Evaluating the Efficiency of Traffic Mitigation Fees at the San Pedro Bay Ports in a Congestion-Pricing Framework

Final Report

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Abstract

This study develops an empirical framework for estimating a peak-period truck toll designed to efficiently balance peak and off-peak truck traffic on the highway system surrounding the San Pedro Bay port complex and at its terminal gates. Like the current OffPeak program's Traffic Mitigation Fee (TMF), this congestion-pricing mechanism operates under the constraints that a toll cannot be assessed during off-peak gate hours, and that the toll is uniform across the peak period. Unlike the TMF, however, the toll applies to all truck trips rather than only to a limited class of gate moves. The distinction is drawn because the toll is aimed at correcting truck-generated congestion externalities, and all port-bound truck trips generate congestion externalities regardless of purpose. Methods for obtaining these cost estimates are also developed in this study and applied to data on highway and terminal-gate traffic conditions.

Estimation results imply a peak-period truck toll of $18.25 per roundtrip, which is expected to generate annual revenues of roughly $14 million at current trip volumes. These revenues are comparable to current off-peak gate costs, suggesting that the efficiency objectives of economic policymakers and cost-recovery objectives of marine terminal operators can be simultaneously achieved.

The results also suggest that the external costs generated by trucks on the highway network enveloping the ports dominate those generated at their terminal gates, motivating a more holistic public discussion of truck congestion at the ports.

The $18.25 toll applied to all peak-period truck trips is small in comparison to the current TMF of $50 per twenty-foot-equivalent container moved. A possible implication is that the burden of relieving congestion and financing off-peak terminal operations can be spread across a broader class of trip purposes while still adhering to efficiency and cost-recovery concerns.

Table of Contents

Index of Tables and Figures

Tables

Figures

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1. Introduction

In 2002, responding to growing concerns about truck queuing at marine terminal gates and the resulting concentration of diesel emissions, the California State Assembly passed Assembly Bill 2650 (AB 2650). The bill offered terminal operators at the Los Angeles and Long Beach ports a choice between two ways to reduce truck queuing: (1) extending gate hours from 40 to at least 70 hours per week or (2) implementing a terminal-gate appointment system. The bill also imposed a fine on operators of $250 for each truck idling at their gates for more than 30 minutes. Terminal operators initially opted for an appointment system.[1] Meanwhile, cargo movement at the ports continued to grow dramatically, as did concerns about port capacity and traffic congestion on surrounding freeways. This prompted the introduction of Assembly Bill (AB 2041), which mandated extended gate hours. Under the pressure of this proposed legislation, the terminal operators formed a consortium known as "PierPass" to implement the "OffPeak" program, which established a voluntary extension of full-service operations at all twelve of the ports' international container terminals.[2]

The OffPeak program began in July 2005 and now divides gate operations into peak and off-peak hours. Peak hours are Monday through Friday from 3:00 a.m. to 6:00 p.m.; off-peak hours are Monday through Thursday from 6:00 p.m. to 3:00 a.m., and Saturday from 8:00 a.m. to 6:00 p.m. Allowing cargo movement during off-peak hours, when the roads surrounding the port complex are relatively clear, offers the promise of improving traffic conditions and air quality around the ports. A "Traffic Mitigation Fee" (TMF) is assessed on certain types of loaded containers entering or exiting marine terminal gates by road during peak gate hours, with fee revenues earmarked to cover increases in off-peak terminal operating costs. PierPass collects these fees from shippers and consignees (truck drivers are not responsible for paying the TMF) and distributes them to terminal operators. When OffPeak first began, the TMF was set at $40 per twenty-foot equivalent (TEU) based on a per-TEU allocation of off-peak gate costs. In April 2006, an independent review of these costs resulted in the current TMF of $50 per TEU.

The TMF can be viewed as a form of "congestion pricing", where tolls are assessed in an effort to improve the efficiency of congested facilities. There is a long and rich economic literature on congestion pricing, which generally aims to correct the negative externalities that result from congested travel.[3] In the context of truck congestion in and around the ports, each truck trip generates negative externalities, for example, by delaying the travel of others and exposing them to increased diesel emissions. If the goal is to maximize the economic efficiency of road use then a toll equal to the external cost generated by each trip would be warranted. The formulation of the current TMF, however, does not consider the magnitudes of these externalities but, instead, focuses solely on cost recovery. This does not imply that the TMF is "wrong" in

[1] See Giuliano et al. (2006)
[2] *Ibid.*
[3] Section 2 provides formal, economic definitions of "efficiency" and "negative externalities".

any sense, but rather that it targets an objective that differs from that of maximizing economic efficiency.

The purpose of the present study is to develop an empirical framework for pricing access to marine terminals in a manner that maximizes the economic efficiency of traffic on highways surrounding the port complex and at terminal gates. In particular, it describes how to measure this toll when, like the current TMF, off-peak access cannot be charged. The magnitude of the toll can then be compared to that of the current TMF in order to gain a sense of how closely the objectives of efficiency-maximization and cost-recovery coincide.

This framework relies heavily on estimating the external congestion costs generated by each truck trip, comprising the bulk of this study's empirical efforts.[4] In short, the toll developed herein is designed to correct these externalities. This implies a key distinction between the current TMF and the toll estimated in this study, where the former only applies to moving a limited class of loaded ocean containers but the latter applies to all truck trips. The rationale is that that all port-bound trucks, regardless of trip purpose, generate congestion externalities when conditions are crowded, warranting a toll on all truck trips. Yet, of particular interest to terminal operators, the revenues implied by this congestion-pricing scheme can be compared to off-peak gate costs to determine if the objectives of efficiency-maximization and cost-recovery from loaded ocean containers can work hand-in-hand.

The results of this study suggest a peak-period toll of $18.25 per truck traveling roundtrip to and from the port complex. This toll is based on optimally balancing peak and off-peak truck traffic on the highway system surrounding the ports and at terminal gates. For reasons discussed in the analysis that follows, the toll is calculated as the difference between the external congestion cost that each truck trip generates during peak and off-peak gate hours. The toll is small in comparison to the current TMF, but it must be kept in mind that the current TMF only applies to trucks carrying certain types of loaded ocean containers. In this sense the $18.25 toll suggests spreading the burden of congestion relief across a wider class of port-related truck trips.

Of the estimated perk-period congestion externalities, about 10% are attributable to queuing at terminal gates, while the remaining 90% can be attributed to highway delays. This result illustrates the importance of considering the surrounding highway network when devising port-related congestion-pricing policies. The analysis also shows that the toll of $18.25 per peak-period trip could generate monthly toll revenues of roughly $13.9 million per month. This level of revenue may be sufficient to reimburse marine terminal operators for increases in their off-peak operating costs.

This report proceeds as follows. Section 2 formally describes the theoretical framework used to calculate economically-efficient congestion tolls in general, and the

[4] To keep the analysis tractable, only externalities attendant to delayed travel are considered. This does not imply that pollution externalities are unimportant. The focus here is on travel-delay externalities because they are typically considered to dominate other road externalities (see Small 1992).

adjustments required when tolls cannot be charged during off-peak hours. Section 3 develops an empirical framework for estimating the external congestion costs that each truck trip generates, which is needed to calculate the tolls discussed in Section 2. Section 4 describes the empirical setting and data used to obtain external cost estimates. Because a single toll for all peak-period trips is called for, requiring a single external cost estimate, the section also develops a procedure for averaging congestion externalities across trip routes and travel periods. Externalities on highways surrounding the ports and at terminal gates are considered in turn. Section 5 reports the uniform, peak-period truck toll implied by these externalities. Section 6 offers a few discussion points, followed by concluding remarks in Section 7.

2. Congestion-Pricing Framework

2.1 Congestion Tolls

Congestible facilities, such as highways and port terminals, suffer the classic economic problem of negative externalities. To understand the problem requires an understanding of the distinction between the private and social costs of using these facilities. Consider, for example, the time costs of using a crowded highway. The private cost to each user is simply the value of their time spent in transit – which we can call their *marginal private cost*. Each additional user, however, consumes scarce road capacity and forces existing travelers to reduce their speeds. In this sense the social cost of an additional trip exceeds its private cost owing to the delay costs imposed upon existing users. Because individual trip decisions are based solely on private costs, the value of the delays imposed on other users is called an *external congestion cost* or *congestion externality*. So the cost to all users resulting from each additional trip is the sum of its marginal private cost and the congestion externality it generates. We can refer to this sum as the *marginal social cost* of each trip.

The *marginal benefit* of a trip is the value that users place on making the trip. The level of road use that maximizes the net benefits to its users occurs when the marginal benefit of the last trip taken equals its marginal *social* cost; this condition describes an *economically efficient* or *optimal* level of use. In equilibrium, however, users enter to the road up to the point where marginal benefit equals marginal *private* cost. What results is an inefficiently large amount of traffic because the marginal social cost of using the road exceeds its marginal benefit. In other words, users (rationally) ignore the congestion externalities imposed on other users, resulting in excessive traffic congestion.

The challenge facing policymakers is to somehow reduce the facility's use to an economically efficient level. There is a rich history in the economics literature on using pricing incentives to accomplish this.[5] The general idea is to charge each user a *congestion toll* that would increase the private cost of each trip and reduce traffic to its

[5] For an excellent overview, see Small (1992).

optimal level. This type of toll is often called a "Pigovian" or "first-best" toll. The amount of the toll is equal to congestion externality generated at the efficient level of traffic.

Formally, define the *total benefit* to road users during a given commute period as $B = \int_0^{v'} d(v)dv$, where *d(v)* is the marginal benefit of road use and *v* represents traffic volume, which serves as a measure of road use.[6] Denote the *total cost* of road use as $C(v) = v \cdot c(v)$, which equals marginal (and average) private cost, *c(v)*, multiplied by the level of use, *v*. Marginal private cost naturally increases with use because the road is congestible.[7] In equilibrium, users enter the road until marginal benefit equals marginal private cost. If it were possible to levy a toll, τ, on each trip then users would enter the road until marginal benefit equals the sum of marginal private cost and this toll. We can refer to this sum as the *generalized price* of each trip, *p*, where $p \equiv c(v) + \tau$. The equilibrium condition then becomes $d(v) = p$.

