TEAMFL
TRANSPORTATION & EXPRESSWAY AUTHORITY MEMBERSHIP OF FLORIDA

ENGINEERING &
TOLL OPERATIONS

Fundamental Concepts in Congestion Pricing

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Outline

- Congestion Pricing
- Successful Implementations
- Fundamental Concepts
- Examples of Pricing Schemes

Congestion Pricing

- The basic concept has been around for over 80 years.
  - The recent advent of electronic tolling makes congestion pricing an efficient method for alleviating congestion.
- Congestion Pricing is different from the traditional tolling that pays for the transportation infrastructure.
- Use tolls to induce users to use routes that lead to a flow distribution with the least delay.

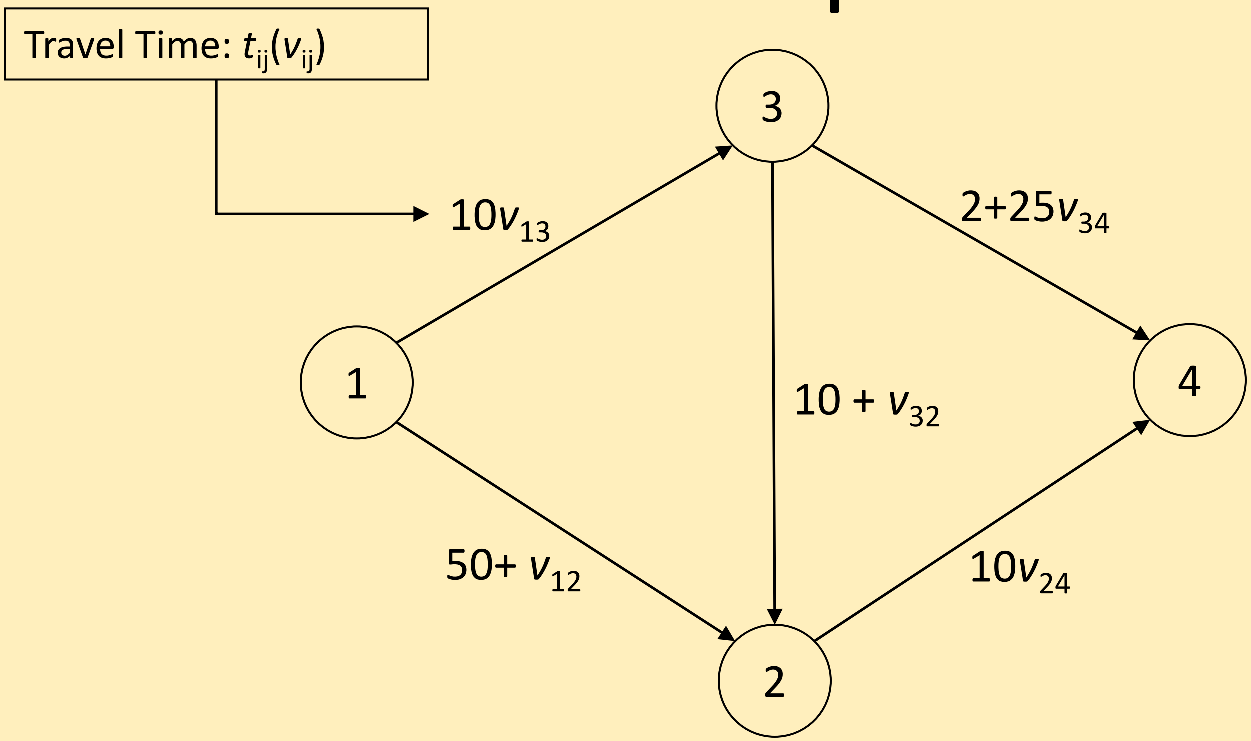
Successful Implementations

- Singapore Electronic Road Pricing
- Toll rings in Norway (Bergen, Oslo, Trondheim)
- London Congestion Charging
- Stockholm Congesting Charging Scheme
- I-15, San Diego
- SR-91, Orange County
- 95 Express, Miami

Basic Models

- System Optimal (SO) Flow Distributions
  - Minimum total travel time or "system delay"
  - Some users have to use longer routes
- User Equilibrium (UE) Flow Distributions
  - No user has any incentive to switch travel routes
  - Longer system delay

