Tax or toll? GPS-based assessment of equity impacts of large scale electronic freeway tolling in Gauteng, South Africa

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ABSTRACT

As user charging increasingly supplements taxation as a transport financing mechanism worldwide, the need to measure and understand its distributional impacts across affected groups grows more critical. The case of the 185-km Gauteng Freeway Improvement Project in the Johannesburg-Pretoria area of South Africa offers an opportunity to empirically examine the equity impacts of large scale road pricing in middle-income countries. The paper reports on the novel use of GPS data from multiple sources to assess the distribution of benefits and costs of electronic tolling across passenger and freight users. GPS data from commercial truck fleets are combined with multiday GPS tracks from a panel of private vehicle drivers to derive measures of user benefit by class. Compared to an alternative hypothecated fuel tax, electronic tolling is more progressive in terms of both income and vehicle class, as it transfers costs from private to commercial vehicles, in line with the greater pavement damage caused by trucks. Time-of-day discounts favour commercial vehicles, suggesting that the injudicious application of discounts and exemptions can distort rather than enhance equity in road pricing projects.

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INTRODUCTION

As revenue sources based on fuel taxes dry up, road finance debates increasingly focus on the viability and impacts of alternative funding mechanisms. Amongst the most popular (among academics, if not politicians) are various forms of direct user charging for road use, as these are widely seen as being more efficient and fairer ways of paying for road infrastructure. Apart from classic road user charging schemes involving tolling of individual facilities, more flexible pricing schemes (which might also have other objectives beyond revenue collection), such as congestion charging and High Occupancy Vehicle/Toll (HOT) lanes and, more recently, mileage-based schemes, have been extensively studied.

A key question that has engaged researchers is the equity implications of these pricing schemes – particularly whether road user charging shifts more of the burden of paying for roads towards some population groups, compared to current taxation methods. Recent reviews generally indicate that the evidence is mixed: user charging can be either progressive or regressive with respect to income, depending on how equity is defined, and on how revenues are applied (*1,2*). The distribution of benefits and costs across the population is clearly influenced by the particulars of each scheme, putting the onus on scheme designers to test for equity impacts early on in the planning process (*2*). Where unacceptable equity effects are found, mechanisms such as public transport investment or toll exemptions are universally accepted as a means of compensating affected populations (*3*).

It is thus useful to examine the performance of alternative schemes to deepen our understanding of how scheme design affects equity. This paper offers an analysis of the equity impacts of an unusual road pricing scheme, and extends the state of practice in several ways. The scheme is a large scale electronic tolling scheme implemented in the Gauteng urban region in South Africa. The scheme is designed as something between a purely distance-based fee and a facility-specific toll. By using state of the art electronic tolling with a system of overhead gantries, user charges will closely correspond to actual road usage. By charging only for travel (by vehicle class) on the freeway network the scheme is a differentiated toll scheme, albeit with exemptions and discounts in place. Revenues are hypothecated to the already completed upgrading of the freeways, so benefits may have a strong spatial equity component related to the location of homes and work places of various user groups in relation to the tolled network. What makes these effects potentially significant is the scale of the network: the 185-km tolled freeway network makes up a significant part of the mobility infrastructure of the large metropolitan area. Insights from this analysis might thus inform future attempts at implementing facility-specific user charges across large jurisdictions.

What makes equity especially relevant in Gauteng's case is the province's extreme levels of income inequality: 58% of income is earned by the richest 10% of the population, and about two-thirds of households do not own cars. Opponents to the charging scheme have, largely based on equity arguments, proposed as an alternative funding mechanism an additional surcharge to the existing fuel tax. The question we ask is, to what extent is the large-scale freeway tolling more or less equitable than an alternative fuel tax funding mechanism?

In terms of methodology the state of practice is extended in several ways. Firstly, we make use of very detailed travel behavior data provided by Global Positioning System (GPS) based technologies. Specific strengths of GPS data for this kind of analysis include its ability to capture route choice very accurately – a key issue in the presence of tolled versus free facilities – and its ability to provide multiday travel data at lower cost than with conventional travel diary methods (*4,5,6*). GPS data also provide a basis for accurate estimation of fuel consumption as a function of actual vehicle speeds (*7*), which is important for estimating the incidence of fuel tax payments. Secondly, we integrate GPS data from two

separate sources to allow us to assess both private road users and commercial (heavy) vehicles in the same equity framework. This is useful as we can show that benefits and costs are distributed very differently between these two user classes, with significant equity implications. Commercial vehicles have largely been ignored in equity analyses. Lastly, we examine the effects of exemptions and discounts to the toll scheme, showing the extent to which such attempts at attenuating unfair burdens on users (and securing greater political support) might have unintended consequences. In this case the time-of-day discount actually makes the scheme less equitable than it would otherwise be, shifting costs away from commercial and towards private vehicle users.