If the policy goal is to induce an economically efficient level of traffic then the objective is to maximize net benefits, *B-C*, with respect to traffic volume:

$$\underset{v}{Max} \int_0^{v'} d(v)dv - v \cdot c(v) \tag{1}$$

Maximizing (1) entails differentiating it with respect to *v* and setting the resulting expression equal to zero; this expression is called a *first-order condition* of the maximization problem.[8] From this first-order condition, it can be shown that

$$c(v) + \tau = c(v) + \frac{\partial c(v)}{\partial v} v \tag{2}$$

Equation (2) shows that the optimal level of traffic is achieved where the generalized price of road use (on the left-hand side) equals its marginal social cost (the right-hand side). As described above, the marginal social cost has two components. The first, *c(v)*, is the addition to social cost privately faced by the marginal traveler. The second, $\frac{\partial c(v)}{\partial v} v$, is the increased cost imposed on all existing users due the marginal traveler's further consumption of road capacity. This latter cost is the congestion externality described above.

[6] *d(v)* is typically called the *demand curve* for road use, and *B* measures the *consumer surplus* enjoyed by users during the commute period. Note also that in the U.S. traffic volume, *v*, is often measured in vehicles per hour.

[7] Because road capacity is treated as fixed, the cost of the road itself is omitted from the total cost of use. As such this cost function is often called *short-run average variable cost*.

[8] At a maximum of any function (if it exists), its derivative with respect to the relevant maximand equals zero indicating that the "top" of the function has been reached.

From (2) it is readily apparent that the optimal toll required to induce an economically efficient level of traffic is

$$\tau = \frac{\partial c(v)}{\partial v} v \tag{3}$$

indicating that the toll equals the congestion externality generated by the marginal traveler (at the efficient level of road use). An analogous approach can be used to derive optimal tolls for other congestible facilities, such as terminals at maritime ports.

2.2 Congestion Tolls with an Untolled Alternative

In many cases it is impossible or politically infeasible to always implement the toll described in the previous section. For example, toll roads are often built with the understanding that an alternative route is available at no charge. In the case of the TMF at the San Pedro Bay ports, no fee is levied on trucks entering the port complex during off-peak gate hours. As such it is not possible to achieve a "first-best" level of truck traffic at the terminal gates and the highways extending to them.[9] Instead, policymakers must find a "second-best" solution, where a toll is sought to maximize economic efficiency under the constraint that tolls are not allowed during off-peak periods.

The approach proposed here is analogous to that derived in the literature on "second-best pricing" in the presence of an "untolled alternative".[10] In this setting, traffic on a given road (such as Interstate 710) can be divided between peak traffic, v_P, and off-peak traffic, v_O. The goal is then to find a toll that optimizes the mix of peak and off-peak truck traffic with the understanding that tolls cannot be charged during off-peak hours. To this end let $d(v)$ represent the marginal benefit of traveling during either period, where overall traffic, v, is now defined as $v = v_P + v_O$. Implicit in this framework is the assumption that peak and off-peak travel are "perfect substitutes". The marginal (and average) private cost in each period for truckers, or those dispatching them, is $c_P(v_P)$ for peak travel and $c_O(v_O)$ for off-peak travel.

The objective is now a slightly more complicated version of equation (1):

$$\underset{v_P, v_O, \tau}{Max} \int_0^{v_P+v_O} d(v)dv - v_P \cdot c_P(v_P) - v_O \cdot c_O(v_O) + \lambda_P \cdot \left[c_P(v_P) + \tau - d(v)\right] + \lambda_O \cdot \left[c_O(v_O) - d(v)\right] \tag{4}$$

[9] Note that the toll described in the previous section applies to cars and trucks alike. But it is currently infeasible to levy tolls on cars traveling the highways leading to the port, representing yet another constraint on achieving an efficient level of overall traffic.
[10] Verhoef et al. (1995) is an important work in this area.

The λ_P and λ_O terms are referred to as "shadow prices" reflecting the value of relaxing the constraints associated with them in equation (4). These constraints are simply the equilibrium conditions for peak travel, $c_P(v_P)+\tau=d(v)$, and off-peak travel, $c_O(v_O)=d(v)$, each stating that marginal benefit equals the "generalized price" in each period. If a toll could be charged during the off-peak period, then the net benefits to travelers would increase by a positive amount equal to λ_O. If the toll is set optimally during the peak period, then no gains can be exploited by changing the toll and we would expect $\lambda_P=0$.

A few caveats are worth pointing out at this point. First, it is understood that the current TMF is designed to generate revenue sufficient to cover off-peak terminal operations. Equation (4) can be modified to explicitly incorporate this constraint, though the result would be a toll that divides off-peak operating costs by the number of trucks traveling during peak gate hours. The relative efficiency of this toll would then depend on the "marginal cost of public funds", a measure of how "distortionary" raising revenue with the TMF is relative to some other means of taxation. The objective here is instead is to determine an optimal mix of truck traffic while setting aside revenue-generation concerns; the revenues implied by this toll are discussed later in this report. Second, it is understood that only certain trucks bearing loaded ocean containers are subject to the current TMF. It is important to understand, however, that each truck traveling to the port generates congestion externalities – loaded or not.[11] Moreover, attempting to gauge the relative efficiency of offering preferential treatment to "bobtails" and "empties" would require ad-hoc assumptions about the marginal benefit of each type of trip. Furthermore, it can be shown that under the constraint of tolling only loaded containers, a congestion-externality based toll would still prevail, but would reduce net benefits relative to more inclusive tolling. In short, the framework developed herein can be viewed as starting with a "clean slate", where the focus is on the efficient pricing of all peak-period truck trips when off-peak trips cannot be tolled.

That said, the first-order conditions from the maximization problem in (4) can be solved to yield the optimal (second-best) peak-period toll:

$$\tau=\frac{\partial c_P}{\partial v}v_P-\frac{\partial c_O}{\partial v}v_O\cdot\frac{-\partial d/\partial v}{\partial c_O/\partial v-\partial d/\partial v} \qquad (5)$$

Equation (5) looks daunting at first glance but has a simple interpretation. The first term on the right-hand side of (5) is the peak-period congestion externality generated by the marginal truck trip (c.f. equation (3)). The last right-hand side term has two parts. The

[11] In other words, trucks hauling empty containers or unloaded chassis are not distinguished from fully loaded trucks (or other large vehicles such as water carriers) because each consumes roughly the same amount of road capacity. One might argue, however, that "bobtails" should receive differential treatment. There is not sufficient evidence, however, to suggest that the PCE for a bobtail is substantially less than that of a laden truck. A notable exception, however, is that some terminals have dedicated bobtail lanes, which would reduce the externalities that they generate at terminal gates. Data on bobtail-only gate moves is fairly sparse, however, so the analysis proceeds by abstracting from this feature.

first part, $\frac{\partial c_O}{\partial v} v_O$, is the congestion externality imposed on off-peak travelers, which results from the switching of some trips into the off-peak period to avoid the toll. If the toll is sufficiently large, it may also result in the "cancelling" of some trips due to shippers opting for alternative ports such as Oakland. The second part of the last right-hand side term, $\frac{-\partial d/\partial v}{\partial c_O/\partial v - \partial d/\partial v}$, is the fraction of the trips displaced from the peak period that are moved to the off-peak period instead of cancelled entirely. So equation (5) can be summarized as follows: the optimal peak-period toll charges the congestion externality generated by each trip, less the congestion externality caused by switching to the off-peak period, after accounting for trips to this port that are cancelled.

It may be reasonable, however, to assume that the toll would not be large enough for shippers to switch to alternative ports. This can be characterized by assuming that the overall demand for trips to the port complex, peak and off-peak, is "perfectly inelastic".[12] The assumption would be consistent with PierPass estimates on the impact of the current TMF, where only switching between peak and off-peak trips is considered.[13] With a perfectly-inelastic demand, note that the $\partial d/\partial v$ term in (5) equals infinity. The term measures the slope of the demand curve for port trips, and this slope is infinite when demand is perfectly inelastic. The fraction $\frac{-\partial d/\partial v}{\partial c_O/\partial v - \partial d/\partial v}$ thus equals one, resulting in an optimal peak-period toll of

$$\tau = \frac{\partial c_P}{\partial v} v_P - \frac{\partial c_O}{\partial v} v_O \qquad (6)$$

Thus when overall demand is perfectly inelastic, the optimal peak-period toll is simply the difference between the congestion externalities imposed on peak and off-peak travelers. In this sense the toll optimally balances the congestion externalities in each period, thereby balancing each period's traffic flows. Note that the demand curve, *d(v)*, no longer appears in the toll expression so applying (6) primarily involves measuring the congestion externalities generated in each period. Henceforth in this analysis, optimal peak-period tolls are calculated using (6).

[12] See Leachman & Associates (2005) for a discussion of port-elasticity estimates for the San Pedro Bay Port Complex.
[13] See http://www.pierpass.org/.

3. Congestion-Externality Framework

3.1 Bottleneck Model of Trip Delays

Equation (6) shows that calculating peak-period tolls requires congestion-externality estimates for each period. These estimates, in turn, depend on how user costs in each period, c_P and c_O, respond to increased traffic flows ($\frac{\partial c_P}{\partial v}$ and $\frac{\partial c_O}{\partial v}$). The economics and engineering literatures on estimating such relationships are voluminous, and several approaches are available. Each relies on some specific functional form relating travel times to traffic flows.[14]

The approach taken in this study is to assume that trip delays result from "bottlenecks" that form on various parts of the highway network surrounding the ports when traffic exceeds "free-flow" capacities. These bottlenecks create queues that users must wait in before resuming free-flowing travel. Truck pedestals at terminal gates can also be viewed as bottlenecks when the inflow of trucks exceeds the pedestal's processing capacity, resulting in gate queues. A bottleneck model is thus capable of characterizing both highway delays and gate delays within a single estimation framework.

Formally, let $c(v) \equiv \gamma \cdot T(v)$ define the marginal private cost for a given portion of a peak or off-peak trip, where $T(v)$ is travel time and γ is the value that users place on that travel time; γ is often referred to as the "value of time" (VOT), which indicates the dollar amount users are willing to pay for a marginal reduction in travel time. This value differs for car and truck drivers because the latter are typically more averse to delays. For example, truck delays can result in missed gate appointments and fewer "turns"; Section 3.2 discusses how to accommodate different values of time for car and truck users.[15] To summarize, the private cost of a given trip is the time it takes to make the trip, multiplied by the monetary value placed on that travel time.