Example

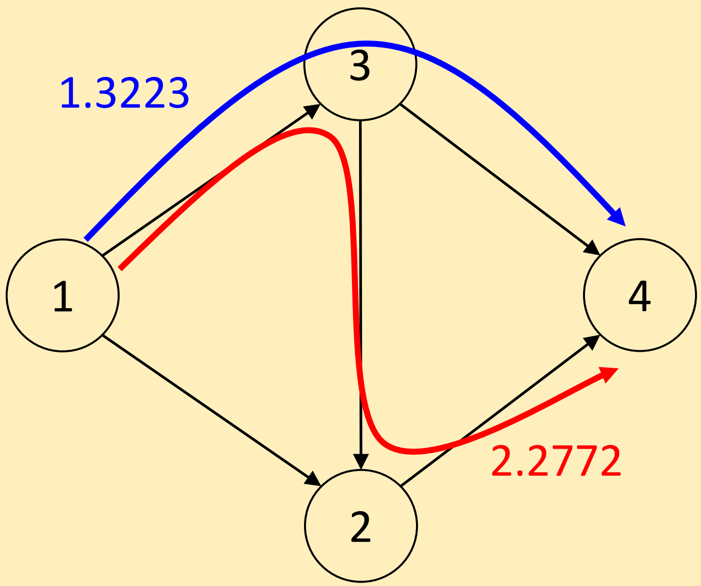


- $t_{ij}(v_{ij})$ = travel time for arc (i, j), where v_{ij} is the flow (rate) on the arc
- There are 3.6K travelers (per hour) for OD pair (1, 4)

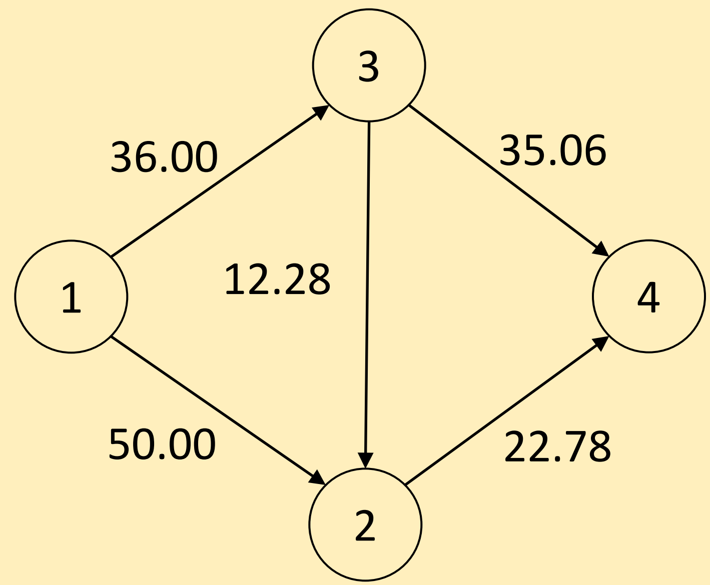
Example (cont.)

User equilibrium solution with **total delay** = 255.82 (in 1000 min.).

- Send 1.3223K along path 1 – 3 – 4 with length/cost 71.06.
- Send 2.2772K along path 1 – 3 – 2 – 4 with length/cost 71.06.
- Send 0 along path 1 – 2 – 4 with length 72.78.



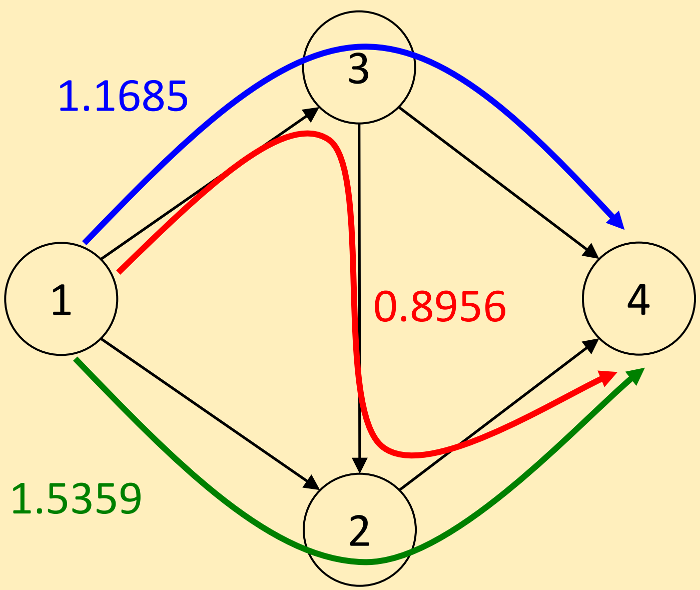
User Equilibrium Flows



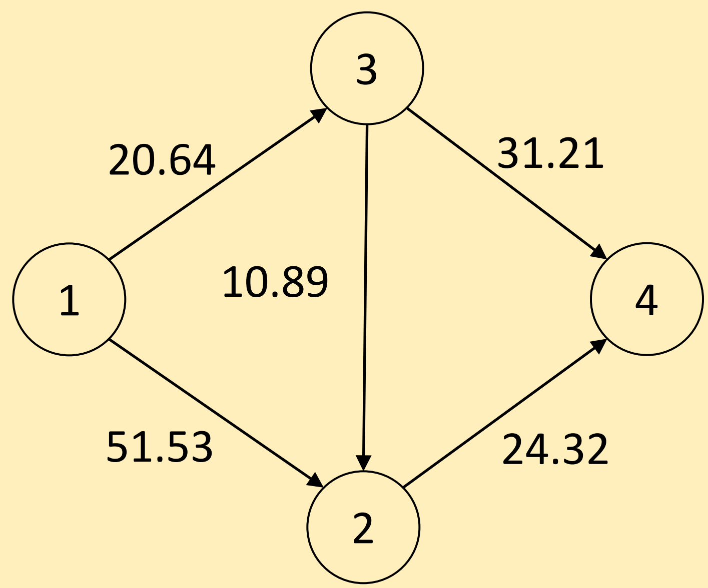
Resulting Travel Times

Example (cont.)

