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How much to pay for a track and trace system: a simulation model for South Africa

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ABSTRACT

Background The illicit trade in tobacco reduces the effectiveness of tobacco-control policies. Independent track and trace (T&T) systems are considered one of the most effective measures available to reduce the illicit tobacco trade. South Africa, with an illicit trade estimated at over 35% of the total market, is yet to implement a T&T system.

Methods An Excel-based simulation model is used to determine the break-even T&T marker cost per pack. At the break-even cost per pack, the government would recover all costs associated with implementing T&T by collecting additional revenues. We conduct a scenario analysis to provide a range of break-even marker costs.

Findings A marker cost of between R2.68 (US\$0.17) and R5.24 (US\$0.34) per pack allows the South African government to collect enough additional revenue to recover all costs associated with T&T. Implementing such a system would reduce cigarette consumption by between 5% and 11.5%. Given that comparable systems cost significantly less than this range (roughly US\$0.02 per pack), the government would in all likelihood be able to implement a system at a cost below the break-even rate, thus generating additional revenue.

Conclusion The break-even simulation model provides a practical tool for the government to plan the implementation of T&T and to set up an evaluation criteria for the T&T tender process. The simulations illustrate that implementing T&T in South Africa would both reduce consumption (licit and illicit) and generate additional revenue. With some modifications, the model can be applied to other countries as well.

INTRODUCTION

The illicit trade in tobacco products undermines the effectiveness of tobacco-control policies and public health because it is a source of cheap cigarettes and/or defies the restrictions imposed on legal supply channels.¹ The illicit trade in tobacco has also been linked to high levels of corruption and networks of organised crime.² Even though the legitimate tobacco industry has been shown to be involved in the illicit trade, it uses the threat of this trade to lobby against tobacco-tax increases.¹ To address the illicit trade issue, the parties to the Framework Convention on Tobacco Control adopted the Protocol to Eliminate Illicit Trade in Tobacco Products (the Protocol) that, as of August 2022, had 65 parties.³

The Protocol requires all parties to implement an independent track and trace (T&T) system. A T&T system is a technological system designed to secure the supply chain for cigarettes (and other products). It relies on marking all products with a

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ According to commercial reports, track and trace (T&T) systems are cost effective. However, governments are often reluctant to implement T&T based on concerns about the cost of these systems. As far as we know, no study has compared the cost of T&T to the potential revenue that would be generated as a result of implementing a T&T system, hence determining the cost-effectiveness of the tool.

WHAT THIS STUDY ADDS

⇒ The study is the first to provide a per-pack cost of a T&T system that would allow the South African government to recover all costs associated with such a system. The simulation illustrates that governments do not need to be concerned about paying for a top-of-the-art T&T system because of the high return on the investment.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ By illustrating that T&T is a cost-effective solution for controlling illicit cigarette trade, the study aims to encourage the South African government to implement a T&T system. The model provides assistance with the T&T procurement process by estimating the maximum costs of the system per pack. Similar models can be created for other countries with sufficient data.

secure, non-replicable identifier that allows them to be traced back to any member of the supply chain and to be tracked along the distribution channel. Implementing an effective T&T system would significantly reduce the presence of illicit cigarettes in the market, would help government collect the excise tax revenue that is owed to them, as well as disrupt the criminal networks and systems of corruption that work hand in hand with the illicit tobacco trade.

South Africa became a signatory to the Protocol in January 2013 but has not yet ratified it. The government organised a tender for T&T implementation in April 2019. This move was probably motivated by concerns about the scale of the illicit cigarette market, as reported by the media and academic studies.^{4–7} Despite this positive intention, the tender deadline was extended several times and eventually cancelled in 2020.⁸ Evidence suggests that tobacco industry interference was a major cause of this.⁹ As a result, South Africa is still exposed to



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a significant unaddressed illicit trade in tobacco, which greatly undermines public health and tax revenue collection.

This paper uses a simulation model to argue for the implementation of T&T in the South African cigarette market. While South Africa is the focus of this paper, with the appropriate data, the model can be adapted to other countries. The premise of the model is that while T&T systems incur costs for implementation, they also generate additional revenue by diverting illicit cigarettes into the legal, taxed market. Therefore, there will be a T&T price at which the cost of T&T will be equal to the additional revenue generated by the newly taxed cigarettes, known as the break-even cost. We estimate the break-even point for South Africa, that is, the price of a T&T marker (eg, tax stamp) that sets additional revenue from T&T equal to the total cost of setting up and operating T&T. At this price, the government fully recovers its T&T expenses through additional tax revenue. If the price of the T&T system is below the break-even point, implementing it will increase government revenue.