The paper starts by providing a brief overview of equity and welfare aspects of road user charging. We then describe the context of the Gauteng freeway upgrading project and electronic toll scheme, and the data collection methods used. Then follows the calculation of user benefits and costs for the toll and tax scenarios, and finally conclusions regarding methodological and substantive findings and recommendations for further research.

EQUITY AND WELFARE IMPACTS OF ROAD USER CHARGING

Equity, or the distribution of benefits and costs of a transport project across members of an affected population, is increasingly receiving attention from analysts and policy makers (*8*). There are two main reasons for this. The first is a public policy concern with distributional fairness and protection of vulnerable groups, as exemplified by notions of environmental justice in the United States (*9*) and social exclusion in Europe (*10*). Secondly, and more pragmatically, political concerns around the adoption of road pricing schemes revolve largely around how benefits and costs are distributed across constituencies (*11*): in Levinson's words, "the issue of who gets to use roads without paying the full cost is critical to understanding the choice of highway finance mechanism" (*12*).

Various notions of equity exist in the literature. Commonly cited definitions look at equity as horizontal (are members of the same group treated equally?), vertical (are members of different groups treated differently?), according to cost (do those who contribute to social costs pay for it?), and according to benefit (do those who receive social benefits pay for them?) (*2*).

Two recent reviews of the literature on equity and road pricing concluded that the evidence is mixed, partly because of the different definitions being applied to the problem (*1,2*). How groups are defined is another source of variation. Most studies are concerned with the distribution of impacts across different income groups – on the basis that those with lower incomes are more vulnerable in the sense of having fewer options for avoiding extra costs imposed on them – or across demographically defined subgroups (e.g. race or disability status).

Despite the variation in findings, most studies seem to agree that fuel taxes are regressive: lower-income households pay a higher proportion of their incomes than do wealthier households (*2,13*). This is not surprising since transport expenditure as a whole make up a larger proportion of incomes of lower than of higher income households (*14*). As a percentage of expenditure rather than income, fuel taxes burden middle-class households more (*15*).

The research on road pricing has identified low-income drivers (*16*), short-distance travelers, and non-commuters (*17*) as potential losers – although this is by no means universal (*1*) – while public transport users (*16, 18*) could benefit if revenues are spent correctly. What is being priced matters: facility-specific tolls would tend to benefit those living in areas closer to the toll roads more (*19*), as well as high-income drivers who tend to use priced lanes more often (*3*). Cordon charges (as in the case of Stockholm's congestion charge) have a greater effect on those living within the charged zone (*18*). Clearly, in the presence of priced and unpriced facilities, equity impacts are very sensitive to where people live and work (*2*).

Recent studies on vehicle miles of travel (VMT) fees, levied on all travel within a jurisdiction, tend to agree that VMT fees are less regressive than fuel taxes, both in terms of income and in terms of

shifting the tax burden from rural to urban households. Overall, though, the distributional impact of VMT fees seems to be negligible (*13, 20, 21*).

The literature further agrees on the fact that equity issues, whether real or perceived, can be addressed by intelligent mechanisms such as cutting other taxes or improving alternatives (*1,2*). The Federal Highway Administration specifically supports the use of exemptions, rebates or other forms of monetary compensation (e.g. tax rebates or toll credits) for low-income motorists who are particularly affected by pricing (*3*).

BACKGROUND: THE E-TOLL DEBATE IN SOUTH AFRICA

South African transport policy has supported user financing of certain types of roads for several decades; 19% of 16,421 km of national intercity roads are operated as toll roads, mostly as concessionary schemes with private sector partners. As urban congestion grows in lock step with fiscal pressure, the government now seeks to apply the user-pays principle also to urban freeways.