- System optimal solution with **total delay** = 227.11 < 255.82.
  - Send 1.1685K along 1 – 3 – 4 with length/cost 51.85.
  - Send 0.8956K along 1 – 3 – 2 – 4 with length/cost 55.85
  - Send 1.5359K along 1 – 2 – 4 with length/cost 75.85



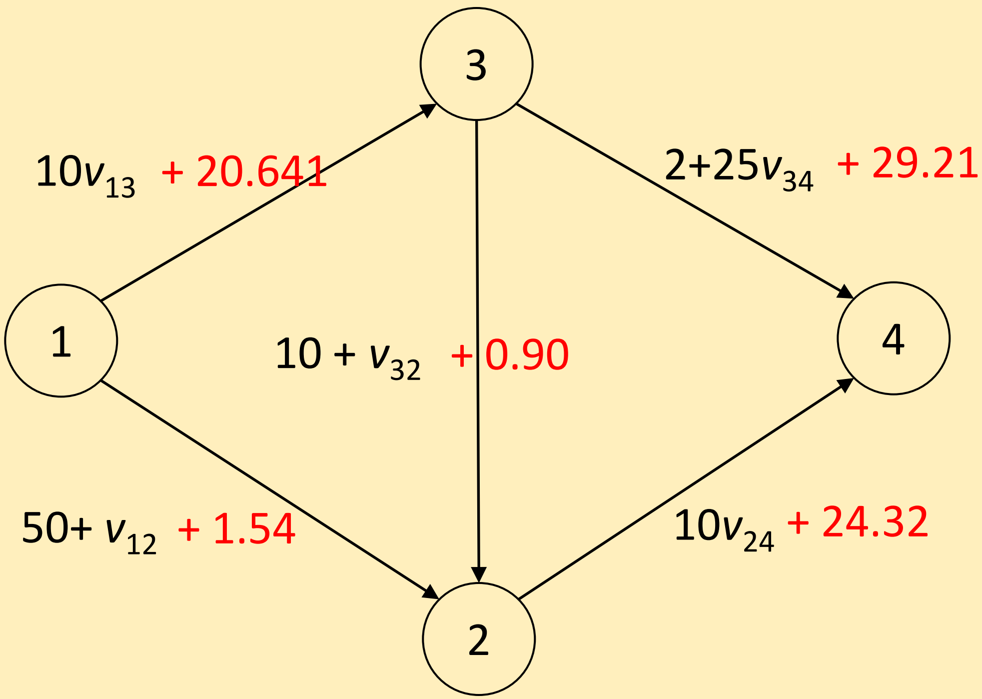
System Optimal Flows



Resulting Travel Times

Marginal Cost Pricing

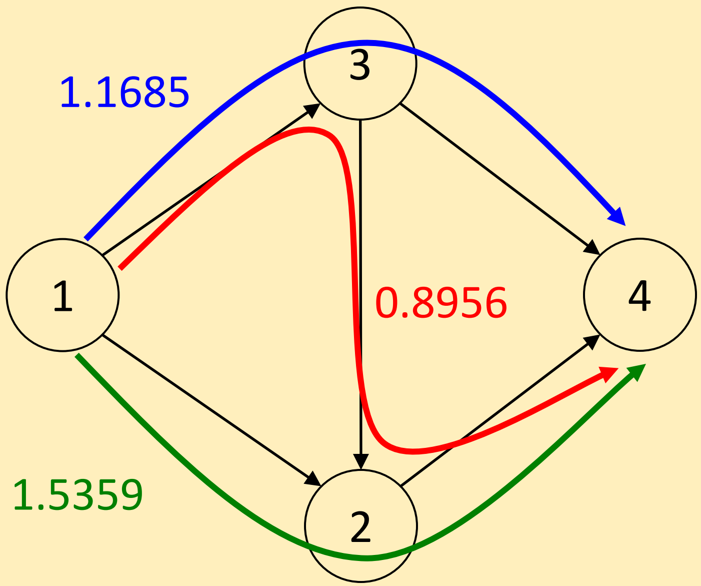
- Set the toll on arc (*i*, *j*) equal to its marginal cost at the system solution, *v**



