Pricing of Transportation Services: Theory and Practice I

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1.201 / 11.545 / ESD.210
Transportation Systems Analysis: Demand & Economics

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Outline

This Lecture:

– **Introduction, Review of cost and demand concepts**

– Public sector pricing in theory

– Issues with marginal cost pricing

– Congestion pricing in theory

Next Lecture:

– Congestion pricing in practice

– Public Sector pricing in practice

– Private sector pricing in theory and in practice
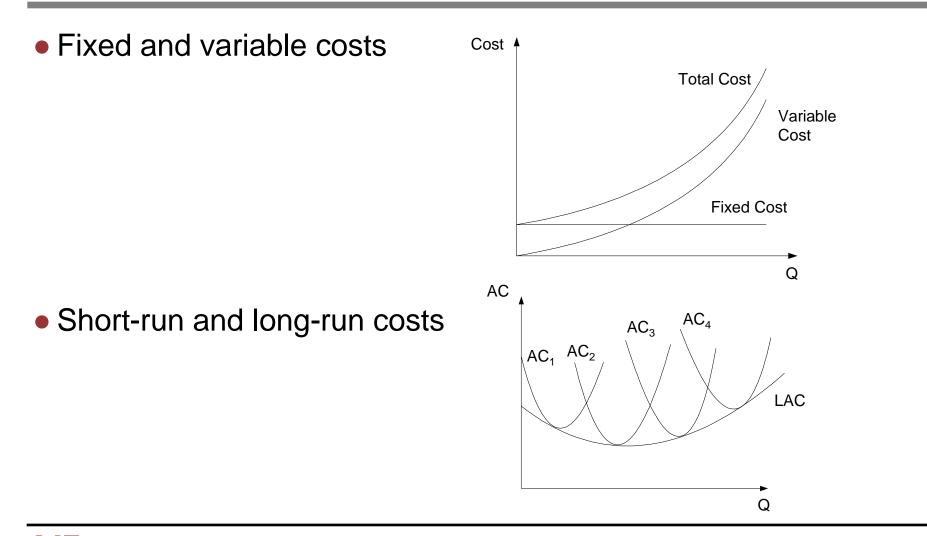
Introduction to Pricing

- Tool: Determining prices for provided services
- Objective: Maximize the economies of a system
  - Public sector: welfare
  - Private sector: profit
- To quantify welfare and profit, need to understand demand and cost

Total, Average, and Marginal Costs

- Total cost: $C(Q)$

- Average cost: $AC(Q)$

- Marginal cost: $MC(Q)$

Other Concepts

- Fixed and variable costs

- Short-run and long-run costs

Demand Function and Price Elasticity

- Demand function

    $Q = D(p)$

    $Q = D(p_q, p_r, p_s, \dots)$

    $\Rightarrow$ complements, substitutes

- Demand price elasticity

    $E_{Q|p} = \partial \ln Q / \partial \ln p$

    $\qquad\qquad = (\partial Q / \partial p) * p / Q$

where p_q is the price of a unit of output and p_r and p_s are unit prices of complements and substitutes, respectively.

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Revenue Elasticity
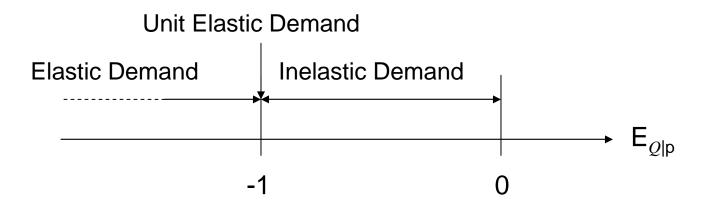
$$\text{Revenue } = R = p \cdot Q$$

$$\text{Revenue arc elasticity} = \frac{\% \text{ change in revenue}}{\% \text{ change in price}} = \frac{\Delta R/R}{\Delta p/p}$$