In a bottleneck framework, assuming a constant inflow of traffic, v, it can be shown that the average travel time (in minutes) for those encountering a bottleneck is

$$T(v) = T_f + \frac{w}{2} \cdot \left[\frac{v}{v_k} - 1 \right] \tag{7}$$

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[14] A comprehensive review of these literatures is beyond the scope of this study. It should be noted, however, that a "bottleneck" or "queuing" approach is adopted here mainly due to (i) concerns about frequent "hypercongestion" on surrounding highways and (ii) a relatively strong statistical fit with traffic data drawn from these highways.

[15] For truck users, VOT is typically referred to as "Commercial VOT".

when traffic flow exceeds the highway's (or terminal gate's) capacity, v_k; w is the amount of time that capacity is exceeded.[16] When capacity is not exceeded, travel time is simply T_f, representing the time required to make a trip under free-flowing conditions (or the time required to complete a pedestal transaction without delay). Equation (7) thus decomposes travel time into a free-flow time plus any time spent in a "traffic jam".

Using equation (7), marginal private cost can be expressed as

$$c(v) = \gamma \cdot \left(T_f + \frac{w}{2} \cdot \left[\frac{v}{v_k} - 1 \right] \right) \qquad (8).$$

Recall, however, that the *external* congestion cost is salient for calculating peak-period tolls. Following the discussion in Section 2.1, the external cost, denoted *EC*, is given by the difference between marginal *social* cost, $\frac{\partial(c(v) \cdot v)}{\partial v}$, and marginal private cost, $c(v)$:

$$EC = \frac{\partial(c(v) \cdot v)}{\partial v} - c(v) = \gamma \cdot \frac{w}{2} \cdot \left[\frac{v}{v_k} \right] \qquad (9).$$

Because this congestion externality is derived from average travel times, it measures the average external cost generated by each vehicle entering the highway (or terminal-gate queue) during congested travel. Note also that this external cost is zero when $v<v_k$, i.e. when traffic flows freely.

3.2 Accommodating Mixed Traffic

Equation (9) provides a general expression for the externality generated by an increase in traffic flow, v, and suffered by users with value of time γ. This expression does not, however, specify the type of vehicle that adds to traffic flow, nor does it consider the different VOT's associated with different types of vehicles. To consider a mix of vehicles sharing a highway, let "cars" denote passenger vehicles and "trucks" denote large commercial vehicles. This raises two immediate questions about the impact of increased traffic flows: (i) what are the external costs suffered by cars and truck drivers together, and (ii) how do the external costs generated by trucks entering the highway compare to those generated by cars?

In this study the first question is addressed by assigning separate VOT's for cars and trucks, then applying them to the proportions of each vehicle type suffering congestion externalities. For example, suppose a vehicle entering the highway creates a one-minute travel delay. If 10% of the highway comprises trucks, then the value that trucks place on this delay is applied to 10% of overall traffic volume, while the value that

[16] For a complete derivation see Small (1992), pp. 72-74. Note also that this formulation is consistent with a "piecewise-linear" model of the relationship between travel times and traffic flows.

cars place on the delay is applied to the remaining 90%. Formally, let γ_T denote truck VOT and γ_C denote car VOT. Also, let α_T and $\alpha_C = (1-\alpha_T)$ represent the share of overall traffic attributable to trucks and cars. For an increase in overall traffic flow, *v*, the value of the external delay, i.e. the external congestion cost (*EC*) is

$$EC = (\gamma_C \cdot \alpha_C + \gamma_T \cdot \alpha_T) \cdot v \cdot \frac{w}{2} \cdot \left[\frac{1}{v_k}\right] \tag{10}$$

which is a simple extension of equation (9).[17]

To address the second question, the impact of a truck entering a highway is described in terms of its "passenger-car equivalent" (PCE). For example, suppose that an entering truck has the same effect on highway travel times as two cars entering. The truck is then said to have a PCE equal to two. The concept of truck PCE's allows for using a single empirical model of travel delays to analyze both car and truck entries. For instance if overall traffic volume is measured in PCE's then the externality generated by an entering car would be given by equation (10). If an entering truck's PCE is two, then the resulting externality is simply two times equation (10).

3.3 Value of Time

Equation (10) shows that measuring congestion externalities requires information on both truck and car values of time. There is an extensive literature on car VOT from which to draw. The most recent, and arguably most reliable, studies are based on real-world choices made by urban rush-hour commuters who can choose a tolled highway to escape congested travel.[18] In short, the combination of tolls paid and travel times saved reveals their value of time. For the handful of studies considered here, this value ranges from \$24 to \$30 for each hour saved. Table 1 summarizes their findings (after adjusting for inflation).

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[17] Note that from equation (7), the external delay is $\frac{\partial T(v)}{\partial v} = \frac{w}{2} \cdot \frac{1}{v_k}$. So equation (10) is essentially a weighted average of this delay across cars and trucks, where $\gamma_C \cdot \alpha_C$ and $\gamma_T \cdot \alpha_T$ serve as weights.

[18] See Brownstone and Small (2005) for a review of such studies.

Table 1
Passenger-Vehicle Value of Time Estimates

Study	Value of Time (VOT)[a]
Lam and Small (2001)	$29.61
Small et al. (2005)	$24.25
Steimetz and Brownstone (2005)	$27.72[b]
Average	**$27.19**

[a] Converted to 2007 U.S. Dollars (Base = 1982-1984).
[b] Estimate based on a sample of California Interstate 15 morning commuters, weighted by income and trip distance to match the California State Route 91 sample of morning commuters used in Brownstone and Small (2005).

To measure external costs using equation (10), the average of these values ($27.19) is used for car VOT, γ_C.

The literature on truck VOT, often referred to as "commercial VOT", is less extensive. Kawamura (1999), however, provides a comprehensive review of this literature. Commercial VOT studies do not typically enjoy the same "real-world" choice data exploited by car VOT studies. Their estimates instead rely on survey data or a method called "switching-point analysis". The findings of Kawamura (1999) and other notable studies are summarized in Table 2.

Table 2
Commercial Value of Time Estimates

Study	Value of Time (VOT)[a]
Texas Transportation Institute (1997)	$57.58
Kawamura (1999)	$33.39 [b]
de Jong (2000)	$50.09
Smalkoski and Levinson (2005)	$55.15
Average	**$49.05**

[a] Converted to 2007 U.S. Dollars (Base = 1982-1984).
[b] Estimate based on data from Truckload (TL) and For-Hire operators only.

The average of the commercial VOT values in Table 2 ($49.05) is used for γ_T when measuring external costs with equation (10).

3.4 Passenger-Car Equivalents

Section 3.2 briefly describes how passenger-car equivalents (PCE's) can be used to estimate the externalities generated by truck inflows. This, of course, begs the question of which PCE value to use for trucks heading to and from the ports. A given truck's PCE depends, *inter alia*, on prevailing traffic conditions and highway grade (i.e. how steep a highway is). Because the highways surrounding the port complex are relatively flat, only PCE estimates based on zero-grade roads are considered here. A handful of studies estimating PCE's under these conditions, including the often-cited 2000 Highway Capacity Manual, is summarized in Table 3.

Table 3
Commercial Truck Passenger Car Equivalent Estimates

Study	Passenger-Car Equivalent (PCE)
Mingo and Zhuang (1994)	4.10
Webster and Elefteriadou (1999)	2.00
Highway Capacity Manual (2000)	2.00
Al-Kaisy et al. (2002)	2.79
Average	**2.72**

The average of these PCE estimates (2.72) is applied to equation (10) when estimating the congestion externalities generated by port-bound trucks on highways surrounding the port complex.

3.5 Summary of Truck Congestion-Externality Measurement

Equation (10) allows for estimating truck-generated congestion externalities when combined with the VOT and PCE estimates discussed above. Equation (6) shows that these estimates yield optimal peak-period truck tolls when (10) is applied separately to peak and off-peak periods.

For estimation purposed, VOT and PCE values are drawn from existing studies following the above discussion. This leaves other parameters to be estimated from data, such as bottleneck duration, w, and free-flow capacity, v_k. Terminal-gate delays are also estimated using equation (10) by setting α_C equal to zero (because car traffic is negligible at terminal gates). The particulars of estimating these parameters are discussed in following sections. Table 4 provides a brief summary of key parameter values required for external-cost estimation.

Table 4
Key Parameters for External Congestion Cost Estimates

Parameter	**Symbol**	**Source**
Passenger-Vehicle Value of Time	γ_C	Previous Studies
Commercial Value of Time	γ_T	Previous Studies
Overall Traffic Volume	v	Measured
Car Proportion of Overall Traffic Volume	α_C	Measured
Truck Proportion of Overall Traffic Volume	α_T	Measured
Highway / Terminal-Gate Bottleneck Duration	w	Estimated
Highway / Terminal-Gate Free-Flow Capacity	v_k	Estimated

4. Empirical Setting and Estimation

4.1 Empirical Setting and Estimation Overview

Following the discussions in Sections 2 and 3, peak-period truck tolls are calculated by first estimating the congestion externalities generated by trucks during peak or off-peak trips using equation (10). These estimates are then applied to equation (6) to yield optimal peak-period truck tolls under the constraint that off-peak trips cannot be charged.

