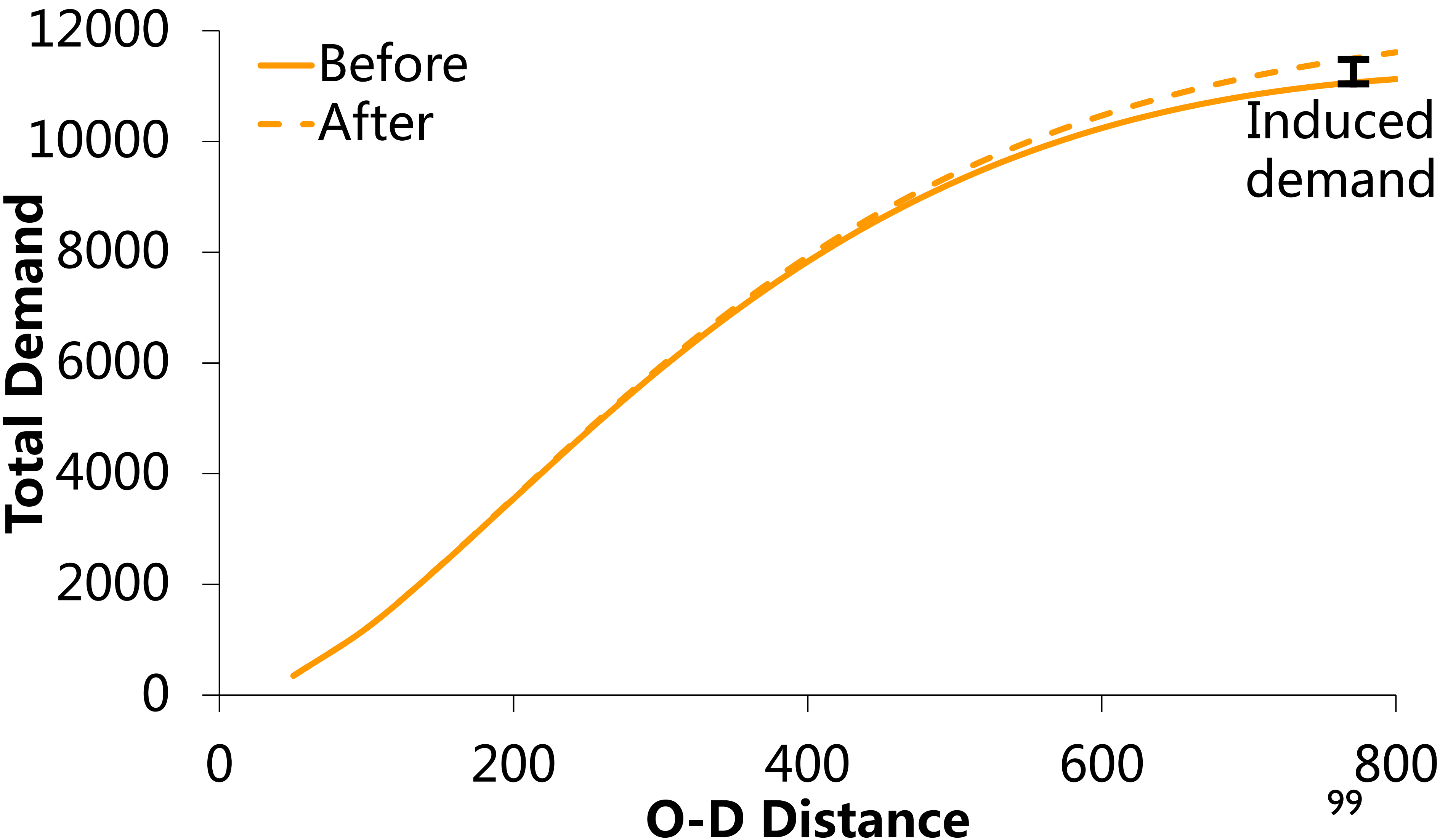
Spoke-spoke market demand shift



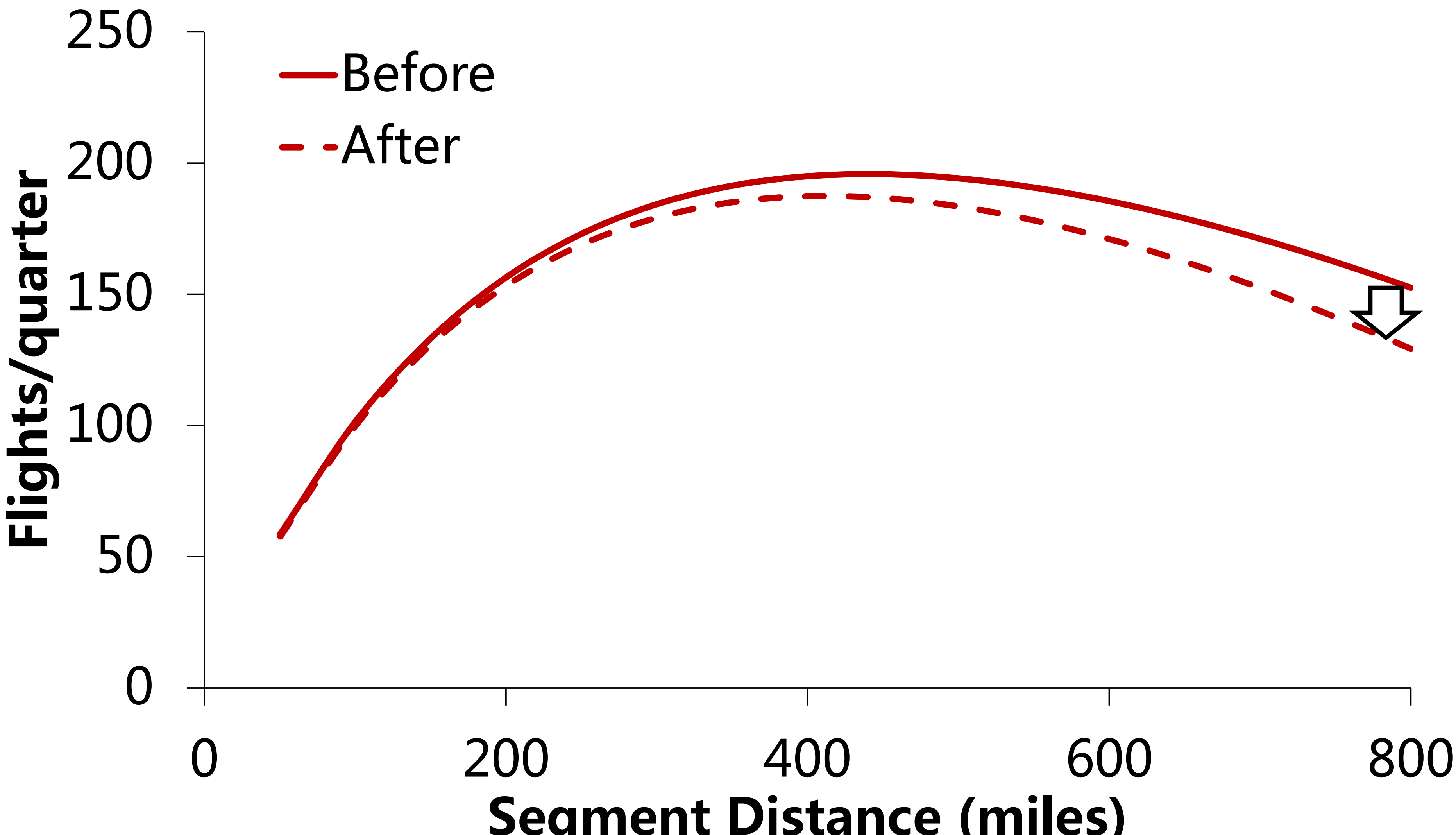
Total spoke-spoke market demand



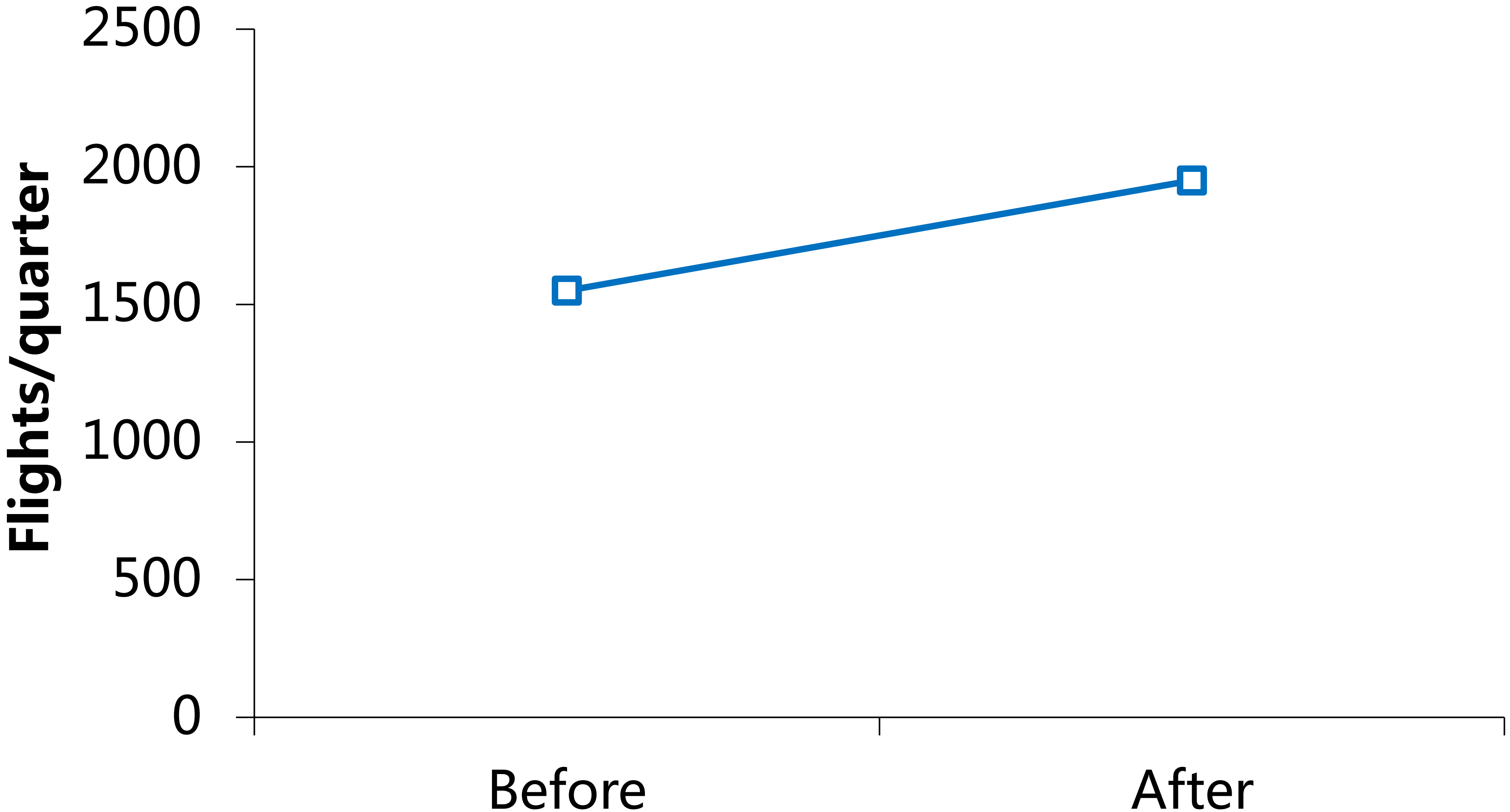
Total spoke-spoke market demand



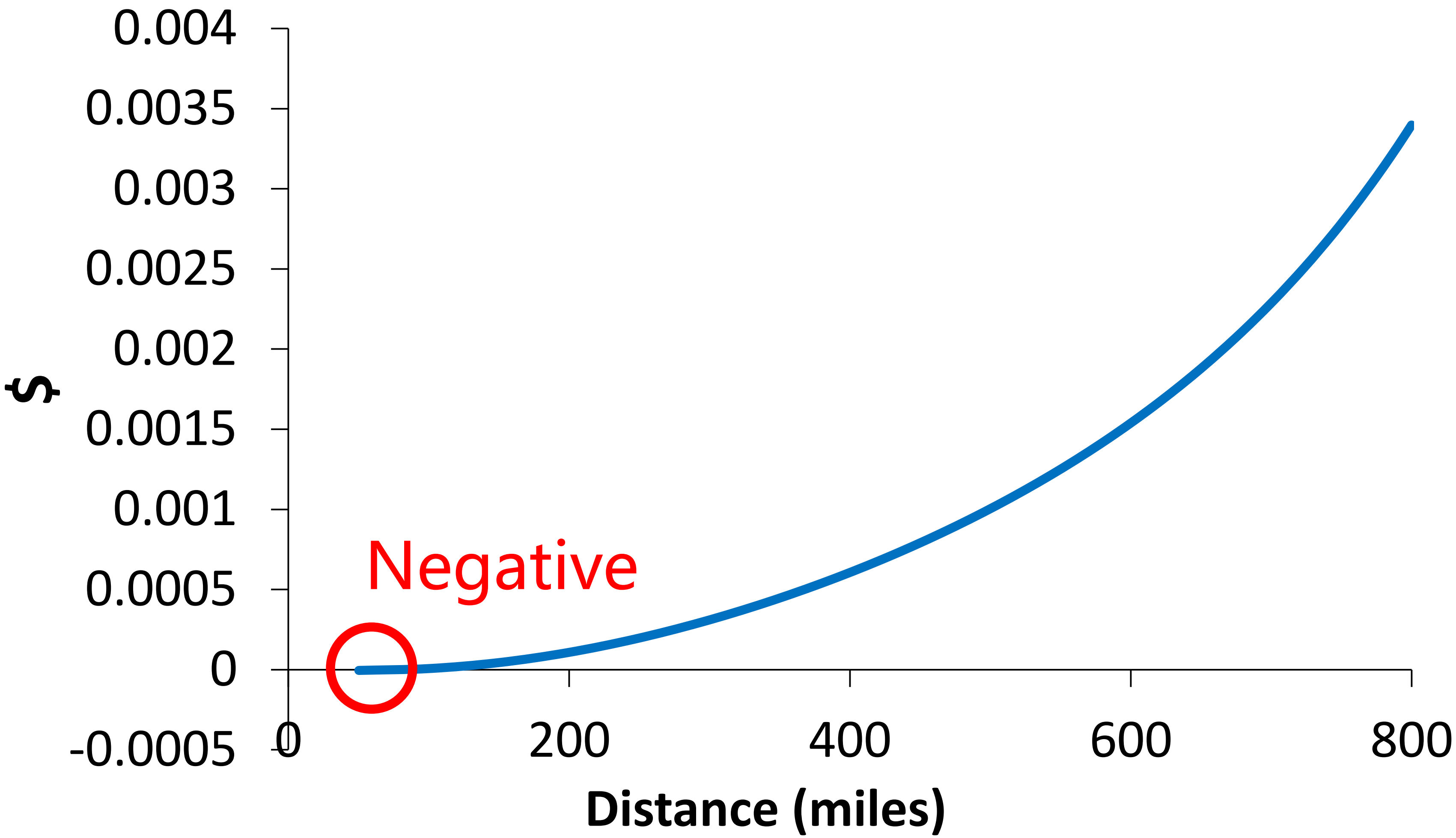
Spoke-spoke segment frequency change



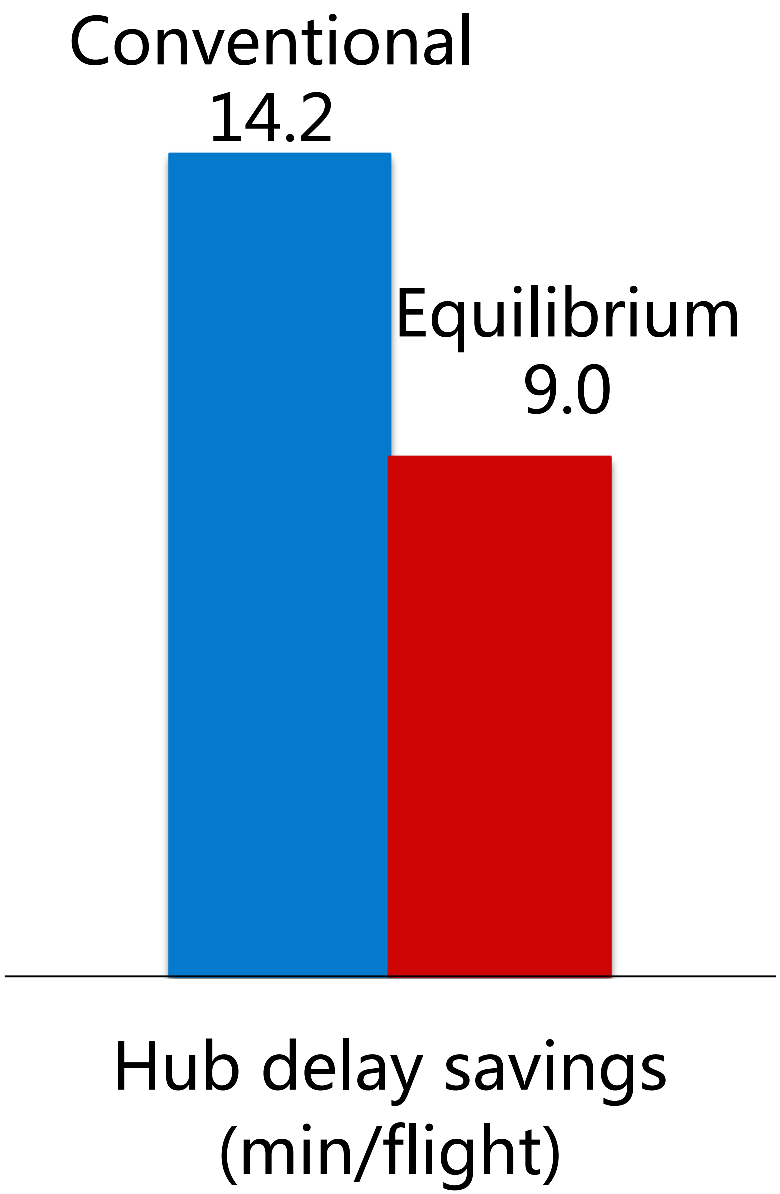
