Chapter 4
Heterogeneous Commuters and Sustainable Transportation With Extending Usage-Dependent Peak-Load Pricing:
Heterogeneous Commuters and Sustainable Transportation

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ABSTRACT

This study extends the bottleneck model of commuting by incorporating heterogeneous arrival windows to reflect the diverse professional and institutional schedules in modern urban environments. By expanding Vickrey's foundational framework, this analysis demonstrates how group-specific timing constraints dictate the formation of equilibrium queues. The resulting congestion follows a triangular–plateau–triangular profile: while excess demand generates early and late arrival "tails," a central plateau emerges, representing the union of all group-specific penalty-free windows. By deriving closed-form expressions for tail length and plateau height, the

DOI: 10.4018/979-8-3373-4611-3.ch004

model reveals that while schedule delays are technically unavoidable when demand exceeds system flexibility, queuing represents a pure waste of resources. To mitigate these inefficiencies, this study proposes two decentralization instruments—a time-dependent toll mirroring queue slopes and a simplified usage-based toll—both of which eliminate queuing without compromising travel feasibility. Ultimately, the findings highlight a critical efficiency-equity trade-off, as commuters with flexible windows avoid penalties by occupying the plateau, whereas those with rigid schedules are forced to absorb the majority of delay costs.

INTRODUCTİON

The economic and environmental externalities of urban traffic congestion—including productivity loss and air quality degradation—remain a critical challenge for modern cities (ECMT, 2007). Commuting delays inconvenient individuals and creates wider externalities, including wasted fuel, lost productivity, higher emissions, and poorer air quality (Small and Verhoef, 2007; Fosgerau and Small, 2021). Within the bottleneck framework, these environmental costs are primarily driven by queuing, which represents the stop-and-go conditions associated with peak emissions. Vickrey's (1969) bottleneck model has long been the foundation for studying such inefficiencies. Subsequent studies examined how queuing, schedule delays, and tolling interact to determine equilibrium outcomes and policy options (Arnott et al., 1993; Lindsey, 2004). Collectively, this body of research provides the economic justification for congestion pricing as a means of mitigating inefficient queuing (Laih, 2025).

Recent changes in work patterns reshapes congestion in ways that highlight clear differences between commuter groups. Highly paid professionals, who are more likely to work from home or have flexible contracts, can avoid the worst peak by spreading their trips over a wider timespan (Golden, 2008; Stiles and Smart, 2021). For example, in the San Francisco Bay Area, remote work among these groups has reduced peak-period vehicle miles traveled, although some of the gains are offset by additional non-work trips (Rezaei et al., 2025). By contrast, lower-paid workers, particularly those in service jobs or shift-based employment, are tied to fixed schedules and have little room to adjust their travel. Handy (2025) shows that while telecommuting lowers total person-miles traveled, households with less flexibility often compensate for it with more mandatory trips, reducing the overall benefit. A modeling study from Quebec City points to the same divide: flexible workers shift some travel to off-peak hours, whereas those with rigid start times remain concentrated in the morning rush, intensifying inequities in congestion exposure (Sweet and Scott, 2024). These differences complicate the congestion pricing.