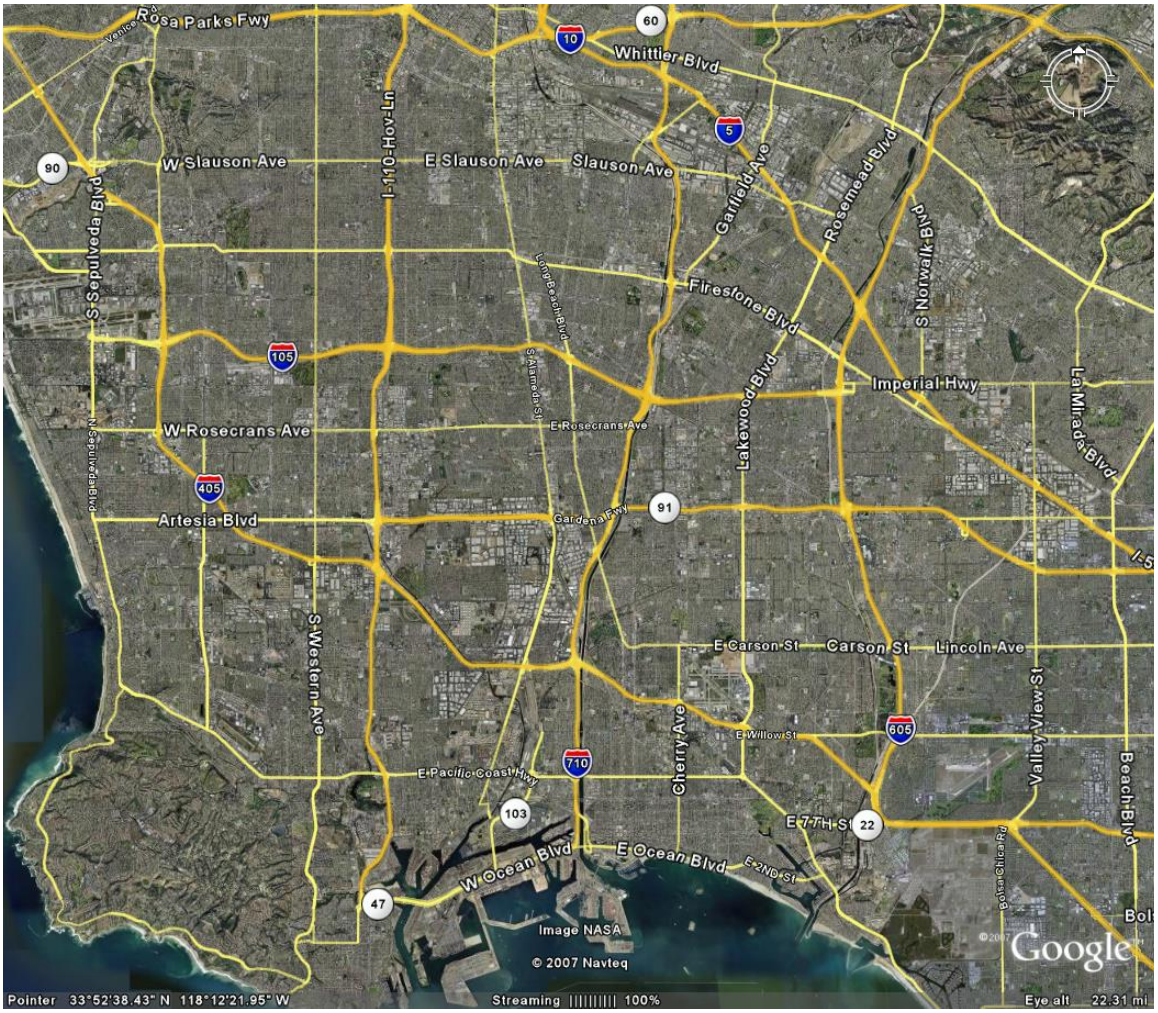
Presuming that multiple tolls within the peak-period are not allowed, the goal here is to calculate a uniform toll that applies to all trucks traveling during peak gate hours. Doing so is consistent with the current TMF in that tolls are not differentiated by exact trip characteristics such as point of origin or arrival time within peak gate hours. To develop a uniform peak-period toll, the notion of an "average externality" generated across peak or off-peak gate hours is introduced. For instance, a truck might depart at noon from an Inland Empire warehouse, travel along Highway 91 West and encounter traffic once in Los Angeles County, connect to Interstate 710 South, and arrive at 2:00 p.m. to wait in a terminal gate queue; the reverse trip might be made at 3:00 p.m. On each leg the truck creates, and suffers, the sum of several congestion externalities: on each highway during inbound travel, at the terminal gate, and on the same outbound highways. These externalities would be different, however, if the trip began at 9:00 a.m. and the driver decided to connect to Interstate 710 via Interstate 605 and Interstate 105. If it is assumed that either scenario is equally likely then the "average" externality generated by the complete trip can be viewed as the average of the externalities that would have resulted from each possible route and departure-time combination.

The above scenario depicts the essence of this study's approach to measuring externalities across an entire peak or off-peak period. Each trip is treated as having some probability of interacting with some portion of the surrounding highway network and during a given travel-time interval. Externalities are then measured by the weighted-average of the externalities created on each potential leg of a trip during each possible travel-time time interval, including those generated at terminal gates.

Figure 1 provides an aerial view of the surrounding highway network that is examined in this study, and Table 5 lists the possible inbound and outbound routes that are considered.[19] Note that some truck trips originate from within the network, thus requiring travel on fewer highways.

[19] All of the aerial highway views provided in this study were generate using "Google Earth" – an application that can be downloaded at http://earth.google.com/

Figure 1
Aerial View of Surrounding Highway System and Truck Routes Considered[a]



[a] Source: Google Earth.

Table 5
Inbound and Outbound Truck Routes[a]

Inbound Route	Outbound Route
10W-605S-105W-710S	710N-105E-605S-10E
10W-605S-91W-710S	710N-91E-605N-10E
605S-105W-710S	710N-105E-605N
605S-91W-710S	710N-91E-605N
105W-710S	710N-105E
91W-710S	710N-91E
405N-710S	710N-405S
105W-110S	110N-105E
91W-110S	110N-91E
405S-110S	110N-405N

[a] Numbers denote highways within the network, letters indicate direction of travel, and dashes denote interchanges. For example, "91W-110S" means westbound travel on State Route 91, followed by southbound travel on Interstate 110, ending at the Port of Los Angeles.

Three peak-period travel-time intervals are considered, which correspond to periods when terminal-gate traffic is heaviest. One off-peak time interval is considered under the assumption that highway and gate delays are negligible after 8:00 p.m. Table 6 summarizes these time intervals.

Table 6
Terminal Trip Travel-Time Intervals (Monday-Friday)

Peak or Off-Peak Gate Hours	Travel-Time Interval
Peak	7:00 a.m. – 9:00 a.m.
Peak	1:00 p.m. – 3:00 p.m.
Peak	3:00 p.m. – 6:00 p.m.
Off-Peak	6:00 p.m. – 8:00 p.m.

4.2 Highway External Cost Estimation

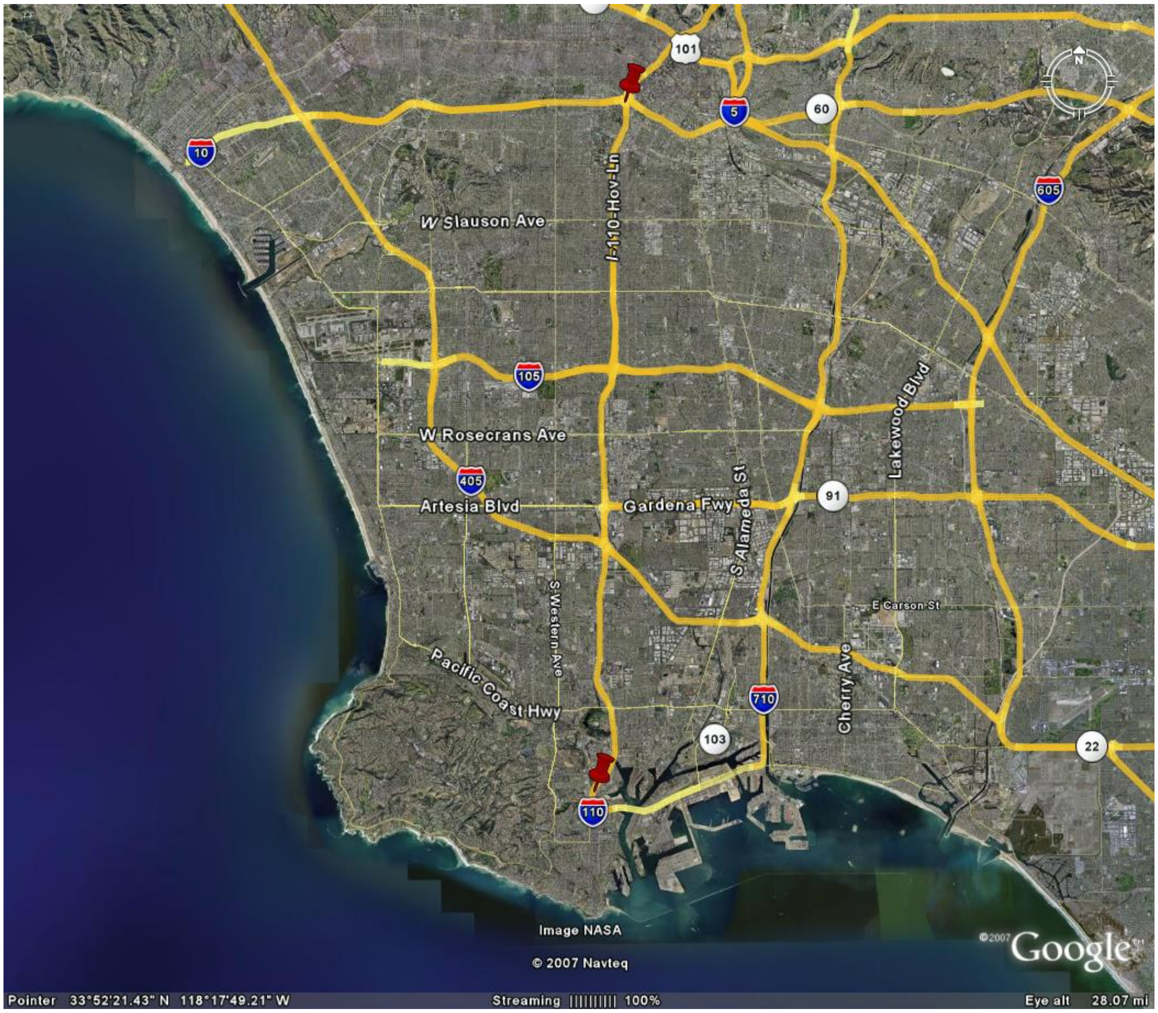
Equation (7) serves as the starting point for estimating the congestion externalities generated by port-bound trucks on the highway system surrounding the ports. The external delay caused by adding a truck to a given highway in the system is estimated by relating the average travel time, T, required to travel that highway to its overall traffic volume, v. The estimated parameters of (7), w and v_k, are then combined with information car and truck VOT and traffic shares and applied to equation (10).