The South African National Road Agency Ltd. (SANRAL) recently completed a $7.1 billion upgrade[1] of 185 kilometers of freeway infrastructure in Gauteng (*22*) (Figure 1). With a population of 11 million and including the commercial and administrative hubs of Johannesburg and Pretoria, Gauteng is South Africa's most densely urbanized province. The Gauteng Freeway Improvement Project (GFIP) was aimed at relieving congestion, improving traffic management through Intelligent Transport Systems deployment, and improving traffic safety on the province's extensive freeway network. Funding for the project was raised from the bond market, to be paid back via user charges collected at a set of 42 open-road tolling gantries. The project, nicknamed *e-toll*, is publicized as being the largest open-road tolling project in the world (*23*).

Not surprisingly, the tolling component of the GFIP is mired in controversy. Implementation of the e-toll started in December 2013, after being halted by court action several times. Opponents cite three specific arguments. The first relates to alleged flaws in the public participation process. The second objection relates to efficiency concerns: the cost of collecting toll charges through the system of open-road toll gantries, with its supporting back-office and enforcement infrastructure, is estimated at a quarter of total revenues (*24*). The third objection is purely equity based: opponents claim the tolling of previously free roadways will be inflationary and raise the cost of living, especially for lower income groups. Toll opponents call for replacing the user charge with a rise in the existing general fuel levy, on the basis of efficiency. The equity implications of such a shift have hardly received a mention. In an effort to address public concern with the toll burden that will fall on specific user groups, namely low-income public transport users, high-frequency freeway users, and off-peak drivers with low values of time, SANRAL plans to implement a series of discounts and exemptions to the toll charge.

DATA SOURCES

Data on current travel behavior in Gauteng Province were obtained from two GPS sources. Venter and Joubert (*7*) describe the data sources and procedures that were used to assemble and validate the data in detail.

GPS data from commercial fleet management sources
GPS records of truck trips, collected by a fleet management company, provided the base data for commercial vehicle movements in Gauteng. We used ignition-related signals in the data to extract activities and activity chains from the records of all vehicles. We distinguished between *intra*-provincial vehicles (10,267), those who conduct at least 60% of their observed activities inside the boundaries of

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[1] *An exchange rate of R10.00 per US Dollar has been used to convert from South African Rand.*

Gauteng, and *inter*-provincial vehicles (11,073). The 60% threshold corresponds with the findings of Joubert and Axhausen (*25*).

Portable passive GPS loggers for private car drivers
The baseline driving patterns of private vehicle users were captured through the use of portable passive GPS logging devices carried in the vehicle by a sample of respondents. A sample of 726 drivers were recruited to carry the self-powered device in their vehicles for three consecutive days during which 'normal' driving activities would be undertaken (including weekends, but excluding holidays or days containing out-of-province trips). Upon completion of the trial, respondents completed a short interview to provide data on household demographics, work location, vehicle details, and household income.

Sampling for the GPS survey was based on a stratified random approach, to ensure representivity of the car owning population in the province, both spatially (at the level of twenty sub-regions within the province), and demographically (with respect to income, gender, and employment status). We oversampled in areas with higher freeway use, to enable accurate measurement in future of driver adaptation in response to tolling.

Sample bias is a potential issue in GPS studies (*5,26*). A subsequent test for sample bias showed that freeway users in the GPS sample correspond closely to those in the population in terms of gender and occupation status, but that our sample was slightly biased towards lower-income freeway users (*7*). We corrected for this by appropriate weighting of the data.

METHODOLOGY: MEASURING THE DISTRIBUTION OF BENEFITS AND COSTS

This work applies the benefit principle to assessing equity: the price paid by various user groups should be commensurate with the benefit they receive (*2*). We compare the distribution of costs and benefits for two basic scenarios: the road pricing scenario whereby distance-based tolls are collected for all travel on the 185km-long Gauteng freeway network, and an alternative funding scenario involving an equivalent increase in the fuel tax for all drivers in the province.

User groups are defined according to income (for private users). We also add commercial vehicles as a user group on the basis that heavy vehicles incur costs and receive benefits that may be very different from those of light vehicles. A significant proportion of heavy vehicle trips – about 52% of trips according to GPS tracks – are long distance trips with origins or destinations outside the province, making it important to differentiate between inter- and intra-provincial commercial vehicles in the analysis. We do not include public transport vehicles in the analysis, as they are to be exempt from the toll charges, and constitute a negligible proportion of freeway trips in Gauteng.

Data were collected after the completion of the GFIP freeway upgrade, but without any large scale tolling in place (apart from a few freeway sections that are already operated as concessionary toll roads), and thus represent a base case scenario.