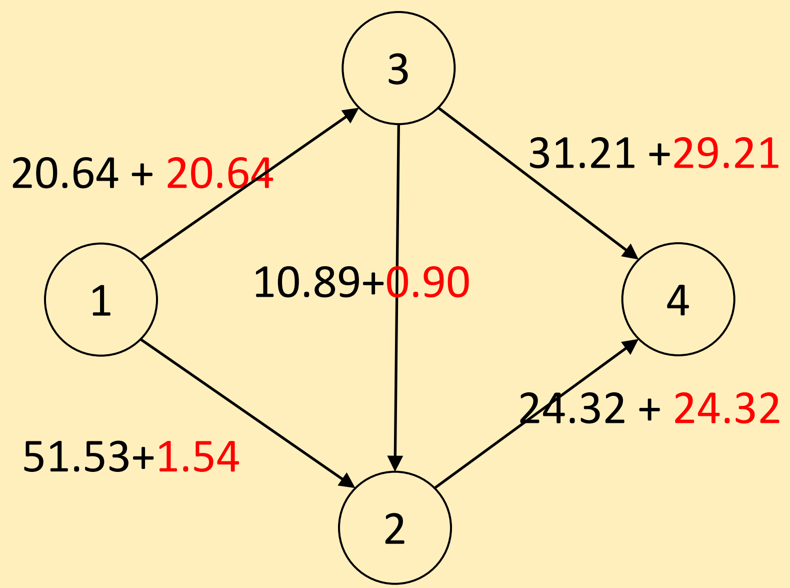
$$\tau_{ij} = t'_{ij}(v^*_{ij})v^*_{ij}$$

Marginal Cost Pricing: Example

- System solution is in a tolled user equilibrium
  - Send 1.1685 units along 1 – 3 – 4 with cost 51.85 + 49.85 = 101.70
  - Send 0.8956 units along 1 – 3 – 2 – 4 with cost 55.85 + 45.85 = 101.70
  - Send 1.5359 units along 1 – 2 – 4 with cost 75.85 + 25.85 = 101.70



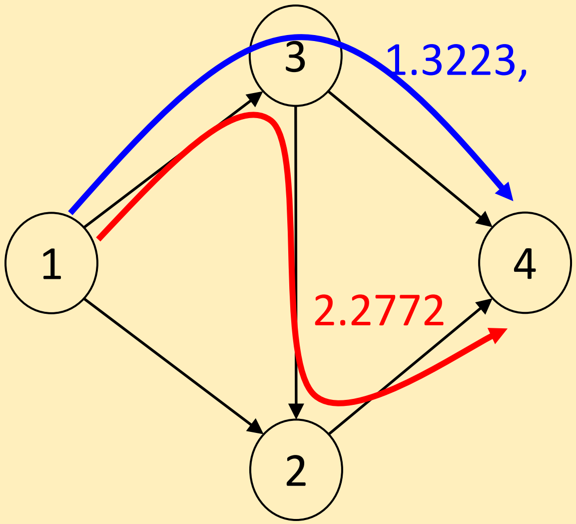
Tolled User Equilibrium Flows



Resulting Travel Times

Marginal Cost Pricing: Comparison

Without tolls



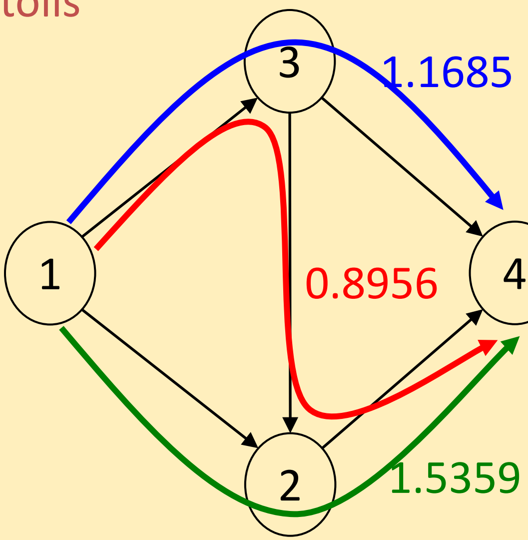
Cost of 1 – 3 – 4 = 71.06.

Cost of 1 – 3 – 2 – 4 = 71.06.