Data on vehicle speeds (used to measure travel times), traffic volumes, and the share of traffic volumes attributable to trucks were drawn from the Freeway Performance Measurement Systems (PeMS) – a traffic database maintained by a collaboration between the University of California at Berkeley, the California Partners for Advanced Transit and Highways (PATH), and the California Department of Transportation (Caltrans).[20] These data were compiled in fifteen-minute intervals through August and September of 2006 for each of the highways listed in Table 5 (both directions). Only data from the segments of these highways that exhibited systematic travel delays were included (because travel delays do not occur on free-flowing segments). The data were then divided into the time intervals shown in Table 6 (three intervals during peak gate hours, one during off-peak hours).

The particulars of estimating external costs using these data with equations (7) and (10) are best understood by focusing on a single highway segment. Consider a 20-mile northbound segment of Interstate 110 leading from the Port of Los Angeles (in this case from Harbor Boulevard to Washington Boulevard). Figure 2 provides an aerial view indicating the endpoints of this segment.

[20] The PeMS data are available at https://pems.eecs.berkeley.edu/

Figure 2
Aerial View of Interstate 110 Segment Leading to the Port of Los Angeles[a]



[a] Source: Google Earth

Looking at equation (7), travel time, T, is the dependent variable (in minutes), whereas overall traffic volume, v, is the independent variable (in vehicles per hour); T_f, w, and v_k are parameters.[21] To keep matters simple, it is assumed that vehicles travel at 65 miles per hour during free-flow conditions, implying that the free-flow travel time, T_f, is $\frac{20}{65} \cdot 60 = 18.5$ minutes. This leaves two parameters to be estimated: the duration of each bottleneck period, w, and the free-flow capacity of the highway segment, v_k. The resulting estimation equation is

[21] More precisely, v is measured as the *inflow* of vehicles at the highway segment's southern end in order to keep consistent with bottleneck modeling.

$$T(v) = 18.5 + \frac{w}{2} \cdot \left[\frac{v}{v_k} - 1 \right] \quad (11).$$

Note that (11) is not linear in v_k so non-linear estimation techniques are required. In this study the method of Non-Linear Least Squares is employed.[22] Table 7 summarizes the results from estimating equation (11) for this highway segment.

Table 7
Average Travel Time Estimation Results for Northbound Interstate 110

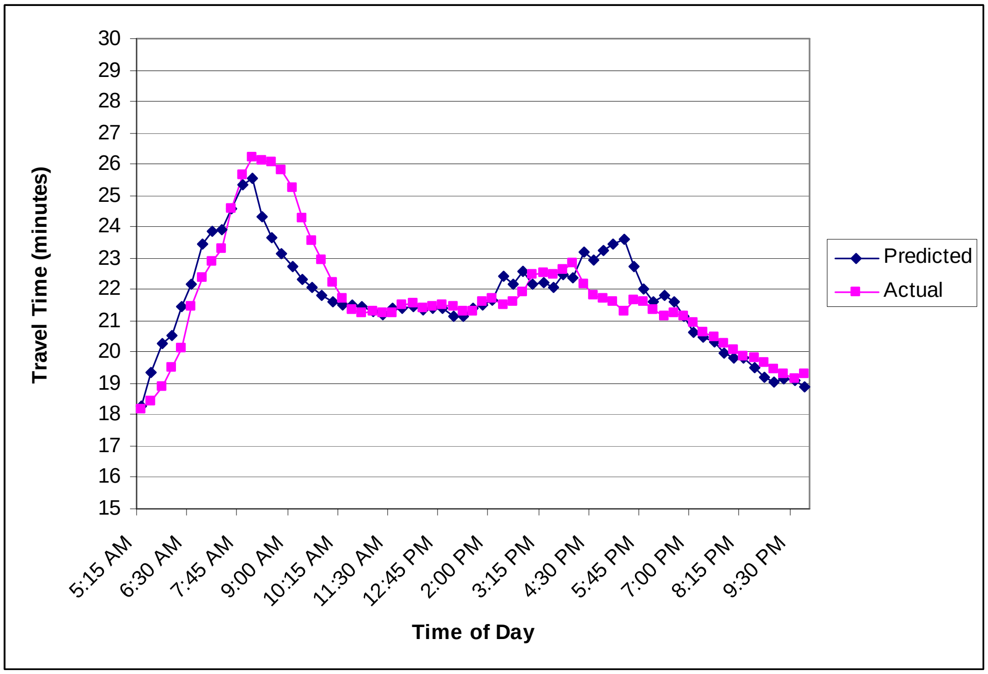
Parameter	Estimate	t-Statistic
Free-Flow Capacity (v_k)[a]	1479.92	29.46
Bottleneck Duration (w)[b]	4.92	9.78
	Adjusted R^2	0.9981

[a] Measured in vehicles per hour.
[b] Measured in minutes.

The table shows that average travel times on northbound I-110 are predicted quite well from the bottleneck model in equation (11), where the adjusted coefficient of determination (R^2) is 0.9981. The estimated parameters suggest that this segment of I-110 is capable of carrying roughly 1,480 vehicles per hour without delayed travel. When traffic exceeds this capacity, delays result from bottlenecks that last for roughly five minutes. Figure 3 plots actual travel times and those predicted by the model in (11) by time of day, illustrating how faithfully the model tracks travel delays.

[22] Specifically, the data are loaded into STATA SE 9.1 statistical software and the parameters of (11) are estimated using STATA's "nl" command.

Figure 3
Predicted and Actual Travel Times by Time of Day



The estimates for w and v_k can now be applied to equation (10), along with the values in Tables 1 and 2 for γ_C and γ_T (the VOT measures for cars and trucks, each converted to dollars per minute). What remains are the shares of overall traffic belonging to cars and trucks, α_C and α_T, during a given time interval. During the 7:00-9:00 a.m. interval, the average overall traffic volume is 2,693 vehicles per hour, 229 of which represent trucks. This implies that the share of volume belonging to trucks during this interval is 9% ($\alpha_T=0.09$), whereas cars comprise the remaining share ($\alpha_C=0.91$).

Applying all of this information to equation (10), and multiplying the results by the passenger-car equivalent given in Table 3, yields the external congestion cost imposed on existing cars and trucks by a truck entering this segment of northbound I-110 during the 7:00-9:00 a.m. interval:

$$EC = (\$0.45 \cdot 0.91 + \$0.82 \cdot 0.09) \cdot 2{,}693 \cdot \frac{4.92}{2} \cdot \left[\frac{1}{1{,}479}\right] \cdot 2.72 = \$5.90 \qquad (12)$$

The calculation in (12) shows that each truck entering during this period generates, on average, an external congestion cost of \$5.90. Note that the product $\frac{4.92}{2} \cdot \left[\frac{1}{1{,}479}\right] \cdot 2.72 = 12.19$ gives the external delay caused by each entering truck – 12.19 minutes in this case – and the remaining terms in (12) place a dollar value on this delay. This does not imply that each entering truck causes a delay of 12.19 minutes to each existing traveler. It instead shows that an entering truck delays each existing traveler by a small amount, and the sum of these small delays adds up to 12.19 minutes. The value of this overall delay to existing cars and trucks, i.e. the external congestion cost, is $5.90.

The above steps are repeated for each highway segment and during each time interval (including during off-peak gate hours) to estimate a set of external congestion costs generated by trucks on the highway system surrounding the ports. Table 8 summarizes these externality measures.[23]

[23] Complete estimation results from applying equation (7) to each highway segment are available from the authors by request.

Table 8

Truck-Generated External Congestion Cost Estimates by Highway Segment and Travel-Time Interval

Highway	Direction	Peak or Off-Peak	Travel-Time Interval	External Cost[a]
710	North	Peak	7:00 a.m. – 9:00 a.m.	$3.25
710	North	Peak	1:00 p.m. – 3:00 p.m.	$3.33
710	North	Peak	3:00 p.m. – 6:00 p.m.	$3.92
710	North	Off-Peak	6:00 p.m. – 8:00 p.m.	$3.11
710	South	Peak	7:00 a.m. – 9:00 a.m.	$3.90
710	South	Peak	1:00 p.m. – 3:00 p.m.	$3.53
710	South	Peak	3:00 p.m. – 6:00 p.m.	$3.47
710	South	Off-Peak	6:00 p.m. – 8:00 p.m.	$0.00
605	North	Peak	7:00 a.m. – 9:00 a.m.	$5.37
605	North	Peak	1:00 p.m. – 3:00 p.m.	$4.83
605	North	Peak	3:00 p.m. – 6:00 p.m.	$5.04
605	North	Off-Peak	6:00 p.m. – 8:00 p.m.	$4.63
605	South	Peak	7:00 a.m. – 9:00 a.m.	$5.37
605	South	Peak	1:00 p.m. – 3:00 p.m.	$4.63
605	South	Peak	3:00 p.m. – 6:00 p.m.	$4.54
605	South	Off-Peak	6:00 p.m. – 8:00 p.m.	$3.84
405	North	Peak	7:00 a.m. – 9:00 a.m.	$2.20
405	North	Peak	1:00 p.m. – 3:00 p.m.	$2.01
405	North	Peak	3:00 p.m. – 6:00 p.m.	$2.12
405	North	Off-Peak	6:00 p.m. – 8:00 p.m.	$1.92
405	South	Peak	7:00 a.m. – 9:00 a.m.	$3.24
405	South	Peak	1:00 p.m. – 3:00 p.m.	$3.20
405	South	Peak	3:00 p.m. – 6:00 p.m.	$3.08
405	South	Off-Peak	6:00 p.m. – 8:00 p.m.	$2.97
110	North	Peak	7:00 a.m. – 9:00 a.m.	$5.90
110	North	Peak	1:00 p.m. – 3:00 p.m.	$4.52
110	North	Peak	3:00 p.m. – 6:00 p.m.	$4.97
110	North	Off-Peak	6:00 p.m. – 8:00 p.m.	$0.00
110	South	Peak	7:00 a.m. – 9:00 a.m.	$3.37
110	South	Peak	1:00 p.m. – 3:00 p.m.	$3.57
110	South	Peak	3:00 p.m. – 6:00 p.m.	$3.45
110	South	Off-Peak	6:00 p.m. – 8:00 p.m.	$3.12
105	East	Peak	7:00 a.m. – 9:00 a.m.	$1.89
105	East	Peak	1:00 p.m. – 3:00 p.m.	$2.07
105	East	Peak	3:00 p.m. – 6:00 p.m.	$1.92
105	East	Off-Peak	6:00 p.m. – 8:00 p.m.	$1.93
105	West	Peak	7:00 a.m. – 9:00 a.m.	$2.69
105	West	Peak	1:00 p.m. – 3:00 p.m.	$3.04
105	West	Peak	3:00 p.m. – 6:00 p.m.	$3.05
105	West	Off-Peak	6:00 p.m. – 8:00 p.m.	$2.83
91	East	Peak	7:00 a.m. – 9:00 a.m.	$5.43
91	East	Peak	1:00 p.m. – 3:00 p.m.	$5.23
91	East	Peak	3:00 p.m. – 6:00 p.m.	$5.33
91	East	Off-Peak	6:00 p.m. – 8:00 p.m.	$4.85
91	West	Peak	7:00 a.m. – 9:00 a.m.	$7.49
91	West	Peak	1:00 p.m. – 3:00 p.m.	$7.14
91	West	Peak	3:00 p.m. – 6:00 p.m.	$7.52
91	West	Off-Peak	6:00 p.m. – 8:00 p.m.	$6.66
10	East	Peak	7:00 a.m. – 9:00 a.m.	$3.03
10	East	Peak	1:00 p.m. – 3:00 p.m.	$3.44
10	East	Peak	3:00 p.m. – 6:00 p.m.	$3.28
10	East	Off-Peak	6:00 p.m. – 8:00 p.m.	$3.23
10	West	Peak	7:00 a.m. – 9:00 a.m.	$3.20
10	West	Peak	1:00 p.m. – 3:00 p.m.	$3.11
10	West	Peak	3:00 p.m. – 6:00 p.m.	$3.33
10	West	Off-Peak	6:00 p.m. – 8:00 p.m.	$2.85

