ISSN: 3065-9779

Review Article

Annals of Civil Engineering and Management

Urban Congestion as a Volatility Pricing Problem: A Call–Put Options Framework with Black–Scholes Travel Time Valuation

Paul T E Cusack*

BScE (Civil), Canada

*Corresponding Author
Paul T E Cusack, BScE (Civil), Canada.

Submitted: 2026, May 13; **Accepted:** 2026, Jun 08; **Published:** 2026, Jun 16

Citation: Cusack, P. T. E. (2026). Urban Congestion as a Volatility Pricing Problem: A Call–Put Options Framework with Black–Scholes Travel Time Valuation. *Ann Civ Eng Manag, 3*(2), 01-03.

Abstract

This paper develops a unified financial-economics framework for urban congestion in which travel time is treated as a stochastic asset with density-dependent volatility. Automobile travel is modeled as a call option on low-congestion travel time, while transit and avoidance behavior act as put-like hedges against congestion risk. We embed a Black–Scholes-type valuation framework to price travel-time uncertainty and derive a congestion pricing rule equivalent to an option premium. Marginal external costs are shown to scale convexly with congestion-induced volatility, providing a structural basis for congestion pricing in urban systems.

1. Introduction

Urban congestion is traditionally modeled using marginal cost pricing:

$MB = MC + MEC$

However, this formulation omits a key empirical feature: travel time is stochastic and volatility increases with density. This paper reframes congestion as a financial options market over uncertain travel-time outcomes, where congestion externalities arise from unpriced volatility risk.

2. Travel Time as a Stochastic Process

$$T = T_0 + \varepsilon$$

$$\varepsilon \sim N(0, \sigma^2(q))$$

$$\frac{d\sigma^2}{dq} > 0$$

Thus, congestion increases both:

- Mean delay (first moment)
- Uncertainty (second moment)

3. Utility Function

$U = V - c - \alpha T$

Substituting:

$U = V - c - \alpha T_0 - \alpha\varepsilon$

Expected utility:

$$E[U] = V - c - \alpha T_0 - \frac{1}{2}\alpha^2\sigma^2(q)$$

4. Call Option Interpretation (Automobile Travel)

Driving is modeled as a call option:

$C = max\ (V - c - \alpha T,\ 0)$

Expected value:

$$E[U_{car}] = V - c - \alpha T_0 - \frac{1}{2}\alpha^2\sigma^2(q)$$

Interpretation:

- Upside in low congestion
- Downside in congestion spikes
- Convex exposure to volatility

5. Put Option Interpretation (Transit / Avoidance)

Transit acts as downside protection:

$$U_{transit} = V - c_t - \alpha(1.69T_0)$$

Interpretation:

- Higher mean travel time
- Low variance exposure
- Behaves like a put-on congestion risk

6. Marginal External Cost (Volatility Externality)

$$MEC = \frac{1}{2}\alpha^2\sigma^2(q)$$

Interpretation:

- Each trip increases system volatility
- This volatility is not priced
- MEC is equivalent to unpriced short volatility exposure

7. Black–Scholes Framework for Travel Time Valuation

7.1. Define the "Travel Asset"

Let:

- S = realized travel efficiency (inverse travel time)
- K = free-flow benchmark efficiency
- σ = congestion volatility
- t = travel horizon
- r = social discount rate

7.2. Black–Scholes Call Option (Driving Value)

$$C = SN(d_1) - Ke^{-rt}N(d_2)$$

where:

$$d_1 = \frac{\ln(S/K) + (r + \frac{1}{2}\sigma^2)t}{\sigma\sqrt{t}}$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

7.3. Interpretation in Transportation Terms

Variable	Meaning
S	realized travel speed
K	free-flow speed
σ	congestion uncertainty
C	value of driving option

Table1

7.4. Key Insight

From Black–Scholes:

$$\frac{\partial C}{\partial \sigma} > 0$$

σ_i^2

Thus:

congestion volatility increases the value of flexibility (driving option) but also increases system inefficiency.

8. Congestion Pricing from Black–Scholes Sensitivity

The marginal congestion toll is derived from volatility sensitivity:

$$\tau(q) \approx \frac{\partial C}{\partial \sigma} \cdot \frac{d\sigma}{dq}$$

Which reduces to:

$$\tau(q) = \alpha\sigma(q)\frac{d\sigma(q)}{dq}$$

or equivalently:

$$\tau(q) = \frac{1}{2}\alpha^2\sigma^2(q)$$

9. CMA Empirical Structure

For each CMA *i*:

- D_i: density
- T_i^{car} : car travel time
- $T_i^{transit}$: transit travel time
- σ_i^2: congestion volatility

- **Volatility Equation**

$$\sigma_i = 0.05 + 0.00015D_i$$

$$\sigma_i^2 = a + bD_i + cD_i^2$$

- **External Cost Equation**

$$MEC_i = \frac{1}{2}\alpha^2\sigma_i^2$$

- **Transit Gap**

$$T^{transit} = 1.69T^{car}$$

$$Gap = 0.69T^{car}$$

10. Structural Results

- **Proposition 1**

Congestion volatility increases convexly with density:

$$\frac{\partial^2 \sigma^2}{\partial D^2} > 0$$

- **Proposition 2**

External costs scale linearly with volatility:

$$MEC \propto \sigma^2$$

- **Proposition 3**

Transit disadvantage increases with congestion risk.