We employ a "static" modeling approach, assuming that all drivers travel exactly the same distances and routes using the same vehicles for both tax and toll options. This method essentially assumes that drivers do not change their travel behavior in response to the charge regime – an unrealistic assumption as both travel behavior theory and empirical evidence on user adaptation to road pricing indicate that drivers might adopt both short-term changes (e.g. in route, departure time, activity chains, or mode choice) and long-term changes (e.g. in type or number of vehicles owned, home or work location) in response to pricing (e.g. *27,28*). Yet there is some evidence that, for the purpose of analyzing *equity* impacts (if not for traffic or economic impacts), the static model provides acceptable results at least in the short run. McMullen et al (*21*) found that the static approach produced results very similar to a more elastic model of vehicle miles travelled when comparing the distributional effects of a VMT charge versus the current fuel tax, also noting that the US Congress Joint Committee on Taxation advocates this approach largely on the grounds that it is more easily understood. Examining the equity impacts of congestion pricing in Stockholm, Eliasson and Mattsson (*18*) argue that initial travel patterns are the most

important for determining equity impacts, as initial travelers are the ones most affected by change. Peters and Kramer make the same argument in work on New York City (*29*).

Work is ongoing to develop the Multi-Agent Transport Simulation (MATSim) platform to allow a more accurate assessment of potential route diversion, activity chain adaptation, and mode change under various funding scenarios.

The first and simplest measure of benefit simply equates benefit with the vehicle kilometers of travel on the freeways. One could argue, though, that not all kilometers travelled receive equal benefit. Benefits of the freeway upgrade are of two kinds: those relating to traffic capacity upgrades, and those relating to improvements to the structural pavement capacity. We thus define two refined benefit measures relating to speed benefits and to pavement damage.

The incidence of toll costs is firstly determined using the base per-kilometer rate of the electronic tolling scheme, reflecting the distribution of payments across freeway user groups before any discounts. To assess whether the system of discounts proposed by the road authority affect equity, we also determine the distribution of payments with a frequent-user discount and a time-of-day discount in place. Lastly, for comparison, we estimate the distribution of tax revenue across the user groups if a province-wide fuel tax were implemented on all vehicles (not just freeway travel).

Benefit by freeway VKT

Benefits of freeway use can most simply be expressed as the percentage of vehicle kilometres of travel (VKT) on the upgraded network. Consider a set of user groups denoted by $\bar{I}$. For user group $i \in \bar{I}$ we calculate this percentage as:

$$\%VKT_i = {d_i}\Big/{\sum_{j \in \bar{I}} d_j} \qquad \forall i \in \bar{I} \dots (1).$$

where d_i = aggregate distance travelled on the freeway by all users in group $i \in \bar{I}$.

Vehicle kilometres of freeway travel are obtained directly from the weighted GPS data.

Benefit by speed-adjusted VKT

The previous metric weighs all freeway kilometres the same, while it might be argued that a kilometre of uncongested travel on a previously congested section should be more beneficial than a kilometre elsewhere. Consider the set $\bar{K}$ of road segments in the network. A speed-adjusted benefit measure is then calculated by replacing d_i in equation (1) with:

$$d_i^s = \sum_{k \in \bar{K}} d_{ki} \left(v_k^{new} / v_k^{old} \right) \quad \forall i \in \bar{I} \dots (2).$$

where d_i^s = speed-adjusted distance travelled on freeway by all users in group $i \in \bar{I}$,
d_{ki} = distance of road segment $k \in \bar{K}$ used by user in group $i \in \bar{I}$,
v_k^{new} = new (after upgrade) speed on segment $k \in \bar{K}$ (obtained from GPS track)
v_k^{old} = old (before upgrade) speed on segment $k \in \bar{K}$ (obtained from base model)

This metric is driven by actual travel time savings, and thus reflects the proportion of the additional traffic capacity benefit that accrues to each user group, taking its route usage and time of day profile into account. Base (before-upgrade) speeds per road segment were estimated from a base year transport model validated to actual travel time and speed measurements taken before the start of construction.

Benefit by pavement damage-adjusted VKT

The idea that road pricing should reflect the fact that benefits of road improvements are related not just to speed increases but also to pavement damage, is not new (*30, 31*). The structural requirements imposed

by heavy vehicles contribute significantly to the overall cost of road construction. There is an argument for measuring benefit (and setting prices) in relation to vehicle weight.