Total Delay = 255.82

Toll Revenue = 0.0

With MC tolls



Cost of 1 – 3 – 4 = 51.85 + 49.85 = 101.70

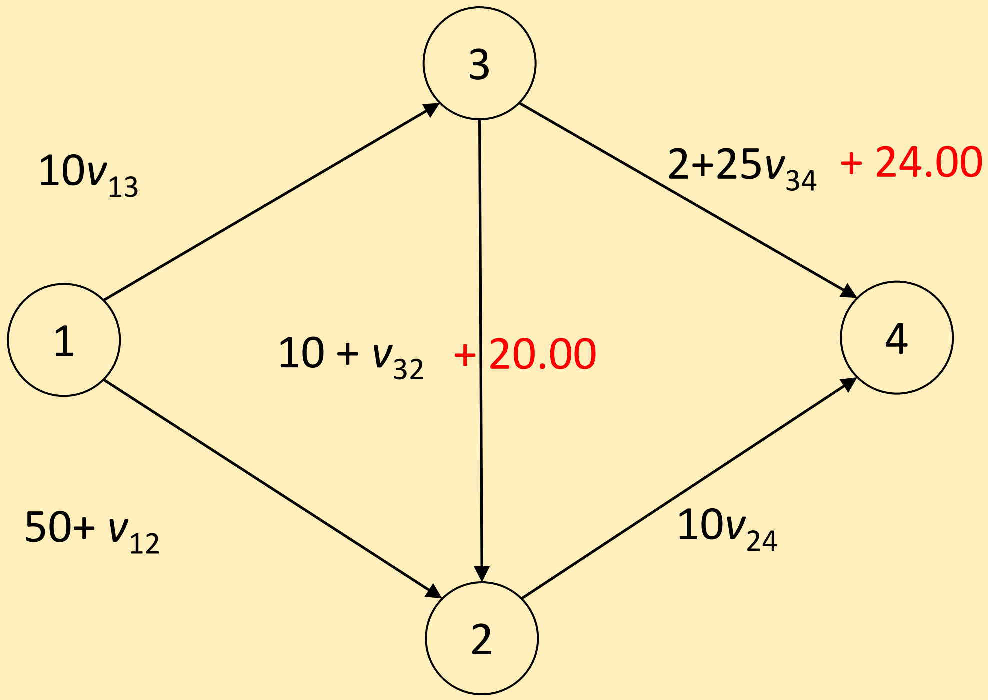
Cost of 1 – 3 – 2 – 4 = 55.85 + 45.85 = 101.70

Cost of 1 – 2 – 4 = 75.85 + 25.85 = 101.70

Total Delay = 227.11

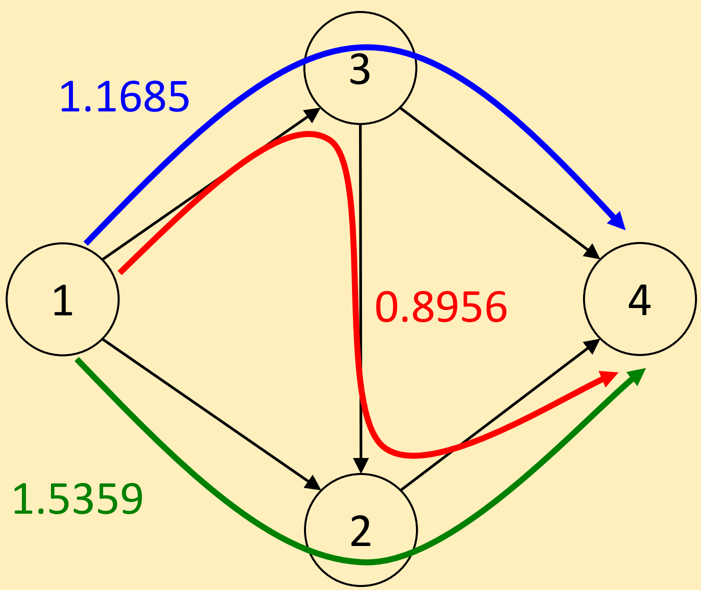
Toll Revenue = 139.02

Alternative Pricing Scheme

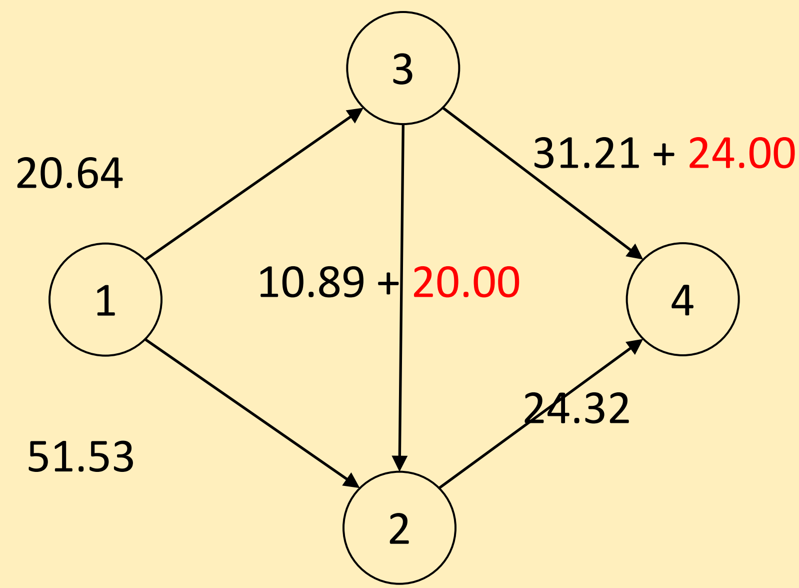


Alternative pricing scheme

- System solution is in a tolled user equilibrium
  - Send 1.1685 units along 1 – 3 – 4 with cost 51.85 + 24.00 = 75.85
  - Send 0.8956 units along 1 – 3 – 2 – 4 with cost 55.85 + 20.00 = 75.85
  - Send 1.5359 units along 1 – 2 – 4 with cost 75.85