11. Conclusion

This paper shows that urban congestion can be modeled as a Black–Scholes-style options market over stochastic travel time. Automobile travel behaves as a call option on free-flow mobility, while congestion externalities correspond to unpriced volatility exposure. Optimal congestion pricing is equivalent to an option premium that internalizes travel-time risk.

11.1. Final Core Result

Urban congestion is a Black–Scholes-style mispriced volatility market in which travel behaves as a call option on stochastic mobility, and marginal external costs arise from unpriced sensitivity to travel-time variance.

References

1. Arnott, R., De Palma, A., & Lindsey, R. (1993). A structural model of peak-period congestion: A traffic bottleneck with elastic demand. *The American Economic Review, 161*-179.
2. Arnott, R., De Palma, A., & Lindsey, R. (1994). The welfare effects of congestion tolls with heterogeneous commuters. Journal of Transport Economics and Policy, 139-161.
3. Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *Journal of political economy, 81(3)*, 637-654.
4. Börjesson, M., Eliasson, J., Hugosson, M. B., & Brundell-Freij, K. (2012). The Stockholm congestion charges—5 years on. Effects, acceptability and lessons learnt. *Transport Policy, 20*, 1-12.
5. Button, K. (2010). Transport economics. Edward Elgar Publishing.
6. Downs, A. (1962). The law of peak-hour expressway congestion. *Traffic Quarterly, 16*(3).
7. Eliasson, J. (2009). A cost–benefit analysis of the Stockholm congestion charging system. *Transportation Research Part A: Policy and Practice*, 43(4), 468-480.
8. Engle, R. F. (1982). Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflation. Econometrica: *Journal of the econometric society, 987*-1007.
9. Fosgerau, M., Hjorth, K., & Lyk-Jensen, S. V. (2010). Between-mode-differences in the value of travel time: Self-selection or strategic behaviour?. T*ransportation research part D: transport and environment, 15*(7), 370-381.
10. Fosgerau, M., & Karlström, A. (2010). The value of reliability. *Transportation Research Part B: Methodological, 44*(1), 38-49.
11. Goodwin, P. B. (1996). Empirical evidence on induced traffic: A review and synthesis. *Transportation, 23*(1), 35-54.
12. Greenshields, B. D., Bibbins, J. R., Channing, W. S., & Miller, H. H. (1935, December). A study of traffic capacity. *In Highway research board proceedings* (Vol. 14, No. 1, pp. 448-477).
13. Knight, F. H. (1924). Some fallacies in the interpretation of social cost. *The Quarterly Journal of Economics, 38*(4), 582-606 .
14. Litman, T. (2023). *Transportation Cost and Benefit Analysis. Victoria Transport Policy Institute*.
15. MERTON, R. (1973). Theory of Rational Option Pricing. Bell *Journal of Economics and Management Science, 4, 141*-183.
16. Mohring, H. (1972). Optimization and scale economies in urban bus transportation. *The American Economic Review, 62*(4), 591-604.
17. Pigou, A. C. (1920). *The Economics of Welfare*. Macmillan.
18. Small, K. A., & Verhoef, E. T. (2007). *The Economics of Urban Transportation. Routledge*.
19. Small, K. A., Winston, C., & Yan, J. (2005). Uncovering the distribution of motorists' preferences for travel time and reliability. *Econometrica, 73*(4), 1367-1382.
20. Train, K. E. (2009). Discrete Choice Methods with Simulation (2nd ed.). *Cambridge University Press*.
21. Vickrey, W. S. (1963). Pricing in urban and suburban transport. *The American Economic Review, 53*(2), 452-465.
22. Vickrey, W. S. (1969). Congestion theory and transport investment. *The American economic review, 59*(2), 251-260.
23. Wardrop, J. G., & Whitehead, J. I. (1952). Correspondence. some theoretical aspects of road traffic research. *Proceedings of the institution of civil engineers, 1*(5), 767-768.
24. These are particularly useful because your paper's novelty is the treatment of congestion as a volatility process.
25. Bates, J., Polak, J., Jones, P., & Cook, A. (2001). The valuation of reliability for personal travel. Transportation Research Part E: Logistics and Transportation Review, 37(2-3), 191-229.
26. Noland, R. B., & Polak, J. W. (2002). Travel time variability: a review of theoretical and empirical issues. *Transport reviews, 22*(1), 39-54.
27. Carrion, C., & Levinson, D. (2012). Value of travel time reliability: A review of current evidence. *Transportation research part A: policy and practice, 46*(4), 720-741.
28. Peer, S., Koopmans, C. C., & Verhoef, E. T. (2012). Prediction of travel time variability for cost-benefit analysis. *Transportation Research Part A: Policy and Practice, 46*(1), 79-90.