METHODS

We develop a three-stage, Excel-based simulation model for South Africa. This model is flexible and could be customised for other countries. While the Protocol allows governments to require the tobacco industry to cover the costs associated with T&T, in this model, we assume that the government covers the entire cost of T&T. The benefit of this is twofold: (1) we simulate the highest possible cost that the government might face when implementing T&T, yet still provide a break-even point; and (2) this assumption is fitting in many contexts, as involving the tobacco industry in implementing T&T could create opportunities for them to delay implementation or have a say in the T&T system selection, which could compromise the effectiveness of the operation.

The first stage of the model describes the cigarette market prior to the implementation of T&T, called the baseline scenario. The key inputs for this stage are the size of the legal market, the market structure (segments, eg, premium and economy), the relative share of each market segment, the approximate size of the illicit market, the cigarette tax system (rates and structure), and the average price for legal (by market segment) and illegal cigarettes.

The second stage of the model simulates changes in prices and consumption as a result of the deployment of T&T. The key assumption is that T&T causes some portion of the baseline illegal sales to move into the legal market, therefore increasing the tax base and the associated government revenues. At this stage, the model also accounts for changes in consumption due to possible price increases. For simplicity, we assume that the tax level and structure remain unchanged, so that all simulated changes can be fully attributed to T&T implementation. We assume that the price of illegal cigarettes will increase because T&T makes the illegal trade more risky and costly due to a greater risk of apprehension and penalties if caught. We also allow for the possibility that cigarette manufacturers might change the price of legal cigarettes when a T&T system is implemented. Various studies have shown that producers of legal cigarettes are often involved in the illicit trade and that illicit products provide important revenue streams for these companies.¹⁰ Since T&T is expected to cause a major reduction in the size of the illicit market, producers may change the price of legal products as they attempt to recover revenue lost from illicit products.

The key parameters that determine the changes in the market are (1) the effectiveness of the T&T system (the proportion of

illegal cigarettes captured by T&T), (2) the extent to which the tobacco industry changes retail prices (legal and illegal), and (3) price and cross-price elasticities of demand for legal and illegal cigarettes.

The effectiveness of the T&T system, λ , ranges between 0 and 1. If $\lambda=0$, T&T is ineffective and no illicit products are detected. If $\lambda=1$, T&T is 100% effective, and all illicit products are detected; the illicit market is eliminated. The value of this parameter will depend on characteristics of the tobacco market and the comprehensiveness and suitability of the T&T solution.

The second set of parameters relates to whether the tobacco industry changes prices. Little *et al*¹¹ find that the price of illicit cigarettes is roughly proportionate to the price of cheap legal cigarettes. Therefore, we assume that the illicit price is a proportion (ρ) of the price of the cheapest legal cigarettes. We define the parameter such that $0 < \rho \leq 1$; if ρ is close to 0, the illicit price is close to 0; if $\rho=1$, the illicit price is equal to the price in the cheapest legal segment. We assume that ρ increases after the introduction of T&T. This is because at its core, T&T is intended to make it more difficult for illicit trading to go unchecked; producers and vendors who continue to sell illegal cigarettes in the presence of T&T will face new and greater hurdles to continue these operations and a greater risk of prosecution. As a result, traders will seek compensation for this increased risk and for their efforts to overcome the new barriers to operate, hence the increase in the price of illegal products. Thus, because ρ changes after T&T is implemented, the illicit price proportion of the cheapest legal price is defined as ρ_{T-1} in the pre-T&T period and ρ_T in the post-T&T period, and $\rho_{T-1} < \rho_T$.

Even though T&T does not directly impact the legal market, the price of legal cigarettes may change in response to T&T as a strategic response by legitimate producers, explained previously. The parameter α indicates the proportionate change in the net-of-tax (NOT) price (which is the retail price minus all taxes), in response to T&T implementation. If $\alpha=0$, NOT goes unchanged. If $\alpha > 0$, NOT increases, and if $\alpha < 0$, NOT decreases.

The final set of input parameters describes how consumers respond to a change in price. The price elasticity of demand for cigarettes, X , quantifies how sensitive consumers in segment X are to a change in the price of X . The law of demand requires X to be negative. The price elasticity is the percentage decrease in cigarette consumption that results from a 1% increase in cigarette price.