Pavement damage rises exponentially with axle weight. We construct a pavement damage-adjusted measure that weighs a kilometre travelled by a truck more heavily, as the pavement damage caused by the truck is commensurate with the benefit it receives of being able to carry a commercial load over that distance. The measure replaces d_i in equation (1) with:

$$d_i^p = d_i . E80s = d_i . \sum_{j=1}^{n_i} (P_j/80)^4 \quad \forall i \in \bar{I} \ldots (3)$$

where d_i^p = pavement damage-adjusted distance travelled on freeway by all users in group $i \in \bar{I}$,
      $E80s$ = number of equivalent 80kN axle loads applied by a typical vehicle in group $i \in \bar{I}$,
      P_i = per axle load (in kN) in group $i \in \bar{I}$,
      n_i = the average number of axles of a typical vehicle in group $i \in \bar{I}$.

We used typical vehicle axle loads to estimate the E80s, which came to 0.00014 for passenger vehicles and between 0.51 and 1.61 for intra-provincial and inter-provincial heavy vehicles.

While the distribution of benefits of the freeway upgrade is independent of the cost recovery mechanism adopted (under the static model), the distribution of costs is not. We calculated the distribution of costs as follows:

Toll by freeway VKT (flat rate)
The open-road tolling system will employ a system of 42 gantries to electronically collect toll fees for each section of toll road traversed. The charge levied against users' accounts at each gantry is proportional to the length of the section; toll charges will thus closely approximate the actual kilometres travelled on the freeway. The distribution of toll costs is thus modelled using the VKT and toll rate per user group i:

$$\%Cost_i = \left.(d_i * t_i)\middle/\sum_{j \in \bar{I}}(d_j * t_j)\right. \quad \forall i \in \bar{I} \ldots (4)$$

where d_i = aggregate distance travelled on freeway by all users in group $i \in \bar{I}$,
      t_i = toll rate (Rands per kilometre) for user group $i \in \bar{I}$.

The published toll rates of R0.30 (light vehicles), R0.75 (non-articulated trucks), and R1.50 (other trucks) were used to estimate toll costs per group.

Toll by freeway VKT (with regular user discount)
But the toll charge is not simply distance-based. The road authority acknowledged that past spatial policies imposed unnecessarily long daily commutes on some low-income workers, potentially causing unaffordably high toll burdens. It thus offers a regular user discount: above a certain monthly threshold tolls are discounted by 15%, and the monthly toll bill is capped at R550 per vehicle. This discount only applies to private vehicles, and not to trucks.

The 3-day GPS tracks allow us to identify regular or high-VKT individuals more effectively than would a single-day snapshot, as it reflects day-to-day variations. Extrapolating the 3-day freeway VKT to a monthly amount, we found that about 18% of private motorists would receive some regular-user discount, and that 8% of drivers would reach the R550 monthly cap; most of them fall in the highest income bracket.

Toll by freeway VKT (with time-of-day discount)
Time-of-day discounts in urban toll systems reflect users' higher price elasticities during off-peak periods, and can also function as a congestion charge to reduce peak volumes. In the Gauteng case,

discounts of 5-10% are offered to all vehicles in the off-peak periods (5-6AM, 10AM-2PM, 6-9PM), and 25% at night. These discounts were applied to the calculated toll charges of existing freeway users, taking the time of each trip (as obtained from the GPS tracks) into account.

Area-wide fuel tax
As an alternative cost recovery method, a constant surcharge can be added to the fuel price payable by all vehicles in the province. As long as the per-litre surcharge is constant for all vehicles, the proportional distribution of taxes paid across the population is identical to the distribution of fuel consumed, and is independent of the actual level of the tax surcharge. (A discrepancy might occur if fuel taxes are not the same for diesel and petrol, as commercial vehicles tend to use diesel more. In South Africa the price of diesel and petrol is state regulated and very similar, rendering any such discrepancy insignificant). It is not relevant here that the tax alternative would lower the *overall* burden of payment across all users relative to the toll option, by avoiding the relatively high costs associated with the collection and enforcement of network wide electronic tolls.

The distribution of revenues is modelled using the fuel consumption for all travel by all vehicles in group $i \in \bar{I}$:

$$\%Cost_i = {c_i}\Big/{\sum_{j \in \bar{I}} c_j} \qquad \forall i \in \bar{I} \dots (5)$$

where c_i = aggregate fuel consumed by all vehicles in group $i \in \bar{I}$.