[a] Measured in 2007 U.S. dollars per trip.

4.3 Time-Averaged Highway Externalities

Table 8 shows that the externality generated by each truck trip varies by time of day for each highway. Because the objective here is to develop a uniform toll, aggregation over time (and space) is required. The approach taken here is to first average these external costs by time interval; Section 4.5 discusses averaging across trip routes. The basic idea is to construct a weighted average of the externalities generated during each of these intervals using the share of truck trips taken in each interval as weights.

Meyer, Mohaddes Associates, Inc. (2004) provides estimates on the share of terminal truck trips taken during each of the peak-period time intervals listed in Table 6.[24] Table 9 summarizes the share of overall trips taken during each peak-period interval.

Table 9

Estimated Share of Terminal Truck Trips Taken During Each Travel-Time Interval

Travel-Time Interval	Peak or Off-Peak	Share of Total Peak or Off-Peak Trips[a]
7:00 a.m. – 9:00 a.m.	Peak	29%
1:00 p.m. – 3:00 p.m.	Peak	44%
3:00 p.m. – 6:00 p.m.	Peak	27%
6:00 p.m. – 8:00 p.m.	Off-Peak	22%[b]

[a] Source: Meyer, Mohaddes Associates, Inc. (2004), Table 5, p. 27

[b] Assumes a uniform arrival rate throughout the off-peak period.

Also reported in the table is the assumed share of trips taken from 6:00-8:00 p.m. during off-peak gate hours. The underlying assumption is that truck trips are roughly uniform over the nine-hour off-peak period, implying that 22% of all off-peak trips occur during these two hours. This is an admittedly strong assumption, but a paucity of data on off-peak gate moves necessitates it. Note also that trips taken after 8:00 p.m. are not considered because it is assumed that off-peak externalities are negligible during late-evening trips.

Table 10 reports the weighted-average externality generated during peak and off-peak gate hours for each of the highway segments belonging to the routes listed in Table 8 (both directions).

[24] See Meyer, Mohaddes Associates, Inc. (2004), Table 5, p. 27. The actual time intervals reported in their table are 8:00-9:00 a.m. (“AM Peak”), 2:00-3:00 p.m. (“Mid-day Peak”), and 4:00-5:00 p.m. (“ PM Peak). Their estimates are used to approximate the distribution of peak-period trips for the travel-time intervals in Table 6.

Table 10
Weighted Average of Truck-Generated External Costs Across Travel-Time Intervals by Highway

Highway	Direction	Weighted-Average Peak-Period External Cost[a]	Weighted-Average Off-Peak-Period External Cost[a]
710	North	\$3.47	\$0.69
710	South	\$3.62	\$0.00
605	North	\$5.04	\$1.03
605	South	\$4.82	\$0.85
405	North	\$2.10	\$0.43
405	South	\$3.18	\$0.66
110	North	\$5.05	\$0.00
110	South	\$3.48	\$0.69
105	East	\$1.98	\$0.43
105	West	\$2.94	\$0.63
91	East	\$5.32	\$1.08
91	West	\$7.35	\$1.48
10	East	\$3.28	\$0.72
10	West	\$3.20	\$0.63

a Measured in 2007 U.S. dollars per trip.

For example, a truck traveling from the Port of Los Angeles on northbound Interstate 110 during the peak-period generates an external cost of \$5.05. According to Table 9, however, the externality would be greater (\$5.90) if travel occurred between 7:00 a.m. and 9:00 a.m., and smaller (\$4.52) for travel between 1:00 p.m. and 3:00 p.m. In averaging across these intervals, more weight is given to the mid-day interval because a greater share of peak-period trips (44%) is taken mid day. The resulting externality measure, including the 3:00-6:00 p.m. interval, is $\$5.90 \cdot 0.29 + \$4.52 \cdot 0.44 + \$4.97 \cdot 0.27 = \$5.05$. For an off-peak trip on I-110N, no externality is generated because traffic typically flows freely from 6:00-8:00 p.m. in that direction.[25] Southbound off-peak truck trips, however, generate a weighted-average externality of $\$3.12 \cdot 0.22 = \$0.69$ because trucks interact with other highway commuters heading to the San Pedro area between 6:00 p.m. and 8:00 p.m.

4.4 Roundtrip Route Externalities

Table 10 provides a measure of the external cost generated by each truck traveling the individual highways surrounding the port complex. The total externality generated by each truck, however, depends on which of these highways are traveled. For example, a peak-period trip to the Port of Long Beach from east of Los Angeles might entail traveling westbound on Highway 91then southbound on Interstate 710. Adding the externalities on these highways, according to Table 10, yields a combined externality of $\$7.35 + 3.62 = \$10.97$ for the inbound trip. Assuming that the outbound trip follows the reverse of this route (710N to 91E), the combined outbound externality is

[25] Note that northbound I-110 is a “reverse commute” for residents of the San Pedro area.

$\$3.47 + \$5.32 = \$8.79$. The total externality for the truck's roundtrip peak-period travel is thus $\$10.97 + \$8.79 = \$19.75$.

The same can be done for each of the routes proposed in Table 5. Tables 11 through 13 report the peak and off-peak average externalities generated on these routes for inbound, outbound, and roundtrip truck travel.

Table 11
Truck-Generated External Costs on Inbound Routes

Route	Peak-Period External Cost[a]	Off-Peak Period External Cost[a]
10W-605S-105W-710S	$14.59	$2.12
10W-605S-91W-710S	$18.99	$2.53
605S-105W-710S	$11.39	$2.99
605S-91W-710S	$15.79	$1.14
105W-710S	$6.57	$1.99
91W-710S	$10.97	$0.43
405N-710S	$5.72	$1.32
105W-110S	$6.43	$2.11
91W-110S	$10.83	$1.80
405S-110S	$6.66	$2.11

[a] Measured in 2007 U.S. dollars per trip.

Table 12
Truck-Generated External Costs on Outbound Routes

Route	Peak-Period External Cost[a]	Off-Peak Period External Cost[a]
710N-105E-605S-10E	$13.77	$2.87
710N-91E-605N-10E	$17.11	$2.12
710N-105E-605N	$10.49	$2.53
710N-91E-605N	$13.83	$2.99
710N-105E	$5.45	$1.14
710N-91E	$8.79	$1.99
710N-405S	$6.65	$0.43
110N-105E	$7.02	$1.51
110N-91E	$10.36	$2.11
110N-405N	$7.14	$1.80

[a] Measured in 2007 U.S. dollars per trip.

Table 13
Combined Truck-Generated External Costs on Inbound and Outbound Routes

Inbound Route	Peak-Period External Cost[a]	Off-Peak Period External Cost[a]
10W-605S-105W-710S	$28.36	$4.98
10W-605S-91W-710S	$36.10	$4.65
605S-105W-710S	$21.88	$5.53
605S-91W-710S	$29.62	$4.14
105W-710S	$12.02	$3.13
91W-710S	$19.76	$2.41
405N-710S	$12.37	$1.75
105W-110S	$13.45	$3.61
91W-110S	$21.19	$3.90
405S-110S	$13.80	$3.91

[a] Measured in 2007 U.S. dollars per *roundtrip*.

4.5 Route-Averaged Externalities

The above table shows that the external cost generated by roundtrip travel to and from the port complex depends, in part, on the route taken. To calculate a uniform toll, averaging across these routes is required. The general procedure is to construct a weighted-average roundtrip external cost using the share of truck trips taken on each route as weights. It is assumed that outbound trips follow the reverse of inbound trips.[26]

There is very little information available on the exact distribution of port-bound trips across routes. However, Meyer, Mohaddes Associates, Inc. (2004) complied data on the number of trucks traveling each highway around the port complex from a comprehensive survey of local truckers; the data are limited to trips taken during the mid-day interval of the peak period.[27] Because this is the only known information of its kind, it is used here to impute the share of trips taken on each route for all travel-time intervals. Assuming that the mid-day trip distribution can be extrapolated to all travel periods is somewhat heroic, but it is presumably superior to constructing a "simple average" across route costs. Table 14 reports the (imputed) share of port-bound trips taken on each route.

[26] An implicit assumption is that peak and off-peak trips do not overlap. For instance, a truck may enter the port complex during peak gate hours and exit during the off-peak period. This possibility is omitted from the analysis due to a lack of data on the frequency of such occurrences.
[27] See Meyer, Mohaddes Associates, Inc. (2004), Exhibit 21, p. 40.

Table 14
Shares of Peak-Period Terminal Trips by Route

Inbound Route	Share of Peak-Period Trips
10W-605S-105W-710S	8.2%
10W-605S-91W-710S	8.2%
605S-105W-710S	7.8%
605S-91W-710S	7.8%
105W-710S	13.7%
91W-710S	14.7%
405N-710S	10.6%
105W-110S	8.1%
91W-110S	8.2%
405S-110S	12.7%

[a] Source: Imputed from Meyer, Mohaddes Associates, Inc. (2004), Exhibit 21, p. 40.