$$E_{R|p} = \frac{\partial R}{\partial p}\frac{p}{R} = \frac{\partial(p \cdot Q)}{\partial p}\frac{p}{p \cdot Q} = \left(Q + p\frac{\partial Q}{\partial p}\right)\frac{1}{Q} = 1 + \frac{\partial Q}{\partial p}\frac{p}{Q}$$
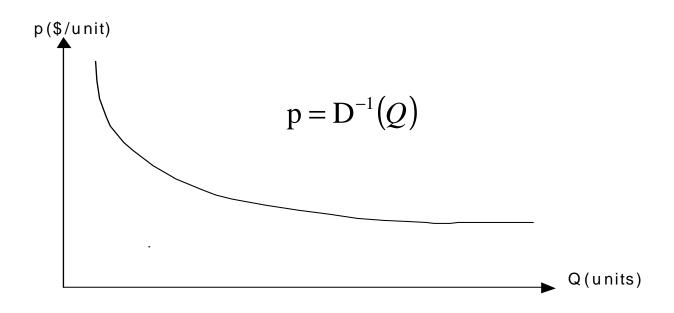
$$E_{R|p} = 1 + E_{Q|p}$$

Example: if the demand price elasticity is −1.5 then a 10% price increase would result in a 5% revenue decline

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Elastic and Inelastic Demand

- Elastic demand: decrease price to increase revenue

- Inelastic demand: increase price to increase revenue

Unit Elastic Demand

Elastic Demand   Inelastic Demand

$E_{Q|p}$

-1   0

Inverse Demand Function

p ($/unit)

$$p = D^{-1}(Q)$$

Q (units)

D^{-1} represents the willingness to pay for a given consumption level. It is a measure of marginal social benefit

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- **Public sector pricing in theory**
- Issues with marginal cost pricing
- Congestion pricing in theory

Public Sector Pricing

- Basic idea: social marginal cost pricing
  - Set price to maximize net "welfare"
  - What is welfare?

    Total social benefits (B) – Total social costs (C)
  - What are social costs?
  - What are social benefits?
  - Both depend on price through quantity consumed
  - Max (B(Q) – C(Q))
  - →Set price so that MB(Q) = MC(Q)
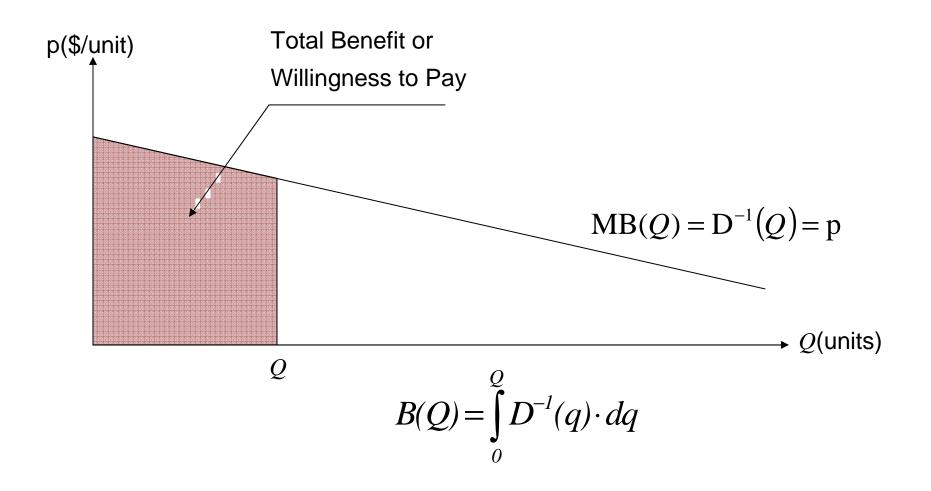
where MB is marginal benefit, and MC is marginal cost

Public Sector Pricing (cont.)

- MB(Q) = D^{-1}(Q) = p

  "willingness to pay"

- Since p = MB(Q) = MC(Q)

$$\boxed{p = MC(Q)}$$

Set price = Social marginal cost

Public Sector Pricing (cont.)

p($/unit)

Total Benefit or
Willingness to Pay

$$\mathrm{MB}(Q) = \mathrm{D}^{-1}(Q) = \mathrm{p}$$

Q(units)

Q

$$B(Q) = \int_{0}^{Q} D^{-1}(q) \cdot dq$$

Public Sector Pricing (cont.)

p($/unit)

Net Benefit

$AC(Q)$

$MB(Q) = D^{-1}(Q) = p$

Total Cost

Q(units)

Q

Public Sector Pricing (cont.)