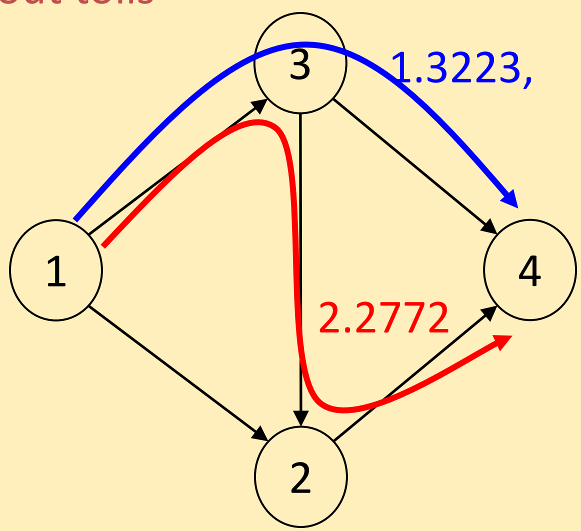
Tolled User Equilibrium Flows



Resulting Travel Times

Alternative pricing scheme: Comparison

Without tolls



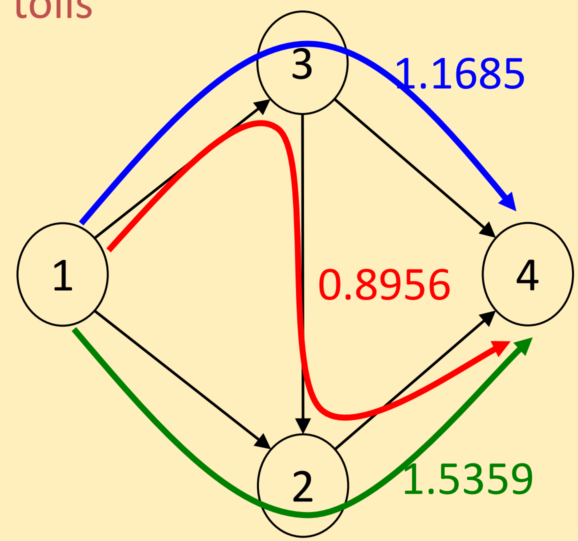
Cost of 1 – 3 – 4 = 71.06.

Cost of 1 – 3 – 2 – 4 = 71.06.

Total Delay = 255.82

Toll Revenue = 0.0

With MC tolls



Cost of 1 – 3 – 4 = 51.85 + 24.00 = 75.85

Cost of 1 – 3 – 2 – 4 = 55.85 + 20.85 = 75.85

Cost of 1 – 2 – 4 = 75.85

Total Delay = 227.11

Toll Revenue = 46.72

Other pricing schemes

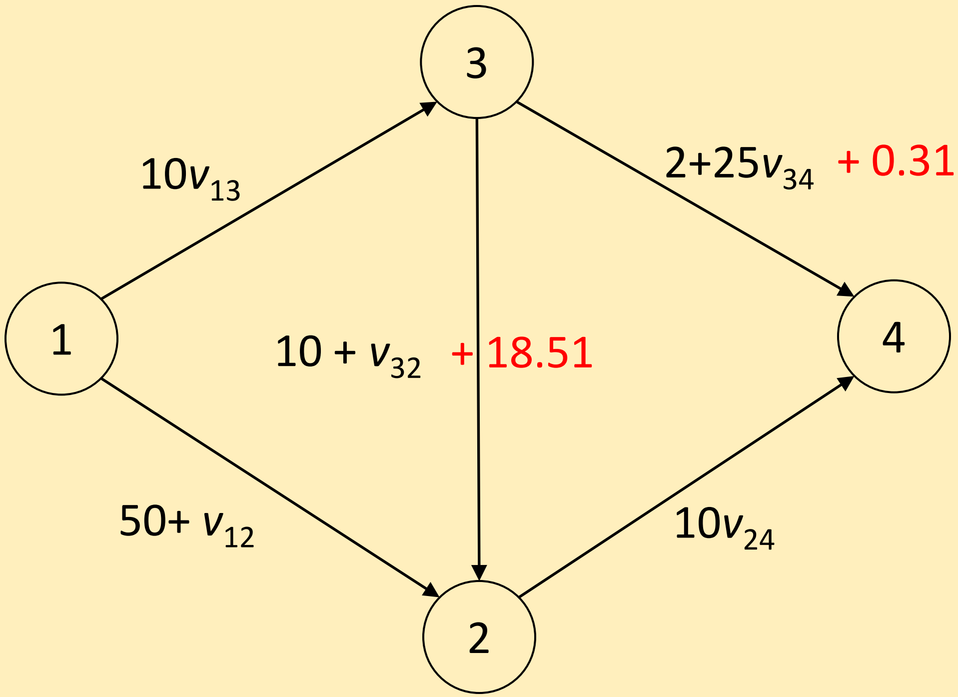
- Minimize the number of toll facilities
- Minimize toll revenue
- Allow negative tolls (i.e., subsidies)
- Area-based
- Cordon-based
- Managed Lanes

Public Perception

- Tolling is unappealing to the public
  - Residents in Hong Kong, Cambridge, and Edinburgh voted against it.
  - "Ten or more congestion pricing proposals were largely abandon in the United Kingdom." May (2005)
  - Similar rejections: New York City and The Netherland (VMT)
  - Despite the success of the Stockholm Congestion Charging Trial in 2006, the results from the referendum are unclear
    - Stockholm: 53% For and 47% Against
    - 14 surrounding municipalities: 39.8% For and 60.2% Against.
  - Hau (2005) states that the marginal cost pricing scheme is "most likely doomed to be political failures."