If the market has more than one segment, we need to consider the cross-price elasticity of demand. Studies suggest that some smokers switch to cheaper cigarette brands in response to an increase in the price of their brand.^{12 13} Cross-price elasticity (YX) indicates by what percentage the consumption in segment Y changes in response to a 1% increase in the price of cigarettes sold in segment X . Since YX reflects the gains to segment X (from segment Y), it is positive. For example, assume a market has two legal segments (premium segment a and discount segment b) and an illegal segment (i). Prices are denoted with subscripts, such that $p_a > p_b > p_i$. In response to a price increase, some consumers will switch to a cheaper segment. Thus, if $ab=0.3$, for every 1% increase in the price of premium, p_a , there is a 0.3% increase in consumption in discount segment b . This 'gain' to segment b (the substitution effect) is equal to the 'loss' from segment a , and this loss is subtracted from segment a 's consumption. A similar substitution effect applies between segment b and the illegal market (i): the loss from b is equal to the gain to i . This amount is subtracted from segment b 's consumption and added to segment i , as consumers shift away from legal cigarettes and towards cheaper, illegal cigarettes.

Table 1 Baseline: price breakdown and quantity and revenue analysis

	Imported	Premium	Popular	Economy	Illicit	Total
Price breakdown (per pack of 20 cigarettes)						
Retail price	R45.00	R48.00	R40.00	R28.00	R19.60	
Taxes						
Excise	R18.78	R18.78	R18.78	R18.78	R0.00	
VAT	R5.87	R6.26	R5.22	R3.65	R0.00	
NOT price	R20.35	R22.96	R16.00	R5.57	R19.60	
Quantity and revenue analysis						
Consumption (million packs)	59	90	476	155	420	1200
Government revenue (R billion)	1.47	2.26	11.41	3.47	0.00	18.61
Excise tax revenue (R billion)	1.12	1.70	8.93	2.90	0.00	14.65
VAT revenue (R billion)	0.35	0.57	2.48	0.56	0.00	3.96
Industry revenue (R billion)	1.21	2.07	7.61	0.86	8.23	19.99
Other assumptions						
Price elasticity of demand (ϵ_x)	-0.4	-0.4	-0.6	-0.8	-0.8	
Cross-price elasticity of demand (ϵ_{yx})	-	-	0.3	0.2	0.2	
We use information on the South African tax structure to decompose each segment's retail price into excise tax, VAT and NOT price. NOT, net-of-tax.						

The final stage of the model calculates the new levels of consumption and government revenue, based on the changes in the legal and illegal markets following T&T implementation. At this point, the model uses Excel's preprogrammed 'goal seek' function to calculate a T&T marker price such that total additional government revenue is equal to the total cost of the T&T system. This is the break-even price of a marker, that is, the cost per pack that allows governments to implement T&T without incurring additional costs.

The step-by-step mechanics of the model are described in online supplemental appendix A.

RESULTS

Table 1 presents the South African cigarette market in the baseline. We assume that there are four legal segments (imported, premium, popular and economy) and an illicit segment. The baseline is an approximate average of the experiences of 2018, 2019 and 2021. We excluded 2020 because cigarette sales were banned for 20 weeks in that year, and the market was highly distorted. The estimates of the size of the legal cigarette market in those 3 years were derived from the government's national budget data.¹⁴ The market share and average price for each segment are based on retail data and Euromonitor data.^{15 16} While these estimates are subject to error, they are not crucial for the workings and outcomes of the model.

Academic studies indicate that illicit trade made up 30%–35% of South Africa's total cigarette market in this period.^{4–6} The illicit market share may have increased following the cigarette sales ban in 2020.¹⁷ For our simulation, we assume that illicit trade is 35% of the total market. We estimate that the average price of an illicit pack is R19.60, which is 70% of the average price of the cheapest legal pack (R28.00 per pack).

The revenues collected by the government and tobacco industry (defined as including both legal and illegal traders) are determined by multiplying each price element by consumption in the relevant market segment. Aggregates are easily calculated thereafter.

The model's assumptions are detailed in **table 2**. In this scenario, we assume that T&T is 60% effective ($\lambda=0.6$); that is, T&T captures 60% of the baseline illicit market *plus* the additional group of consumers who might have switched from the

legal market (because of a possible change in the price of the discount segment that coincides with the introduction of T&T). The illicit price is assumed to be 70% of the economy price pre-T&T (ie, $\rho=0.7$) and 80% post-T&T. We assume that the NOT price of legal cigarettes remains unchanged ($\alpha=0$).