$p(\$/unit)$

MC(Q)

AC(Q)

p_{opt}

$MB(Q) = D^{-1}(Q) = p$

Q(units)

Q_{opt}

Marginal Cost (MC) Pricing

- Set prices at marginal costs
  - An individual will make an additional trip only when the value to them of doing so is at least as great as the cost of providing the service they are using

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- Introduction, Review of cost and demand concepts
- Public sector pricing in theory
- **<u>Issues with marginal cost pricing</u>**
- Congestion pricing in theory

Issues with MC Pricing: Equity

- It is sometimes argued that public services should not be priced at marginal cost because the poor or disadvantaged are less able to pay than others and yet may need the services more than others

- In general, pricing is an efficient means of allocating resources, but an inefficient means of achieving income redistribution or other social objectives

- In principle, it's more efficient to price public services at marginal cost and make appropriate lump sum payments to needy population groups

- Things rarely work that way in practice

Issues with MC Pricing: Externalities

- Divergence between
  - Average cost to individual (AUC)
  - Marginal cost to society (MC)

$$MC(Q) = \frac{\partial C(Q)}{\partial Q} = \frac{\partial (AC(Q) \times Q)}{\partial Q}$$

$$= AC(Q) + Q \times \frac{\partial AC(Q)}{\partial Q}$$

Example: The Congestion Externality

- Consider a link on which the travel time is characterized by the following:

$$tt = t_0 \left(1 + (Q/\text{cap})^2\right)$$

tt = an individual vehicle's travel time on a road

t_0 = free flow travel time on the road

Q = the road's traffic flow (veh/hr)

cap = the road's "capacity" (veh/hr)

(Note: this is an *average* cost function)
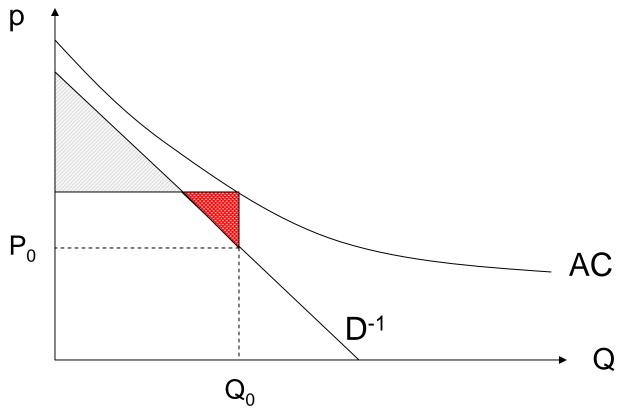
Example: The Congestion Externality (cont.)

- Suppose:

  t_0 = 20 min

  Q = 2000 vehicles $\longrightarrow$ $tt = 20 (1 + (Q/2000)^2)$

  cap = 2000 vehicles

  then tt = 40 min

  and total travel time = 80,000 min

- Now another vehicle comes along:

  vol = 2001 vehicles

  then tt = 40 min, 1.2 seconds

  and total travel time $\approx$ 80,080 min

  so change in total travel time $\approx$ 80 min (= MC)

  = 40min, 1.2 sec for vehicle (= AC)

  + 40 min for all other vehicles ($= Q . \dfrac{\partial AC(Q)}{\partial Q}$)

Issues with MC Pricing: Cost Recovery

- Q consumers each paying MC(Q) generate Q MC(Q) in revenue

- The actual cost of serving the Q consumers is
  C(Q) = Q AC(Q)

- MC(Q) > AC(Q) → the cost of the service will be covered

- MC(Q) < AC(Q) → the cost of service will not be covered
  - MC(Q) < AC(Q) implies increasing returns to scale,
    a common situation in transportation technologies,
    because of typically significant fixed costs

Cost Recovery (cont.)

- In the following, a subsidy is needed at any price:

Inverse Elasticity Pricing (Ramsey Pricing)

- Ramsey pricing addresses situations in which MC(Q) < AC(Q)
- Pricing under budget constraint
- Solve:

$$\max \int_0^Q D^{-1}(q)dq - C(Q)$$

$$s.t. \quad pQ - C(Q) \geq \pi^*$$

where π^* - minimum profit

Ramsey Pricing (cont.)