Spoke-hub segment frequency change

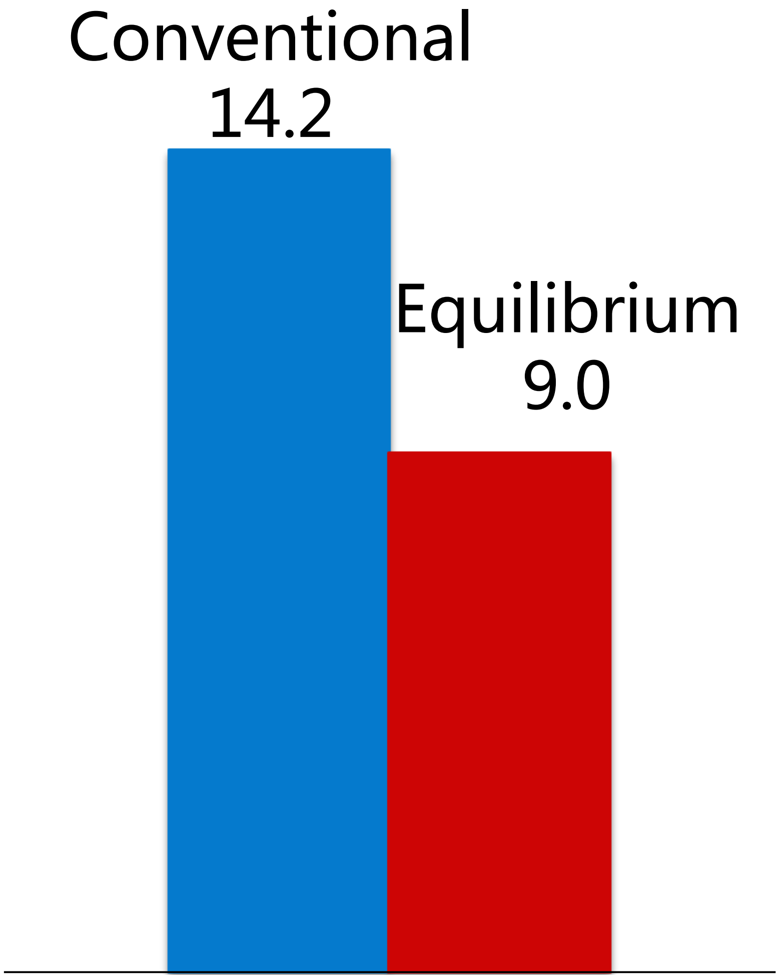


Consumer surplus change per air travel decision making

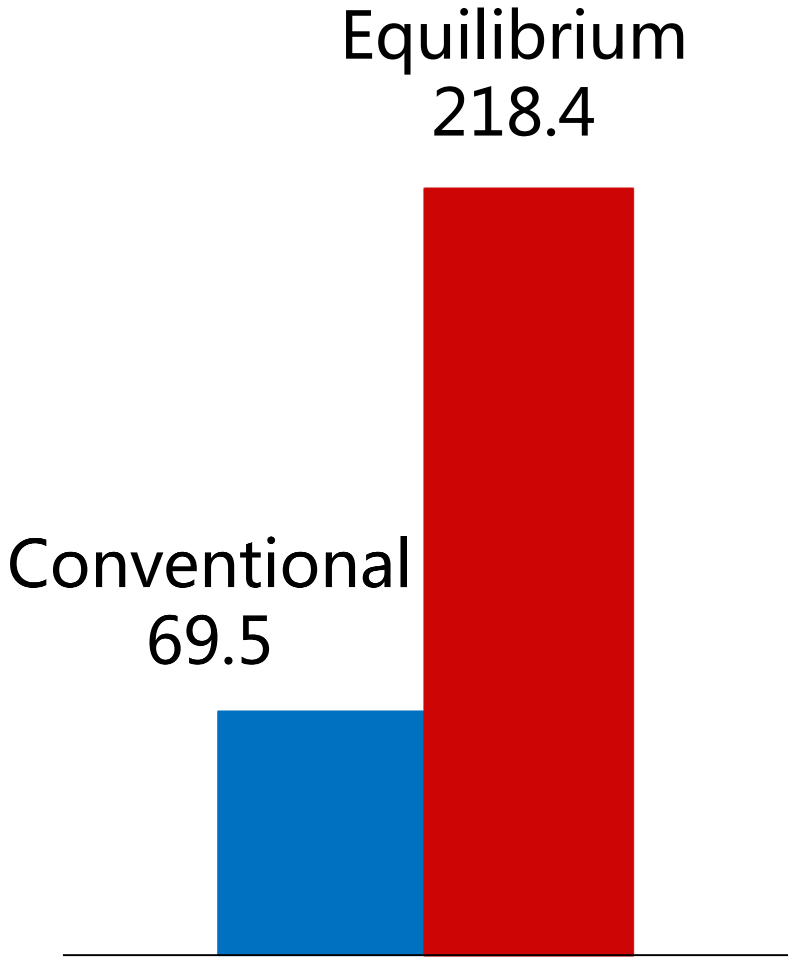


Comparison between equilibrium and conventional approaches


Conventional
14.2
Equilibrium
9.0
Hub delay savings
(min/flight)



Hub delay savings (min/flight)



Passenger welfare gain (million$/qtr)

Outline

- Background
- Research Framework
- Equilibrium Models
  - Airline competition model
  - User equilibrium model
- **Conclusion**

Summary

- An equilibrium framework

Summary

- An equilibrium framework
- Larger and broader benefits

Summary

- An equilibrium framework
- Larger and broader benefits
- Additional insights
  - Delay triggers investment

Summary

- An equilibrium framework
- Larger and broader benefits
- Additional insights
  - Delay triggers investment
  - Returns more than delay savings

Summary

- An equilibrium framework
- Larger and broader benefits
- Additional insights
  - Delay triggers investment
  - Returns more than delay savings
  - Delay reduction less than expected

Summary

- An equilibrium framework
- Larger and broader benefits
- Additional insights
  - Delay triggers investment
  - Returns more than delay savings
  - Delay reduction less than expected
  - Investment paradox: some markets can be worse off

Extensions

Extensions

- Infrastructure investment decision making
  - Size, location, timing

Extensions

- Infrastructure investment decision making
  - Size, location, timing
  - Environmental externalities

Extensions

- Infrastructure investment decision making
  - Size, location, timing
  - Environmental externalities
- Consider intermodal competition

Thank you!

Questions?