The fuel consumption was estimated for each vehicle in the GPS sample, taking into account the vehicle's type, engine size, and fuel economy (from published rates for the South African fleet). As fuel consumption is also dependent on the speed of travel (both very low and very high speeds raise fuel consumption), it varies according to the type of road used and the time of day. We used data on segment speeds from the GPS tracks to estimate fuel consumption at a disaggregate (link) level, before aggregating it up to arrive at total fuel consumption per user group. Venter and Joubert (*7*) describe this procedure in more detail.

For commercial vehicles, we used the class of vehicle (rigid versus articulated) and average rates provided from industry sources to estimate fuel consumption.

RESULTS: EQUITY IMPACTS OF ALTERNATIVE FREEWAY FUNDING OPTIONS

Benefits
Table 1 contains the results of the distributional analyses.

The second column shows that about 93% of the VKT on the upgraded network comes from private car users. Medium and high-income drivers travel the majority of these kilometres. This is explained by two aspects of the travel behaviour of South African drivers. Firstly, as one would expect, medium and high-income drivers travel more kilometres in a day than lower-income drivers, as shown in Figure 2. Secondly, high-income drivers make much more use of freeways, with the highest income groups travelling 43% of daily kilometres on freeways as opposed to only 18% for lower income groups. This is most likely related to the fact that the freeway network is located to serve the commuting needs of higher income drivers better than those of lower income neighborhoods, for historical settlement and road development reasons.

Commercial vehicles contribute about 7% of freeway VKT. Trucks have much longer daily trips than private vehicles. Intra-provincial commercial vehicles make more use of arterial roads and local streets than inter-provincial vehicles, while the latter shows much higher VKT on the freeway network, consistent with the long-haul nature of their trips.

When looking at the speed-adjusted VKT in Table 1, reflecting the speed benefit enjoyed by each class of user, the benefit is distributed very similarly to the simple VKT measure. This suggests that the

benefit of the traffic capacity upgrade accrues evenly across user groups. This is despite the fact that higher-income drivers travel disproportionately more during peak periods – when the congestion relief might be expected to be highest – while low-income drivers make more use of shoulder and off-peak periods (Table 2). Clearly not just the temporal but also the spatial distribution of freeway use plays a role here: freeways used by higher income drivers in peak periods were originally less congested than those used by lower income drivers, eroding the per-trip travel time benefit received by high-income users.

Inter-provincial heavy vehicles gain slightly in terms of speed improvement, indicating that they used more-heavily congested freeways before the upgrade. Commercial vehicles in general, as illustrated in Figure 3, are more active during the off-peak periods than private cars.

The pavement-adjusted VKT benefit measure, correcting for the amount of pavement damage caused by heavy vehicles, skews benefit entirely towards heavy vehicles, especially interprovincial trucks which tend to use larger, more heavily loaded vehicles (Table 1). This is not unexpected, as light vehicles contribute very little to pavement damage. The latter two metrics both need to inform an equitable cost recovery mechanism. Heavy vehicles use both traffic capacity and pavement capacity, and should thus contribute more than the 8.4% of revenue indicated by its share of speed-adjusted benefit.

Costs: Electronic tolling
How do these benefits compare to the distribution of toll costs under electronic tolling? Using the base toll before discounts (Table 1), we estimate that the toll scheme undercharges private vehicles and overcharges trucks, compared to the percentage of VKT each travels on the tolled network. Commercial vehicles, while responsible for 6% of VKT, would contribute almost 20% of revenues. This is consistent with the additional pavement damage caused by heavy vehicles, although far less than the 99% of pavement damage actually caused by them.

Regular user discount has little impact on equity. As it only applies to private vehicles, the toll burden is shifted slightly towards commercial operators. But so few drivers qualify for the discount that it has no significant effect on the distribution of costs across income groups. Regular-user caps and discounts might be a useful way to reduce political resistance and to avoid imposing excessive costs on some users, without affecting toll revenues and equity substantially.

Lastly, the off-peak and nighttime discounts apply to all users, private and commercial. Their benefits are seen to accrue much more to commercial than to private vehicles: revenue from commercial vehicles drops from 20% to 6% of the total (Table 1). This is consistent with trucks' greater proportional use of freeways in off-peak than peak periods (Figure 3). In fact, the time-of-day discount results in a cost distribution that is almost identical to the unadjusted VKT distribution across user groups, thus eroding the pavement damage-related premium built into the base rate for commercial vehicles.