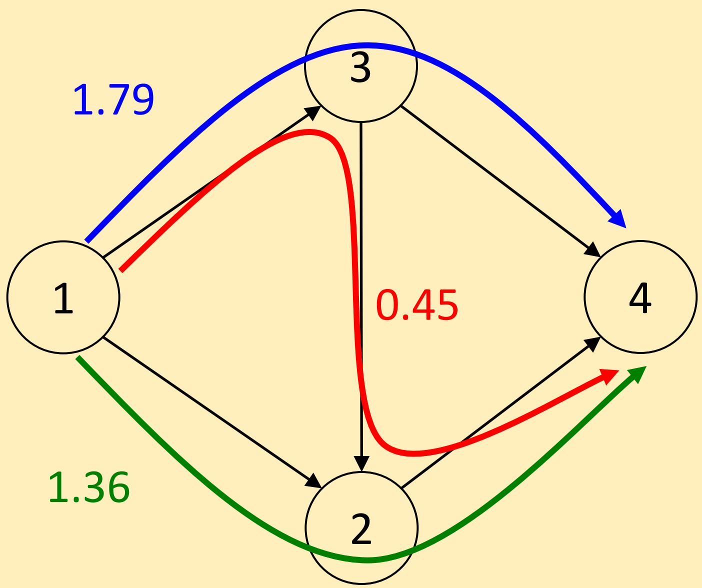
Pareto-improving Tolls

- Consider the following set of tolls

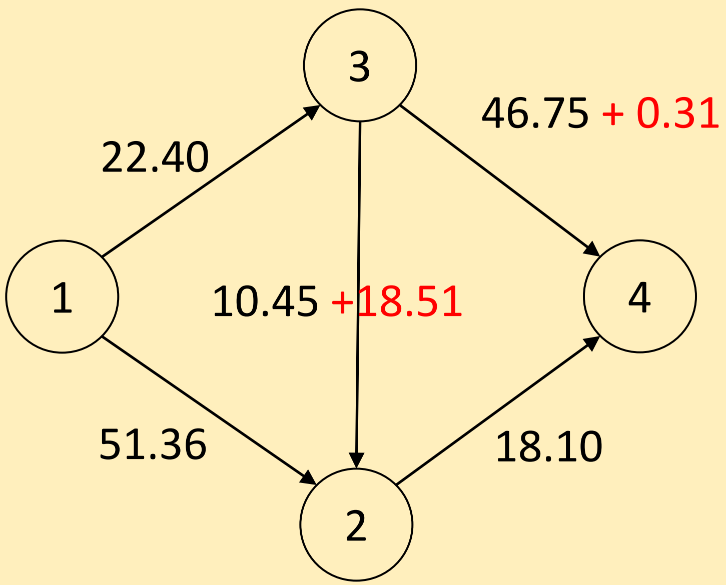


Pareto-Improving Tolls: Example

- Resulting Flow Distribution has a total delay of 241.17
  - Send 1.79 units along 1 – 3 – 4 with cost 69.15+0.31 = 69.46
  - Send 0.45 units along 1 – 3 – 2 – 4 with cost 50.95+18.51 = 69.46.
  - Send 1.36 units along 1 – 2 – 4 with length 69.46



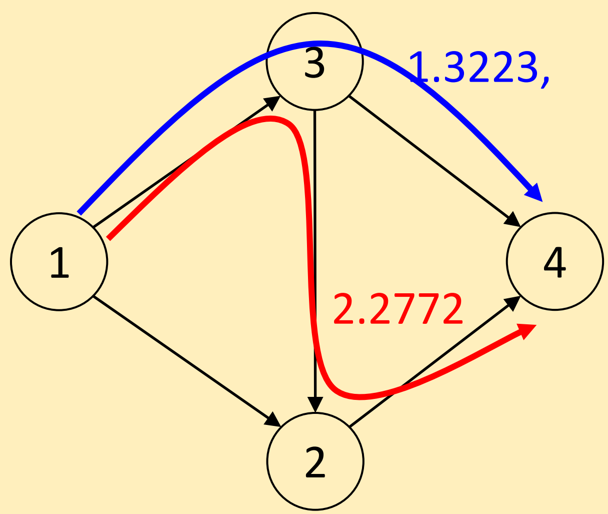
Dominating Flow Dist.