- Solution:

$$\frac{p - MC}{p} = \frac{k}{E_{Q|p}}$$

- k is chosen to generate enough revenue to cover costs
- The markup charged over the marginal cost is inversely proportional to the demand elasticity w.r.t. price

Ramsey Pricing (cont.)

- Limitations:
  - Price elasticities tend to increase (in absolute values) with price
  - Over time, consumers paying higher prices reduce their demand, revenue decreases, and the pricing scheme fails

Issues with MC Pricing: Distortions Elsewhere in the Economy

- If the inputs, or complements or substitutes of a product are not priced at MC, then the product should not be priced at MC either!

- "First-best" pricing:

    Everything is priced at marginal cost

- "Second-best" pricing:

    When substitutes or complements are mispriced

Second-Best Pricing

$$p_i - MC_i = -\sum_{j \neq i} \frac{E_{Q_j|p_i}}{E_{Q_i|p_i}} \frac{Q_j}{Q_i} \left(p_j - MC_j\right)$$

with   i = the good or service to be priced

          j = complement/substitute good or service

Suppose j is priced *under* its marginal cost $p_j < MC_j$

if j is a substitute for i, $E_{Q_j|p_i} > 0$, i should be priced *under* MC

if j is a complement to i, $E_{Q_j|p_i} < 0$, i should be priced *over* MC

Issues with MC Pricing: Joint Costs

- Multiple users share the same transportation infrastructure (such as trucks and cars, peak and off peak travel)
- Economy of scope

  Joint production of two products is cheaper than separate production

$$C(Q_1, Q_2) < C(Q_1, 0) + C(0, Q_2)$$

- Example: peak and off peak demand.
  - Capacity designed for peak period traffic automatically provides off peak capacity
  - Capacity costs are joint costs

Joint Costs Allocation

- Usually, joint costs are assigned to the dominant demand (e.g. peak demand)
- If prices depend on allocation of joint costs, then the quantities of dominant demand may depend on allocation of costs
  - Peak toll may cause shift in peak time
- Circular logic - need to find an equilibrium solution

Allocating Costs between Cars and Trucks

- Highway serves different users: cars, trucks
- Joint costs, economies of scope
- Highway provides two products:
  - Capacity
  - Surface durability

Allocating Costs (cont.)

- Capacity
  - PCE - Passenger Car Equivalent
  - Truck = 1.2 - 4 PCE depending on geometry
- Durability
  - Damage to pavement by an axle pass
  - ESAL - Equivalent Standard Axle Load
  - Truck axle pass = ~10^4 car axle passes
  - Economy of scale in paving

Allocating Costs (cont.)

- FHWA: "cost occasioned" allocation
  - Base highway only for cars
  - Improvements for trucks are allocated to them
- Which should be the base vehicle?
- Ignores capacity issues

Allocating Costs (cont.)

- Small, Winston and Evans
  - Two price components:
    - Pavement damage
    - Congestion
  - Found under-paving of highways
  - Wrong pricing for trucks
    - Based on total weight instead of on weight per axle
    - Would shift to multi-axle trucks

Summary of Issues with MC Pricing for Transportation Services

- Provision of transportation services involves some equity considerations. MC pricing may conflict with such issues

- Many externalities associated with transportation services
  - Example: Congestion charging accounts for costs imposed on others

- Due to economies of scale and large fixed costs associated with infrastructure, marginal costs in many transportation services are smaller than average costs. MC pricing does not generate enough revenues to cover the costs
  - Ramsey pricing addresses this issue

Summary of Issues with MC Pricing for Transportation Services (cont.)

- MC pricing may not be optimal if substitutes and complements are not priced at marginal cost
  - Second-best pricing strategies address this issue
- Some transportation services are shared by different types of users (e.g. cars and trucks on highways). How should costs be allocated among these users?