For example, the table suggests that 14.7% of all inbound trips occur on westbound Highway 91, connecting to southbound Interstate 710, representing trips from east of Los Angeles to the Port of Long Beach.

Using these route shares as weights, a weighted-average, roundtrip external cost is constructed across these routes for peak and off-peak travel. Of course, the routes listed are by no means exhaustive; it is assumed that these routes are the most heavily traveled by port-bound trucks and that the externalities generated on omitted routes are small by comparison. Table 15 reports the peak and off-peak roundtrip external costs for each route and the route shares used as weights for each route.

Table 15
Weighted-Average of External Costs Across Routes[a]

Inbound Route	Peak External Cost	Off-Peak External Cost	Route Share	Share-Weighted Peak Externality	Share-Weighted Off-Peak Externality
10W-605S-105W-710S	$28.36	$4.98	8.2%	$2.32	$0.41
10W-605S-91W-710S	$36.10	$4.65	8.2%	$2.96	$0.38
605S-105W-710S	$21.88	$5.53	7.8%	$1.71	$0.43
605S-91W-710S	$29.62	$4.14	7.8%	$2.32	$0.32
105W-710S	$12.02	$3.13	13.7%	$1.64	$0.43
91W-710S	$19.76	$2.41	14.7%	$2.90	$0.35
405N-710S	$12.37	$1.75	10.6%	$1.32	$0.19
105W-110S	$13.45	$3.61	8.1%	$1.09	$0.29
91W-110S	$21.19	$3.90	8.2%	$1.74	$0.32
405S-110S	$13.80	$3.91	12.7%	$1.75	$0.50
Weighted Average				**$19.75**	**$3.63**

a Measured in 2007 U.S. Dollars per roundtrip.

The sum of the weighted route costs gives the weighted-average external cost for peak and off-peak trips. The table shows that, on average, each truck making a roundtrip during the peak period generates an externality of $19.75; an average externality of $3.62 is generated during each off-peak trip.

4.6 Terminal-Gate Externalities

Table 15 above only provides estimates for the external congestion costs generated along the Los Angeles highways leading to and from the port complex. External delays are also suffered, however, upon arrival by trucks waiting to be processed at terminal gates. It is also quite likely that trucks suffer external delays inside the terminals as well. The externalities suffered on terminal property, however, are beyond the scope of the present study. Instead, the external costs at terminal gates are measured from arrival at the terminal to departure from the gate pedestal.[28]

Equation (7) is particularly useful for estimating external delays at terminal gates because these gates exhibit classic bottleneck behavior. When the arrival rate of trucks (v) exceeds the pedestal's processing capacity (v_k), the pedestal acts as a bottleneck and delays are generated in the form of truck queues. The external cost caused by an additional truck arrival is given by equation (9), noting that only truck VOT and inflows are relevant (γ and v). So the analysis proceeds similarly to that conducted for highways in previous sections. In this case, truck waiting times (T) are related to truck arrival rates in order to estimate the parameters of equation (7).

Only a handful of studies provide information on waiting times and arrival rates at the San Pedro Bay port complex, most notably Ioannou et al. (2006), Giuliano et al. (2006), and Lam et al. (2006). Data for the present analysis are drawn from Ioannu et al. (2006), however, because waiting times and arrival rates are available by peak-period time of day. This also provides enough data points to estimate (7) and allows for separating the resulting externality estimates into the time intervals given in Table 6. Table 16 and Figure 4 depict the relationship between waiting times (in minutes) and truck inflows (in arrivals per minute) for a single day at an undisclosed terminal gate.[29]

[28] A gate pedestal is where truck transactions are processed. For example, a truck dropping off a load requires a "ticket" issued at the pedestal before entry into the terminal is permitted. At busy terminal gates, truck queues typically form behind each pedestal.

[29] See Ioannu et al. (2006), Figure 41, p. 76.

Table 16

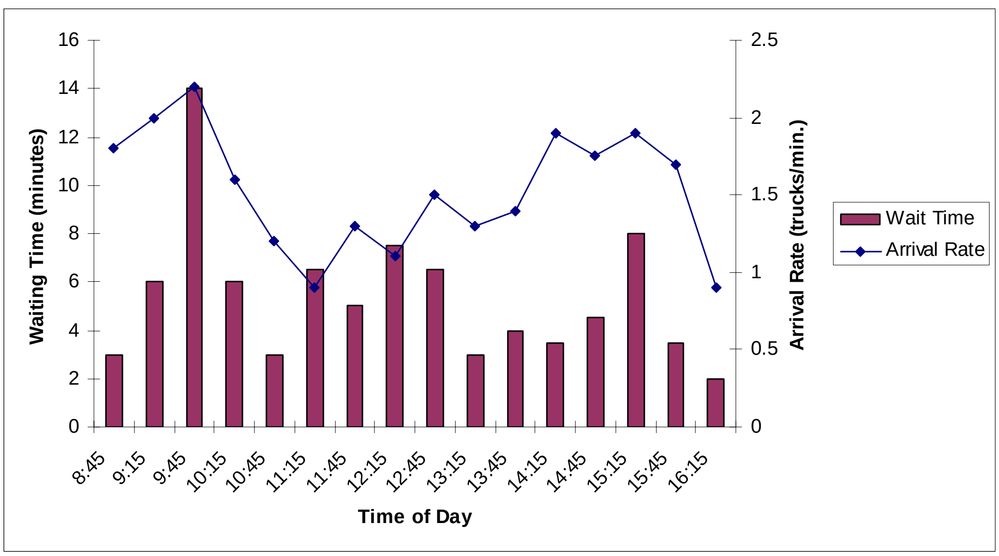
Peak-Period Terminal-Gate Truck Waiting Times and Arrival Rates by Time of Day[a]

Time of Day	Waiting Time[b]	Arrival Rate[c]
8:45	3.0	1.80
9:15	6.0	2.00
9:45	14.0	2.20
10:15	6.0	1.60
10:45	3.0	1.20
11:15	6.5	0.90
11:45	5.0	1.30
12:15	7.5	1.10
12:45	6.5	1.50
13:15	3.0	1.30
13:45	4.0	1.40
14:15	3.5	1.90
14:45	4.5	1.75
15:15	8.0	1.90
15:45	3.5	1.70
16:15	2.0	0.90

[a] Source: Ioannu et al. (2006), Figure 41, p. 76.
[b] Measured in minutes.
[c] Measured in trucks per minute.

Figure 4

Terminal-Gate Waiting Times and Truck Arrival Rates by Time of Day[a]



[a] Source: Ioannu et al. (2006), Figure 41, p. 76.

The shortest waiting time given in Table 16 (the last entry) is two minutes. This value is used for the "free-flow" parameter, T_f, in equation (7), which implicitly assumes that pedestals can process one truck every two minutes without creating queues.

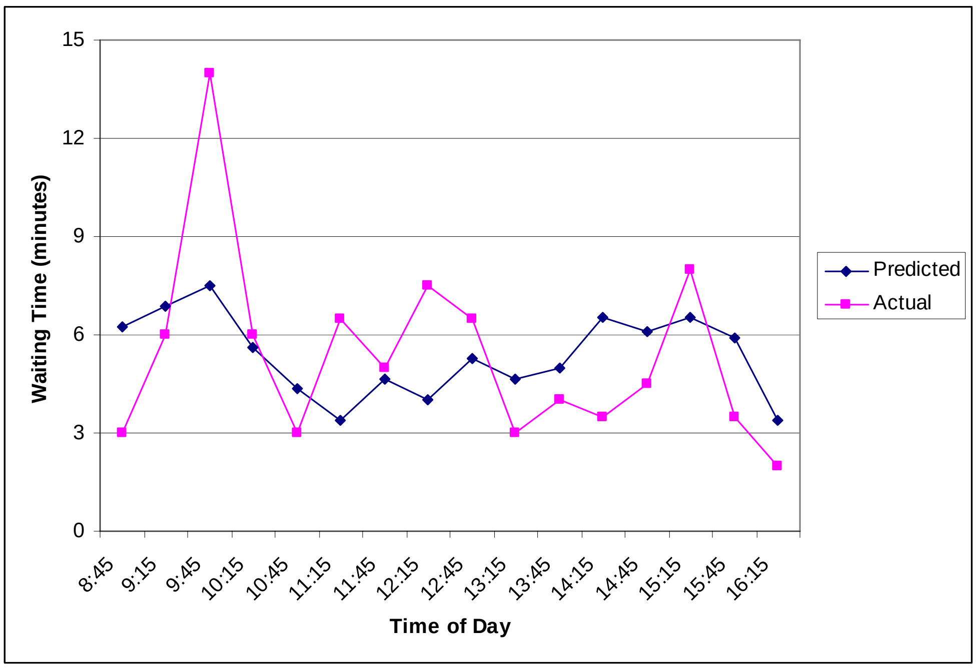
The results from estimating (7) are provided in Table 17. Figure 5 plots the actual waiting times and those predicted from (7) by time of day. The figure shows that predicted waiting times follow actual waiting times somewhat closely.[30]

Table 17
Estimation Results for Truck Waiting Times at Terminal Gates

Parameter	Estimate	t-Statistic
Pedestal Processing Capacity (v_k)[a]	0.3031	4.20
Bottleneck Duration (w)[b]	0.9587	3.40
	Adjusted R^2	0.7981

[a] Measured in trucks processed per minute.
[b] Measured in minutes.

Figure 5
Predicted and Actual Terminal-Gate Waiting Times by Time of Day



Using equation (9), Table 18 reports the external costs produced at terminal gates by each additional truck arrival. These costs are separated into those generated during the three peak-period intervals in Table 6, based on the average arrival rates during those intervals. By assumption, terminal-gate externalities are negligible during off-peak gate hours. The table also reports the share of peak-period trips taken during each of these intervals based on the information in Table 9.

[30] The model underestimates one large waiting time, which could bias the resulting externality estimates slightly downward.

Table 18
Terminal-Gate External Costs by Peak-Period Travel-Time Interval

Travel-Time Interval	Truck Arrival Rate[a]	External Cost[b]	Share of Peak-Period Trips
7:00 a.m. – 9:00 a.m.	1.90	$2.49	29%
1:00 p.m. – 3:00 p.m.	1.53	$1.99	44%
3:00 p.m. – 6:00 p.m.	1.53	$1.99	27%
	Weighted Average	**$2.13**	

[a] Measured in trucks per minute.
[b] Measured in 2007 U.S. Dollars per trip.