For simplicity, we assume no tax or other policy changes; thus, all estimated market changes are attributed to T&T.

Since we assume that the legal industry does not change the NOT price in response to T&T, only the illicit price changes. The illicit price increases from R19.60 to R22.40 per pack because ρ increases. We calculate that in this scenario, a T&T marker cost of R4.02 per pack results in additional government revenue of R3.82 billion (**table 3**), which is equal to the total cost of T&T, also R3.82 billion (R4.02×950 million packs). Therefore, the government breaks even.

Table 3 shows the estimated changes to the price breakdown, as well as the quantity sold and the revenue after T&T.

Total consumption decreases by 99 million packs, whereas legal consumption increases by 170 million packs. The illicit market decreases from 420 million packs in the baseline to 151 million packs after T&T (a 269 million pack reduction). This change can be decomposed into various effects, which are laid out in **table 4**.

We first consider the price effect. As was motivated in the Methods section, we assume that the price of illicit cigarettes increases after T&T because traders who continue to sell illegal cigarettes face greater hurdles to continue their illicit operations and a greater risk of prosecution and will increase their prices to be compensated for this. Because of this price increase, we expect illicit consumption to decrease by 43 million packs to 377 million illicit packs. This price effect is an indirect outcome

Table 2 Model input assumptions

T&T effectiveness (λ)	0.6
Industry response	
Pre-T&T illicit price proportion of economy price (ρ_{T-1})	0.7
Post-T&T illicit price proportion of economy price (ρ_T)	0.8
% increase in NOT price for legal segments (α)	0
NOT, net-of-tax; T&T, track and trace.	

Table 3 Quantity and revenue before (baseline) and after T&T

Quantity and revenue	Baseline			Post-T&T			Change		
	Total	Legal	Illicit	Total	Legal	Illicit	Total	Legal	Illicit
Consumption (million packs)	1200	780	420	1101	950	151	-99	170	-269
Gov revenue (R billion)	18.61	18.61	-	22.43	22.43	-	3.82	3.82	-
Specific (R billion)	14.65	14.65	-	17.85	17.85	-	3.20	3.20	-
VAT (R billion)	3.96	3.96	-	4.58	4.58	-	0.62	0.62	-
T&T cost (R billion)	-	-	-	3.82	3.82	-	-	-	-
Industry revenue (R billion)	19.99	11.76	8.23	16.09	12.71	3.38	-3.90	0.95	-4.85

Consumption indicates consumption once all substitution has occurred (within and across segments). The additional revenue and total cost of T&T are both highlighted, as these values are equal to each other by definition of the model (break-even).
T&T, track and trace.

of T&T, as it is purely a consumer response to the higher prices and not related to T&T effectively reducing illicit trade.

Second, [table 4](#) shows the direct effect of T&T on the illicit market. Of the remaining 377 million packs, 60% (226 million packs) are removed from the illicit market because they are detected due to the T&T system (T&T is assumed to be 60% effective, [table 2](#)). This leaves 151 million packs in the illicit market. The consumers who would have purchased these 226 million packs are now forced to either purchase legal packs (which are more expensive than what these consumers previously paid for illegal cigarettes) or to quit smoking/reduce consumption. Based on the price elasticity of demand of these smokers, the model estimates that 170 million packs will be diverted to the legal economy segment, while 56 million packs will be forgone because they have become too expensive.

SCENARIO ANALYSIS

The results from the preceding section assume T&T effectiveness of $\lambda=0.6$ and that legal producers do not change their prices. However, it is possible that T&T is either more or less effective than 60% or that the legal tobacco industry changes their prices in response to T&T (ie, $\alpha \neq 0$).

Between 2001 and 2015, tobacco companies in South Africa undershifted excise tax increases, with a shifting rate ranging between 0.9 (pre-2010) and 0.5 (post-2010).¹⁸ The tobacco industry absorbed some of the excise tax by reducing their own NOT price. Given the increasingly competitive cigarette market in South Africa, especially post-2010, this strategy may have been an attempt to preserve market share by lessening the impact of tax increases on prices. The tobacco industry may respond to T&T in a similar way by reducing the NOT price. Alternatively, they may increase the NOT price to increase profitability per

Table 4 Illicit market dynamics

Illicit market dynamics	Million packs
Baseline illicit trade	420
Price effect	
Reduction due to increased illicit price	-43
Illicit trade accounting for all price effects	377
T&T effects	
Previously illicit packs now detected because of T&T	226
Of which recovered due to T&T (now part of the economy segment)	-170
Of which reduced consumption due to higher prices	-56
Illicit market remaining	151
T&T, track and trace.	

pack. Either way, the industry's response, and indeed the effectiveness of the T&T system, is unknown. To account for these unknowns, we present a scenario analysis as follows.