Examples

- Roy (2001) compared the price for the user with the marginal cost for the operator for various public transit agencies in Europe

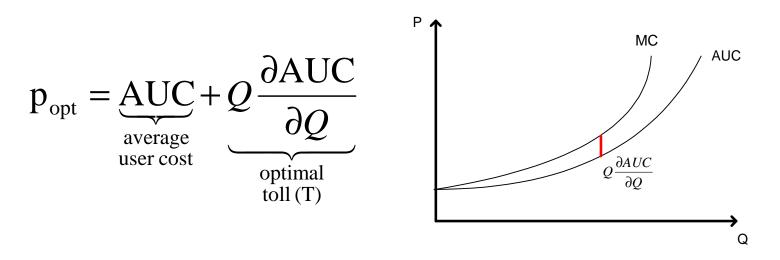|	Price for user	MC excl. VAT for operator
London Underground, peak	0.153	0.053
London Underground, off-peak	0.124	0.030
London buses, peak	0.127	0.150
London buses, off-peak	0.113	0.140

All figures are in Euros per passenger km

Source: Roy, R. (Ed.) (2001), Revenues from Efficient Pricing: Evidence from the Member States, UIC/CER/European Commision DG-TREN study: final study report, UIC, Paris.

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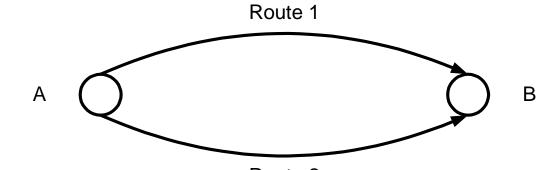- **Congestion Pricing in theory**

Congestion Pricing in Theory

- Marginal cost pricing

$$p_{opt} = \underbrace{AUC}_{\substack{\text{average} \\ \text{user cost}}} + \underbrace{Q\frac{\partial AUC}{\partial Q}}_{\substack{\text{optimal} \\ \text{toll (T)}}}$$

- Optimal price includes additional costs to other users from congestion externality

- These can be imposed as a road user charge T

Congestion Pricing: Example

- Two alternative routes connect A to B

Route 1

A   B

Route 2

- Route 1 is shorter but has limited capacity

- Route 2 is longer but has larger capacity

Congestion Pricing: Example (cont.)

- Peak hour demand is inelastic, 6000 veh/hr
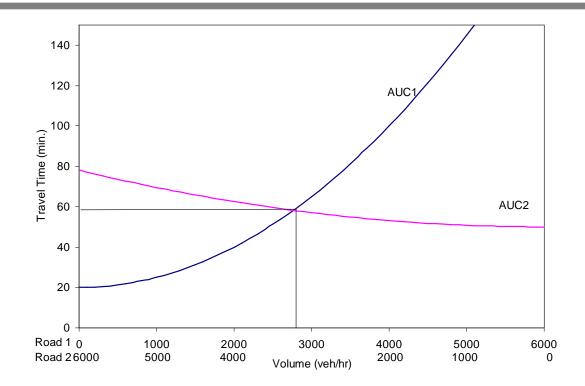- The travel time on each route is a function of the volume on that route:

$$tt_1(Q_1) = 20\left[1 + \left(\frac{Q_1}{2000}\right)^2\right] \qquad tt_2(Q_2) = 50\left[1 + \left(\frac{Q_2}{8000}\right)^2\right]$$

- Assume that AUC includes only travel time and toll

With No Tolls

- What will the volumes and travel times be?

- AUC equilibrium analysis:
  - $AUC_1 = AUC_2$
  - The volumes on each route will be such that travel times on both routes will be equal
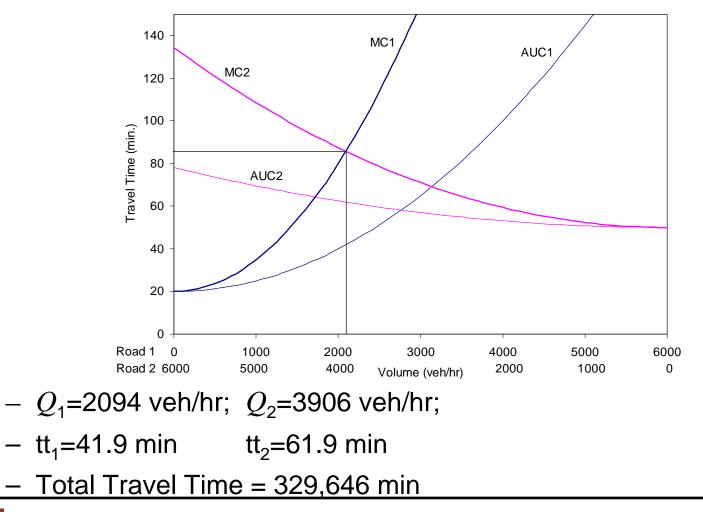
AUC Analysis Solution