Costs: Area-wide fuel tax
The results in Table 1 show that drivers in the lowest income category will be disproportionately burdened, if the tax revenues solely pay for upgrading freeways: while contributing 13% of freeway VKT, low-income drivers would contribute almost 20% of payments. This is in line with the literature generally finding fuel taxes to be more regressive with respect to income than distance-based charging. Low income drivers are least likely to use freeways, so would be cross-subsidizing higher income, freeway-using drivers. Commercial vehicles, having low fuel efficiency, will also pay more than their share of freeway VKT, but this can be justified using pavement damage arguments.

All other private car users would pay less than their share of VKT, with drivers in the highest income bracket enjoying the greatest degree of undercharging. This is somewhat surprising, as richer drivers in the sample drive larger vehicles with lower fuel efficiency: the average vehicle engine size among high-income drivers in the sample is 2000cc, compared to 1600cc for other groups. High income drivers also tend to travel more in the peak (when congestion reduces fuel efficiency). This is off-set by their greater use of fuel-saving freeways (which, with average speeds of about 90 km/h, flow twice as fast as arterials and local streets). The implication is that a ringfenced fuel tax mechanism would doubly penalize low-income drivers: not only do they pay more taxes by driving older, less fuel efficient models

on generally more congested streets, but their taxes go towards upgrading freeways that reduce fuel consumption and fuel tax revenues for richer drivers.

CONCLUSIONS

The paper describes a method for assessing the equity impacts of large scale electronic freeway tolling using GPS data of travel patterns. The analysis is novel as it includes both private and commercial user groups. Whereas heavy vehicles are often omitted from equity analyses, the results show that their inclusion adds significant new insights regarding equity.

Despite comprising a small proportion of total traffic, heavy vehicles are significant beneficiaries of freeway upgrades through their ability to use the structural capacity to transport commercial loads – a fact that should be reflected in the allocation of user charges across private and commercial users. This allocation affects equity, though, especially if – as we show for the Gauteng case – freeway usage patterns of commercial vehicles differ from those of private users, and a higher proportion of discounts are inadvertently captured by commercial vehicles. The findings suggest that commercial vehicles should be given much stronger consideration in equity analyses in future. Unfortunately the sophistication with which commercial vehicles are modeled traditionally has lagged that of private and public transport. One assignable cause often cited is the sensitivity of information. We hope that the equity impact shown in this paper will contribute to motivate industry to be more forthcoming with data related to the flow of vehicles, and commodities, so as to improve our understanding of the overall movement of commercial vehicles. This is particularly important in South Africa as the majority of logistics service provider contracts stipulate that all regulatory cost increases, of which toll is one, can be directly passed on to the customer. One implication is that price increases of consumer goods and produce, which will be born by the citizens and impact affordability further, can not currently be taken into account is evaluating equity impacts.

Methodologically we demonstrate the feasibility and usefulness of using GPS data from multiple sources to derive measures of driving activity that are needed for equity analyses. Benefits of GPS data, specifically suited to equity analysis of road pricing schemes, include the accuracy with which routes, timing of travel, and travel speeds can be identified, as well as the ability to use multi-day data to identify regular or high-mileage users with greater accuracy than what would be obtainable from standard travel surveys. While not replacing the use of standard transport models for deriving such measures, GPS data might significantly enhance their scope and validity.

The analysis compares the distribution of costs and benefits of freeway tolling with that of a fuel tax surcharge, levied on all travel in the province but hypothecated to the freeway program. In line with findings in the literature, the fuel tax is found to be more regressive (in terms of income) than electronic tolling: lowest-income users pay 20% of taxes while contributing only 13% of freeway kilometers. Drivers in the highest income bracket pay 18% of taxes while contributing 23% of freeway kilometers. GPS tracking data showed that two factors account for this: lower-income drivers make less use of freeways than higher income drivers; and lower-income drivers tend to consume more fuel per kilometer of travel through their greater use of slow, more congested roads (streets and arterials).

However, fuel taxation is progressive with respect to vehicle class: heavy commercial vehicles as a class, being far less fuel efficient than light vehicles, contribute a greater share of tax revenue than their share of freeway usage demands. This higher charge might be justified, however, if pavement damage is taken into account, as trucks contribute far more to pavement damage than do light vehicles.