We consider nine sets of assumptions. For T&T effectiveness, we allow for low ($\lambda=0.4$), moderate ($\lambda=0.6$) and high ($\lambda=0.8$) system effectiveness. We also vary the legal tobacco industry's response, allowing for a 10% decrease in NOT price, NOT price remaining unchanged and a 10% increase in NOT price. Note that we maintain the original assumption that the illegal price is 80% of the price in the cheapest legal segment after T&T ([table 2](#)). We include all possible variations of these assumptions, where moderate effectiveness and legal industry NOT price remaining unchanged is the same as the scenario presented in the previous section.

In cases where the NOT price—and in turn the retail price of legal cigarettes—does not change, the price elasticity for the legal segments and cross-price elasticity are of no consequence for the model. For the other scenarios, all retail prices change after T&T is implemented, and elasticities come into effect.

The price and cross-price elasticities that are applied are indicated in [table 1](#). The price elasticities are in line with estimates for South Africa and other low-income and middle-income countries.^{19 20} It has been shown that smokers of cheaper brands are more sensitive to price increases than smokers of more expensive brands.²¹ For this reason, we assume larger (absolute) price elasticities for the cheaper segments than for more expensive segments. In addition, evidence suggests that some smokers switch to cheaper brands when their brand becomes more expensive.^{12 13} We therefore assume positive cross-price elasticities for popular, economy and illicit consumers. The premium segment has no higher price category, so this segment cannot gain from cross-market substitution. Imported cigarettes are assumed to be distinct from local cigarettes; thus, we expect no cross-market substitution for this segment. We have assumed the same price and cross-price elasticities for the economy and illicit segments, since the consumers in these groups will likely have similar characteristics and represent the lowest socioeconomic group among smokers. This group is likely to be the most price sensitive, as this is a low-income group. For technical details regarding the shifts between segments and changes in consumption, see online supplemental appendix A.

In [tables 5 and 6](#) we present the outcomes for the nine scenarios: [table 5](#) shows the break-even marker cost per pack for each scenario; [table 6](#) shows the percentage change in total consumption for each scenario, when break-even is achieved.

It is clear from the results that the effectiveness of the T&T system is the key variable in determining the cost per marker; the industry strategy has only a small impact on the marker cost. For example, assuming the industry decreases NOT by 10%,

Table 5 Scenario analysis: break-even marker price

	T&T effectiveness (λ)			
	0.4	0.6	0.8	
% change in net-of-tax price (a)	-10	R3.03	R4.20	R5.24
	0	R2.85	R4.02	R5.06
	10	R2.68	R3.85	R4.89

Each number represents the marker cost per pack that allows government to break even when implementing T&T at that cost, that is, additional revenue from T&T equals total cost of T&T. The highlighted cells present the minimum and maximum break-even marker costs.
T&T, track and trace.

increasing T&T effectiveness from 40% to 80% raises the break-even marker price from R3.03 to R5.24, a 73% increase. On the other hand, if the T&T system is only 40% effective, the break-even marker price decreases from R3.03 to only R2.68 (a 12% decrease) if the industry opts to increase, rather than decrease, NOT prices by 10%.

From the nine scenarios, the break-even marker cost is estimated to be between R2.68 (US\$0.17) per pack and R5.24 (US\$0.34) per pack. Implementing T&T is assumed to result in between a 5% and 11.5% reduction in overall cigarette consumption.

DISCUSSION

Implementing an effective T&T policy represents a public health win, since T&T is expected to reduce illicit and total consumption, at no additional net cost to government.

If the government can secure a T&T system for less than the estimated R2.68–R5.24 per pack (and achieve at least a 40% T&T effectiveness), it will generate additional revenue. The estimated minimum break-even marker cost of R2.68 per pack (US\$0.17) is many times higher than the actual cost of existing T&T systems. For example, in Brazil, the estimated cost is US\$0.016 per pack,²² while in Kenya, it is US\$0.023 per pack.²³ This means that a T&T system in South Africa is very likely to generate additional revenue.