- Q_1=2764 veh/hr; Q_2=3236 veh/hr
- tt_1 = tt_2 = 58.2 min
- Total Travel Time = 349,134 min

Optimal Solution

- Marginal Cost (MC) equilibrium analysis:
  - $MC_1 = MC_2$
  - In an optimal solution the volumes on each route will be such that marginal travel times on both routes will be equal
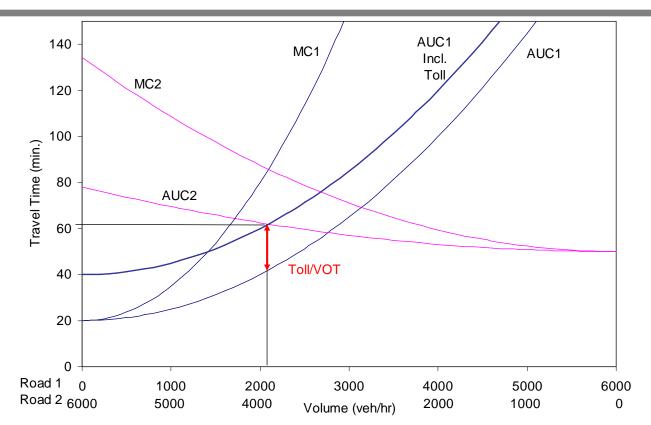
Optimal Solution (cont.)

- Q_1=2094 veh/hr; Q_2=3906 veh/hr;
- tt_1=41.9 min tt_2=61.9 min
- Total Travel Time = 329,646 min

Optimal Toll

- The potential savings from optimal usage of the routes:

  ΔTotal Travel Time = 349,134-329,646 = 19,488 veh-min/hr

- How can we force the optimal solution on users?

- Introducing a toll that will divert the required amount of traffic from route 1 to route 2

Optimal Toll Solution

- Optimal toll is equivalent to 20 min of travel time
- Assuming VOT=$10/hr, Toll=20/60*10=$3.3

Review

We covered:

- Introduction, Review of cost and demand concepts
- Public sector pricing in theory
- Issues with marginal cost pricing
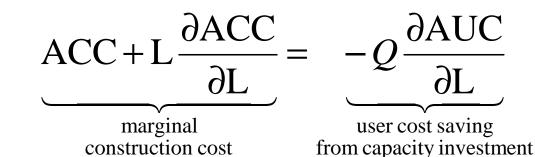- Congestion Pricing in theory

Next Lecture:

- Congestion pricing in practice
- Public Sector pricing in practice
- Private sector pricing in theory and in practice

Appendix

Using toll revenues for capacity investments

Optimal Investment in Capacity

- What is optimal level of investment in capacity?

- Choose L to minimize user + investment costs

$$\underbrace{ACC + L\frac{\partial ACC}{\partial L}}_{\substack{\text{marginal} \\ \text{construction cost}}} = \underbrace{-Q\frac{\partial AUC}{\partial L}}_{\substack{\text{user cost saving} \\ \text{from capacity investment}}}$$

Toll Revenues for Capacity Investments

- Do toll revenues cover the infrastructure investment?

  - from the functional form of the average cost:

$$\mathrm{AUC} = \mathrm{AUC}(\frac{Q}{L}) \quad \Rightarrow \quad \frac{\partial \mathrm{AUC}}{\partial L} = -\frac{Q}{L} \cdot \frac{\partial \mathrm{AUC}}{\partial Q}$$

  - and the optimal infrastructure investment:

$$\mathrm{ACC} + L\frac{\partial \mathrm{ACC}}{\partial L} = -Q\frac{\partial \mathrm{AUC}}{\partial L}$$

Toll Revenues for Capacity Investments (cont.)

- Substitute in the expression for the optimal toll to obtain:

$$T = Q\frac{\partial AUC}{\partial Q} = -L\frac{\partial AUC}{\partial L} = \frac{L}{Q}\left[ACC + L\frac{\partial ACC}{\partial L}\right]$$

- In the absence of scale effects in capacity provision,

$$T = L\frac{ACC}{Q}$$

- In the presence of economies of scale, revenues from optimal toll will not cover capacity cost

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