Is electronic tolling necessarily less regressive than hypothecated fuel taxes? The answer depends heavily on how tolls, and especially discounts, are structured. When tolls are related simply to vehicle class, and commercial vehicles are charged at a higher per-kilometer rate than light vehicles, tolls are progressive. All private users pay less than their share of freeway use and time-saving benefits captured, in line with the higher structural capacity benefit enjoyed by commercial users. However, when time-of-day discounts are applied, charging between 5% and 30% less for off-peak and nighttime travel, benefits

are skewed significantly in favor of commercial vehicles, which travel more frequently in discounted periods than do private commuters. Some of these savings in logistics costs might be passed back to consumers, but the potential for cross-subsidization of commercial operators by private users needs further investigation. It is possible that discounts, a potentially effective tool for correcting equity imbalances, might reduce, rather than enhance, an equitable distribution of costs relative to benefits. If nothing else this study demonstrates the care with which discounts should be designed and applied.

In terms of how equity relates to the politics of road pricing, this study is also instructive. Equity issues feature strongly in public debates around the Gauteng e-tolling, and are clearly a powerful political concern in this unequal society. Yet the reality of equity impacts actually contradicts the claims of opponents to electronic tolling: hypothecated fuel taxes, proposed by them as an alternative freeway funding mechanism, are clearly more regressive than tolling. Public arguments and actual accounting of winners and losers do not match.

Advances in electronic tolling technology, coupled with the need for better highway funding mechanisms, might see more applications of large-scale network pricing worldwide. Pricing schemes might increasingly adopt a mix-and-match approach, combining features from facility-specific tolling, congestion charging, and distance-based pricing to suit local objectives and conditions. The equity implications of these schemes are likely to grow in importance, warranting development of better analysis tools and better means of communicating their findings to the public.

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List of captions

FIGURE 1

FIGURE 2

FIGURE 3

TABLE 1

User group	Distribution of user benefit			Distribution of user payment			
	All VKT on freeways	Speed-adjusted VKT	Pavement damage-adjusted VKT	Toll by veh-km (flat rate)	Toll by veh-km (with regular user discount)	Toll by veh-km (with off-peak discount)	Area-wide fuel tax
Private car users							
Income[1] up to R6,000	12.7%	13.1%	0.03%	11.0%	10.4%	12.7%	19.2%
R6,001 to R11,000	13.9%	13.2%	0.03%	11.9%	11.7%	13.8%	12.8%
R11,001 to R20,000	25.5%	24.8%	0.06%	22.0%	22.0%	25.8%	23.0%
R20,001 and up	23.2%	23.0%	0.05%	20.0%	18.5%	23.3%	17.9%
Refuse/Did not know	18.1%	17.6%	0.04%	15.6%	16.3%	18.1%	16.2%
ALL CAR USERS	93.3%	91.6%	0.22%	80.5%	78.9%	93.7%	89.0%
Commercial vehicles							
Intra-provincial heavy vehicles	2.2%	2.8%	32.74%	6.4%	6.9%	2.1%	4.9%
Inter-provincial heavy vehicles	4.5%	5.6%	67.04%	13.1%	14.2%	4.2%	6.1%
ALL COMMERCIAL VEHICLES	6.7%	8.4%	99.78%	19.5%	21.1%	6.3%	11.0%
TOTAL: All vehicles	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Notes:
1 Personal monthly income reported in GPS survey. An exchange rate of R10.00 per US Dollar can be used to convert from South African Rand

TABLE 2

	AM and PM peaks (6-10AM, 2-6PM)	Off-peak (5-6AM, 10AM-2PM, 6-9PM)	Night (9PM-5AM)	TOTAL
Private car users				
Income[1] up to R6,000	47%	39%	14%	100%
R6,001 to R11,000	54%	35%	11%	100%
R11,001 to R20,000	61%	34%	5%	100%
R20,001 and up	59%	35%	6%	100%
Refuse/Did not know	52%	42%	6%	100%
Commercial vehicles				
Intra-provincial heavy vehicles	50%	43%	6%	100%
Inter-provincial heavy vehicles	50%	43%	6%	100%

Notes: 1 Personal monthly income reported in GPS survey. An exchange rate of R10.00 per US Dollar can be used to convert from South African Rand