By way of illustration, assume that South Africa can secure a T&T system at a cost of US\$0.023 or R0.35 (local currency) per pack, which is the price of the Kenyan system. If the system is 60% effective ($\lambda=0.6$) and the legal industry does not change NOT prices, we estimate that the government will collect R3.82 billion in additional revenue while incurring a total cost of R333 million, thus net additional revenue is R3.49 billion per annum. Even if T&T effectiveness is low ($\lambda=0.4$) and the industry increases NOT prices, the government will make a net additional revenue of R2.04 billion (additional revenue of R2.35 billion and T&T costs of R307 million).

Table 6 Scenario analysis: percentage change in total cigarette consumption

	T&T effectiveness (λ)			
	0.4	0.6	0.8	
% Change in net-of-tax price (a)	-10	-5.0	-6.5	-7.9
	0	-6.7	-8.2	-9.8
	10	-8.3	-9.9	-11.5

Each number represents the estimated percentage change in cigarette consumption, with the corresponding break-even marker cost from table 5. The green cell represents the largest estimated reduction in consumption, while the red cell represents the smallest reduction in consumption.
T&T, track and trace.

We could also consider the lowest possible T&T effectiveness that would still result in net gains to government. Using a marker cost of R0.35 (the cost in Kenya) and assuming no change in the NOT price, we estimate that a T&T effectiveness of as little as 4.5% (ie, $\lambda=0.045$) would still generate net additional revenue for the government (government would more than cover the total cost of T&T).

The scenarios reveal that the government should be less concerned with the industry's strategic pricing response to T&T than with the effectiveness of the T&T system. A more effective system will result in higher additional revenues for the government, and larger reductions in the illicit market and overall consumption. For this reason, the government should avoid the use of T&T systems which are influenced by the tobacco industry.¹⁰ The European experience, where Philip Morris International's 'Codentify' traceability system was implemented, strongly suggests that implementing a system with connections to the tobacco industry would be generally ineffective at eradicating illicit trade.²⁴

While this paper presents a case for T&T implementation in South Africa, the model can easily be reworked to produce similar simulations for other countries that are considering T&T.

LIMITATIONS

Some input assumptions, for example, the T&T effectiveness coefficient, are not well known. Because of this, we have run multiple scenarios to provide a range of estimates for the T&T marker cost, as opposed to a single point estimate.

In this model, we have assumed that consumers can only shift between legal and illegal products, excluding the possibility of substituting to other tobacco products.

CONCLUSION

Our T&T break-even simulation model can be a tool for governments to plan the implementation of a T&T system and to set up an evaluation criterion in a T&T tender. The model provides a range of marker prices that allow government to fully recover the costs of T&T. Given our range of assumptions, the break-even marker price is between R2.68 and R5.24 per pack. Securing an effective, industry-independent T&T system for any price below this cost would allow the government to generate additional revenue. Even the lowest estimated break-even marker cost is well above the cost of existing T&T systems in comparable countries.

The simulation illustrates that implementing T&T in South Africa would be beneficial. Even if the T&T system has a relatively low effectiveness, and irrespective of the industry's response, implementing T&T will reduce illicit trade and cigarette consumption and yield additional tax revenue. If the system were more effective, the additional revenue to government and the reduction in illicit trade and consumption would be even larger.

We hope that if policy makers can see the financial and public health benefits of a T&T system, this will motivate South Africa and other countries to join the Protocol to eliminate the illicit trade in tobacco products.

Correction notice This article has been corrected since it was first published. The open access licence has been updated to CC BY.

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manuscript. KvdZ, CVW and HR reviewed, edited and revised the manuscript. KvdZ is acting as guarantor for the research.

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Appendix A

The introduction of a T&T system does not necessarily coincide with a change in cigarette prices, but the model allows for such price changes. The step-by-step mechanics of the model are as follows:

- 1) For each market segment X , the price increases from $p_{X(T-1)}$ to $p_{X(T)}$, where T is the period after T&T is implemented, and $T - 1$ is the period before T&T is implemented. The absolute difference between $p_{X(T-1)}$ and $p_{X(T)}$ will depend on ρ (the extent to which the illicit price increases relative to the cheapest legal segment price), and α (the percentage increase in the legal net-of-tax price).
- 2) For each market segment X , consumption responds to the price change in two ways:
 - i. A within-segment demand reduction as $p_{X(T)}$ increases (consumers quit or reduce daily demand). This change in consumption is dependent on the own-price elasticity of demand ε_X and is calculated as follows:

$$C_Prelim_{X(T)} = C_{X(T-1)} \times \frac{\left(1 + \varepsilon_X * \frac{(p_{X(T)} - p_{X(T-1)})}{(p_{X(T)} + p_{X(T-1)})}\right)}{\left(1 - \varepsilon_X * \frac{(p_{X(T)} - p_{X(T-1)})}{(p_{X(T)} + p_{X(T-1)})}\right)}$$