Resulting Travel Times

Pareto-Improving Tolls: Comparison

Without tolls



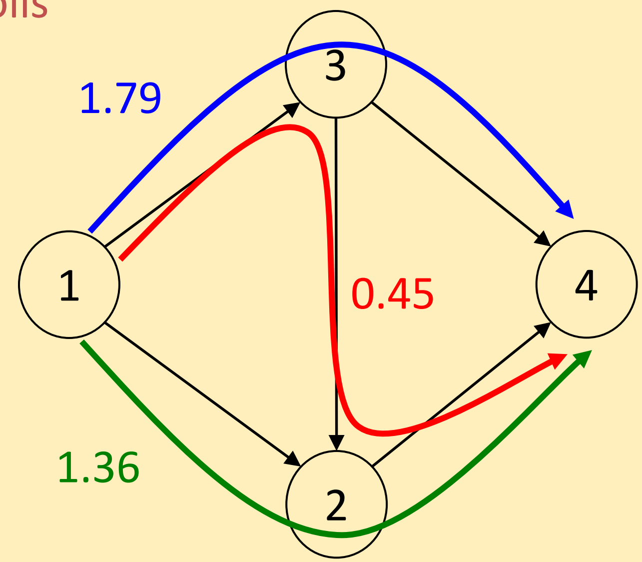
Cost of 1 – 3 – 4 = 71.06.

Cost of 1 – 3 – 2 – 4 = 71.06.

Total Delay = 255.82

Toll Revenue = 0.0

With PI tolls



Cost of 1 – 3 – 4 = 69.15+0.31 = 69.46

Cost of 1 – 3 – 2 – 4 = 50.95+18.51 = 69.46

Cost of 1 – 2 – 4 = 69.46

Total Delay = 241.17 > 227.11

Toll Revenue = 8.88 < 139.02

Pareto-Improving Tolls

- We developed methodologies for determining PI tolls on transportation networks.
- Our experiments with transportation networks from the literature indicate
  - PI tolls may not lead to significant reduction in system delay when applied to a single mode.
  - PI tolls can significantly reduce system delay when
    - There are multiple modes of transportation.
    - Users are allowed to slightly worse-off, e.g., $\leq$ 10%

Relevant Publications

- Lawphongpanich, S., Hearn, D.W., 'An MPEC approach to second-best toll pricing,' Mathematical Programming, Series B, 101, 33 – 55, 2004
- Bai, L., Hearn, D.W., Lawphongpanich, S., 'Decomposition techniques for the minimum toll revenue problem,' Networks, 44(2), 142 – 150, 2004
- Bai, L., Hearn, D.W., and Lawphongpanich, S., 'Relaxed Toll Sets for Large-Scale Toll Pricing Problem,' Mathematical and Computational Models for Congestion Pricing, Editors: S. Lawphongpanich, D.W. Hearn, and M. J Smith, 2006, 23 – 44
- Lawphongpanich, S., 'Dynamic Slope Scaling Procedure and Lagrangian Relaxation with Subproblem Approximation," Journal of Global Optimization, 35, 121 – 130, 2006
- Mathematical and Computational Models for Congestion Pricing, Editors: S. Lawphongpanich, D.W. Hearn, and M. J Smith, Springer, New York, 2006
- Hamdouch, Y., Florian, M., Hearn, D.W., and Lawphongpanich, S. 'Congestion Pricing for Multi-Modal Transportation Systems,' Transportation Research, Part B., 41, 2007, 275 - 291
- Yin, Y, Lawphongpanich, S., "Alternative marginal-cost pricing for road networks," *Netnomics*, 77 – 83, 2009

Relevant Publications

- Lou, Y., Yin, Y., Lawphongpanich, S., "A robust approach to discrete network designs with demand uncertainty," Transportation Research Record, Journal of the Transportation Research Board, No. 2090, 86 – 94, 2009
- Song, Z., Yin, Y., Lawphongpanich, S., "Nonnegative Pareto-Improving Tolls with Multiclass Network Equilibria," *Transportation Research Record*, Transportation Research Record, Journal of the Transportation Research Board, No. 2091, 70 – 78, 2009
- Lou, Y. Yin, Y., Lawphongpanich, S., "Robust congestion pricing under boundedly rational user equilibrium," *Transportation Research Part B*, Vol. 44, 15 – 28, 2010 (January)
- Lawphongpanich, S., Yin, Y., "Solving the Pareto-Improving Toll Problem via Manifold Suboptimization," *Transportation Research Part C*, Volume 18, 234 – 246, 2010 (April).
- Hamdouch, Y., Lawphongpanich, S., "Congestion Pricing for Scheduled-Based Transit Networks," *Transportation Science*, in press.

Relevant Publications

- Bai, L., Hearn, D.W., Lawphongpanich, S., "A heuristic method for the minimum tollbooth problem, *Journal of Global Optimization*, available on-line at http://www.springerlink.com/content/p6783vm412j460m1/
- Lawphongpanich, S., Yin, Y., "Area-Based Pricing," *Transportation Research Part A*, revised and resubmitted
- Wu, D., Yin, Y., Lawphongpanich, S., "Pareto-Improving Congestion Pricing on Multimodal Transportation Networks," *European Journal of Operational Research*, submitted.
- Wu, D., Yin, Y., Lawphongpanich, S., "Pareto-Improving Strategies for Multimodal Transportation Networks with Trip Chaining," *Transportation Research Part B*, submitted.