Table 18 also reports a weighted-average external cost across these intervals, where the trip shares reported in Table 18 serve as weights. This represents the average external cost generated by each truck arriving at a terminal gate during peak gate hours and facilitates the construction of a uniform peak-period truck toll.

5. Peak-Period Truck Tolls

Table 19 summarizes the external costs implied by the all of the estimates developed in Section 4.

Table 19
Summary of Roundtrip External Cost Estimates[a]

	Peak Gate Hours	Off-Peak Gate Hours
Average Highway External Cost	$19.75	$3.63
Average Terminal-Gate External Cost	$2.13	-
Sum of External Costs	$21.88	$3.63

a Measured in 2007 U.S. Dollars per roundtrip.

The optimal peak-period truck toll is given by the difference between the peak and off-peak congestion externalities generated by truck trips to and from the port complex, including those generated at terminal gates during peak gate hours. With the constraint that no tolls can be levied during the off-peak period, and assuming that the toll is not large enough to divert shipments to competing ports, equation (6) prescribes the optimal toll. Because a single, uniform toll is desired, the external-cost measures applied to (6) represent weighted-average costs, where averaging is performed across time and routes.[31]

[31] Given that off-peak tolls are prohibited, "optimal" is used here in a "second-best" context. Moreover, the averaging of external costs across routes and travel-time intervals may reduce the relative efficiency of this toll.

The results in Table 19 suggest levying a toll of \$18.25 (i.e. $\$19.75 + \$2.13 - \$3.63$) for each round-trip taken by all trucks during peak gate hours. Of this toll, \$16.12 (i.e. $\$19.75 - \$3.63$) is attributable to congestion on the highway system surrounding the port complex, and \$2.13 is attributable to congestion at terminal gates.

6. Discussion Points

6.1 Levying Tolls on All Truck Trips

A key distinction between the current Traffic Mitigation Fee and the toll estimated herein is that the latter does not discriminate by trip purpose. The TMF applies to loaded ocean containers, but does not apply to bobtails, empty chassis, domestic containers, or containers designated for transshipment to other ports. Intermodal containers that depart or arrive via the Alameda Corridor for import or export are also not subject to the TMF. However, the above estimates demonstrate that all port trips regardless of purpose generate congestion externalities, which must be considered if tolls are aimed at correcting highway and terminal congestion externalities. The \$18.25 toll is small in comparison to the current fee of \$50 per TEU, which often amounts to \$100 per loaded truck.[32] From the standpoint of alleviating congestion externalities, it might be argued that shippers and consignees subject to the current TMF are paying "too much" while those dispatching trucks for other purposes are paying "too little". Of course, there may be political or institutional objections to levying tolls on all truck trips. But the sizeable discrepancy between the current TMF and the optimal toll might warrant further discussion on why the burden of relieving congestion and financing off-peak operations falls squarely on those conducting a limited class of gate moves.

6.2 Congestion Externalities on Surrounding Highways

Much of the public discussion on congestion at the San Pedro Bay ports revolves around traffic along the two major highways leading to the ports, Interstates 710 and 110, and at terminal gates. The results presented here emphasize, however, that port-bound trucks also interact with non-port traffic throughout the surrounding highway system. For instance, Table 13 shows that peak-period roundtrip travel using Interstates 10, 605, 91, and 710 generates a congestion externality of \$36.10. This is mainly attributable to trucks interacting with large volumes of regular commuters on each of these heavily-traveled highways. By comparison, the peak-period congestion externality suffered at terminal gates is \$2.13. Although adding one truck to a gate queue delays all trucks further back in the queue, the sum of these delays is small in comparison to summing the delays imposed by the same truck on a large number of highway users. As such, traffic solely along I-710, I-110, and at terminal gates is only responsible for a relatively small

[32] The most common container size encountered at the port complex is 40 feet or two TEU's.

portion of the congestion costs created by port traffic. This portion becomes smaller if considering a larger area of the highway system than depicted in Figure 1. A more holistic view of port-related congestion may thus be warranted when prescribing truck tolls to manage this congestion.

6.3 Revenue Requirements

A critical concern for terminal operators is ensuring enough revenue to cover the increased gate costs resulting from off-peak operations. The current TMF of $50 per TEU is calculated strictly on the basis of cost recovery. The salient question is whether or not the revenues generated by the $18.25 toll determined above, which is estimated without any revenue-requirement constraint, would be sufficient to cover these increased gate costs.

According to PierPass (2006), the net increase in gate costs resulting from the current OffPeak program is roughly $12.6 million per month. A monthly volume of roughly 263,000 twenty-foot-equivalent containers are subject to the TMF. Dividing the increased gate cost by this volume yields a cost per TEU of about $48. Adding $2 for overhead costs yields the current TMF of $50 per TEU. Total TMF revenue is about $13 million per month, or $657,000 per day.

Based on estimates from Port of Long Beach (2004) and Meyer, Mohaddes Associates, Inc. (2004), about 30,000 trucks per month passed through terminal gates during peak hours in 2005.[33] Assuming an annual growth rate in trip volume of 7.6% (Fischer 2005), roughly 38,000 trucks per month will make peak-period trips in 2008. Applying a toll of $18.25 to this volume of trips yields $693,500 in daily toll revenue, or roughly $13.9 million per month.[34]

Note, however, that the toll is likely to induce some non-loaded truck trips into the off-peak period, but may also shift some loaded truck trips back into the peak period (because this toll is lower than the current TMF). The net effect is not known as the OffPeak program is relatively new and the data required for estimating peak-period trip demand is quite scarce. The preceding monthly revenue estimate of $13.9 million assumes that the net effect maintains current peak-period truck volumes and should thus be regarded as a first-order approximation. The point to be taken from the above discussion, however, is that the revenue generated by an $18.25 toll on all truck trips may be sufficient to cover increases in off-peak gate costs.

6.4 Caveats and Suggestions for Further Research

The analysis in this study attempts to gauge the magnitude of an economically efficient peak-period truck toll, and how it compares to the current TMF. The toll

[33] See Meyer, Mohaddes Associates, Inc. (2004), Table 5, p. 27.
[34] The monthly figure assumes twenty peak periods per month.

estimated herein is based entirely on external costs attendant to delayed travel. Several strong assumptions are required to achieve this estimate and, as such, it should be viewed more as a useful starting point rather than a toll that warrants immediate implementation. Ultimately, this study's primary contribution is the development of a framework for pricing port-related traffic, not necessarily the price itself. To implement this framework, further consideration must be given to each of the key assumptions and estimated parameters discussed throughout this study.

Note also that the idea of pricing externalities extends beyond those attendant to travel delays. For example, a major policy concern is the external pollution costs generated by trucks idling inside terminal gates. Further study on the per-trip magnitude of environmental externalities would be most useful for expanding the scope of the tolls discussed here. The same can be said for other external costs, such as the accident risk and even noise generated by port-bound trucks.

Also warranted is comprehensive research on estimating the overall demand for trips to the port complex, the available routes for completing each trip, and the share of trips taken on each route and during each time period. This would allow for more through toll estimates and analyses of toll revenues, and the possibility of relaxing the assumption that overall trip demand is perfectly inelastic. Moreover, estimates on the overall trip-demand elasticity would allow for investigating the impact of truck tolls on future port-utilization forecasts. Data limitations impede current efforts to do so, but collaboration among researchers, terminal operators, port agencies, and the trucking community would be extraordinarily valuable.

Furthermore, this study only considers the external delays generated on the surrounding highway network and at terminal gates. Trucks encounter considerable peak-period delays, however, *inside* terminal gates resulting in grater turn times and thus reduced income opportunities. Research on the *marginal* delay generated after each terminal entry, combined with efforts to estimate the value of this delay, would allow for a more comprehensive analysis of truck-tolling possibilities.

7. Summary

The OffPeak program can be viewed as an investment in capacity expansion, where revenues from the program's Traffic Mitigation Fee pay for this investment. However, fully exploiting the economic efficiency of this expansion, taking into account the congestion externalities generated by truck travel to and from the ports, requires a congestion-pricing mechanism that looks beyond cost recovery.

This study develops an empirical framework for estimating a peak-period truck toll designed to efficiently balance peak and off-peak truck traffic on the surrounding highway system and at terminal gates. Like the current TMF, this pricing mechanism operates under the constraints that a toll cannot be assessed during off-peak gate hours, and that the toll is uniform across the peak period. Unlike the TMF, however, the toll developed herein applies to all truck trips rather than only to a limited class of container moves. This distinction is drawn because the toll is designed to correct congestion externalities, and all port-bound truck trips generate these congestion externalities regardless of purpose.

Estimation results suggest that the bulk of the congestion externalities generated by trucks during the peak period occur on the highway network enveloping the ports – beyond more-often discussed facilities such as Interstates 110 and 710 and terminal gates. The intuition is that trucks typically interact with thousands of vehicles on several crowded highways during each leg of their inbound and outbound trips. As such, using tolls to correct these externalities may warrant a more holistic public discussion of port-related congestion.

The peak-period truck toll estimated herein is $18.25 per roundtrip and is expected to generate roughly $14 million in monthly toll revenues during the coming year. These revenues are on the same order as the current net increase in off-peak terminal operating costs, suggesting that an efficiency-maximizing toll may be compatible with the cost-recovery goal of the current TMF.

Compared to the current TMF, which often amounts to $100 per loaded-container move, the toll of $18.25 is small. A possible interpretation of this result is that the burden of relieving congestion and financing the OffPeak program may be focused to narrowly on a limited class of container moves. By assessing the $18.25 toll on all truck trips, including the movement of empties, domestic containers, intermodal containers, and containers designated for transshipment, this burden can be spread to a broader class of trip purposes while still meeting the objectives of economic policymakers and terminal operators.

Overall, this study aims to guide further research on managing truck congestion at maritime ports. Although its empirical results are informative, they can be dramatically affected by modifying their underlying assumptions or adopting alternative estimation methods. Moreover, the empirical framework developed in this study can be greatly improved, for instance, by broadening its scope to include other externalities such as air pollution, and by incorporating detailed information on the overall demand for port traffic. Efforts to improve this framework would greatly benefit from cooperation and data sharing between policymakers, analysts, port authorities, trucking firms, and marine terminal operators.

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