Equation 1

Where $C_Prelim_{X(T)}$ is the preliminary consumption in segment X in time T (post-T&T) and $C_{X(T-1)}$ is consumption in segment X in $T - 1$ (pre-T&T). This formula takes cognisance of the price change in segment X , but cross-segment

substitution has not yet been accounted for. Equation 1 is derived from the standard formula for the arc elasticity of demand.

- ii. As prices increase, some consumers shift to the next cheapest segment to maintain their consumption and to avoid the higher price. Consider a hypothetical market with two legal segments (premium a and discount b) and an illicit market, i . The consumption change is calculated as:

$$C_Gain_{b(T)} = C_Prelim_{b(T)} \times \left(\frac{\left(1 + \varepsilon_{ab} * \frac{(p_{a(T)} - p_{a(T-1)})}{(p_{a(T)} + p_{a(T-1)})} \right)}{\left(1 - \varepsilon_{ab} * \frac{(p_{a(T)} - p_{a(T-1)})}{(p_{a(T)} + p_{a(T-1)})} \right)} - 1 \right)$$

Equation 2

Where $C_Gain_{b(T)}$ is the gain in consumption to discount segment b from premium segment a and $p_{a(T-1)}$ and $p_{a(T)}$ are the prices in segment a before and after T&T implementation. The gain in consumption in segment b is a loss in consumption in segment a , and thus $C_Gain_{b(T)}$ needs to be subtracted from $C_Prelim_{a(T)}$. There will be a similar shift in consumption from segment b to the illicit market, i . The gain in consumption in the illicit market needs to be subtracted from $C_Prelim_{b(T)}$. This equation is derived from the standard formula for the arc cross-price elasticity of demand.

Equation 1 captures the reduction in the size of the cigarette market while Equation 2 captures shifts between the market segments (in response to relative price changes), including the shift from the cheapest legal segment into the illicit market.

In a market with multiple segments, total consumption post-T&T for the legal market segments (with the exception of the cheapest legal segment—to be discussed in point (4) below) is defined as:

$$C_{X(T)} = C_Prelim_{X(T)} + C_Gain_{X(T)} - C_Gain_{Y(T)}$$

Equation 3

Where $C_{X(T)}$ is consumption in segment X post-T&T, $C_Prelim_{X(T)}$ and $C_Gain_{X(T)}$ are defined as given in Equation 1 and Equation 2, and $C_Gain_{Y(T)}$ is the gain to the next cheapest segment (Y) from segment X . The highest-priced market segment will experience a loss equal to the gain in the next segment, but will experience no gain.

- 3) The size of the illicit market after T&T (I_T) will depend on various market shifts. First, the illicit market will reduce in size (to $C_Prelim_{i(T)}$) as a result of the increase in the illicit price. Secondly, the illicit market could increase in size if prices in the cheapest legal segment go up and some of their consumers switch to the cheaper illicit cigarettes ($C_Gain_{i(T)}$). Lastly, there will be a reduction in illicit consumption as T&T reduces the supply of illegal cigarettes, denoted as $I_{T\&T}$. These effects are summarised as follows:

$$I_T = C_Prelim_{i(T)} + C_Gain_{i(T)} - I_{T\&T}$$

Equation 4

$I_{T\&T}$ is dependent on l (the T&T effectiveness parameter), and is calculated as:

$$I_{T\&T} = \lambda (C_Prelim_{i(T)} + C_Gain_{i(T)})$$

Equation 5

Of $I_{T\&T}$ —the portion of illicit trade that is prevented by T&T—some portion will be shifted back into the legal market ($I_{T\&T_Legal}$). The remainder of $I_{T\&T}$ is effectively priced out of the market. This is because these smokers now face higher *legal* prices, and respond by either quitting or reducing daily consumption. This reduction in consumption is denoted as $I_{T\&T_Reduce}$. The breakdown of $I_{T\&T}$ into now-legal consumption and reduced consumption is as follows:

$$I_{T\&T} = I_{T\&T_Legal} + I_{T\&T_Reduce}$$

Equation 6

It is assumed that $I_{T\&T_Legal}$ is diverted into the cheapest legal segment (denoted CS), as this is the closest segment in terms of price that is available to these consumers. $I_{T\&T_Legal}$ is therefore a function of ε_i , the price elasticity of demand for illicit consumers, $p_{CS(T)}$ —the post-T&T price for the cheapest legal segment (the price these consumers will now face)—and $p_{i(T-1)}$, the pre-T&T illicit price (the price they previously faced). $I_{T\&T_Legal}$ is defined as follows:

$$I_{T\&T_Legal} = I_{T\&T} \times \frac{\left(1 + \varepsilon_i * \frac{(p_{CS(T)} - p_{i(T-1)})}{(p_{CS(T)} + p_{i(T-1)})}\right)}{\left(1 - \varepsilon_i * \frac{(p_{CS(T)} - p_{i(T-1)})}{(p_{CS(T)} + p_{i(T-1)})}\right)}$$

Equation 7

$I_{T\&T}$ is determined by Equation 5.

- 4) The cheapest legal market post-T&T, $C_{CS(T)}$ (special case of Equation 3) is therefore calculated as:

$$C_{CS(T)} = C_{Prelim_{CS(T)}} + C_{Gain_{CS(T)}} - C_{Gain_{i(T)}} + I_{T\&T_Legal}$$

Equation 8

- 5) We calculate the total revenue (from all tax sources, including excise, VAT, etc.) before and after T&T.
- 6) Lastly, we calculate the price of the T&T marker per pack, such that the additional revenue earned is equal to the total cost of the T&T system:

$$Marker = \frac{(Rev_T - Rev_{T-1})}{N_T}$$

Equation 9

Where Rev_{T-1} and Rev_T are the aggregate tax revenues from cigarettes pre- and post-T&T, $Marker$ is the T&T cost per pack and N_T is the total number of legal packs consumed in the post-T&T period. In this way, the model estimates the maximum price of a T&T solution per pack, i.e. additional tax that must be collected to cover the total cost of T&T, which is the break-even cost. Any T&T marker price lower than the break-even marker price will generate additional revenue for the government.

Appendix A

The introduction of a T&T system does not necessarily coincide with a change in cigarette prices, but the model allows for such price changes. The step-by-step mechanics of the model are as follows:

- 1) For each market segment X , the price increases from $p_{X(T-1)}$ to $p_{X(T)}$, where T is the period after T&T is implemented, and $T - 1$ is the period before T&T is implemented. The absolute difference between $p_{X(T-1)}$ and $p_{X(T)}$ will depend on ρ (the extent to which the illicit price increases relative to the cheapest legal segment price), and α (the percentage increase in the legal net-of-tax price).
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$$C_Prelim_{X(T)} = C_{X(T-1)} \times \frac{\left(1 + \varepsilon_X * \frac{(p_{X(T)} - p_{X(T-1)})}{(p_{X(T)} + p_{X(T-1)})}\right)}{\left(1 - \varepsilon_X * \frac{(p_{X(T)} - p_{X(T-1)})}{(p_{X(T)} + p_{X(T-1)})}\right)}$$

Equation 1

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substitution has not yet been accounted for. Equation 1 is derived from the standard formula for the arc elasticity of demand.

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Equation 2

Where $C_Gain_{b(T)}$ is the gain in consumption to discount segment b from premium segment a and $p_{a(T-1)}$ and $p_{a(T)}$ are the prices in segment a before and after T&T implementation. The gain in consumption in segment b is a loss in consumption in segment a , and thus $C_Gain_{b(T)}$ needs to be subtracted from $C_Prelim_{a(T)}$. There will be a similar shift in consumption from segment b to the illicit market, i . The gain in consumption in the illicit market needs to be subtracted from $C_Prelim_{b(T)}$. This equation is derived from the standard formula for the arc cross-price elasticity of demand.

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Equation 3

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$$I_{T\&T_Legal} = I_{T\&T} \times \frac{\left(1 + \varepsilon_i * \frac{(p_{CS(T)} - p_{i(T-1)})}{(p_{CS(T)} + p_{i(T-1)})}\right)}{\left(1 - \varepsilon_i * \frac{(p_{CS(T)} - p_{i(T-1)})}{(p_{CS(T)} + p_{i(T-1)})}\right)}$$

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