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Smoking Intensity, Compensatory Behavior and Tobacco Tax Policy

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Abstract

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Abstract

Smokers not only choose the number of cigarettes to smoke in any given period on the basis of price, they also choose the intensity with which to smoke - that is, how much nicotine to inhale. The possibility that quantity-reducing tax policies may be mitigated, or even completely offset, by higher intensity has been raised recently by Adda and Cornaglia (2006). The objective of this paper is to examine this possibility in the context of a utility-maximizing model of smoking that is based on known toxicological patterns. After calibrating this model to reflect observed behaviors, it is concluded that continuing smokers offset about one third of the quantity-reducing impact of higher taxes. Compensatory behavior thus reduces tax effectiveness, but does not render it neutral. While toxicology has long recognized that nicotine inventory management is a key ingredient in smoking behaviour, this paper is the first to incorporate such knowledge into a utility-price based maximizing model.

1 Introduction

All studies of the demand for cigarettes confirm that higher cigarette prices lead to a decrease in the quantity demanded. There is a degree of consensus that the aggregate price elasticity of demand is around one half, though estimates vary. Consequently governments in virtually all developed economies have used higher taxes as a means of discouraging smoking. And indeed smoking rates have fallen, sometimes dramatically, in recent decades.

However, a very recent piece of research (this *Review*, Adda & Cornaglia, 2006) suggests that smokers may be quietly "undoing" much of the impact, or health benefit, of the reduced number of cigarettes purchased and smoked. Using data for the US (primarily for the period 1988-1994) they find that smokers inhale their reduced number of cigarettes more intensively and offset most of the impact of higher taxes in the process. This finding is disturbing, because it suggests that a type of 'policy neutrality' may be at work.

The present paper argues that the economics of this problem can be developed substantially by drawing on a large existing body of literature in toxicology, and that the resultant economic model can be used to analyze a number of important policy issues - specifically the degree of intensity compensation that might be anticipated from a reduced number of cigarettes smoked, in turn caused by an increase in taxes. This is the principal objective of the paper. A behavioral approach to this issue is valuable both because the number of econometric studies is small, and because it is useful to import knowledge from other disciplines if this helps to conceptualize problems and better formulate policy. In addition the paper offers some cautions on how to interpret the econometric results of Adda and Cornaglia.

The next section of the paper explains the toxicological background; the third section builds the utility model, based on an inventory management approach, calibrates it and solves for optimal responses. The fourth section presents findings on the likely degree of intensity compensation. Section five offers some observations on Adda and Cornaglia's results, and section six concludes. To preview the findings: compensatory behaviour indeed appears to be important, but it is not sufficiently strong to generate a tax 'policy neutrality' outcome.

2 Background and some relevant literature

Researchers in toxicology and biology, and a few in economics, have for some time recognized the role played by the intensity choice in smoking. This is partly as a result of a long-running disagreemnet on the use of the descriptors 'light' and 'mild' on cigarette packages. Opponents of the use of these descriptors (mainly government regulators and health researchers) have argued, rightly, that smokers inhale not much less nicotine and toxins from an average 'light/mild' cigarette as from a 'regular' cigarette. The essential difference between a regular strength cigarette and a light one is in the porosity of the sleeve. The light variety has more perforations than the regular type and consequently allows more air to flow through the sleeve than down the tube. As a consequence, when the cigarettes are smoked by mechanical devices, the nicotine and tar values registered differ substantially between light/mild and regular. See, for example, Jarvis, Boreham *et al* 2001, Kozlowski *et al*, 1998, or US DHHS 2000.

However, human behavior offsets much of the impact of the more porous sleeve: individuals in tests are observed to cup their fingers around the sleeve/filter and so block the perforations, and to inhale for a longer period – perhaps two seconds rather than one and one half seconds. There is no longer any doubt about these practices, and it is really just a question of to what degree an individual will offset the potential reduction in toxic intake in the lighter cigarette (e.g. Hammond *et al*, 2006, or Harris, 2004).

Figure 1 below is taken from Jarvis, Boreham *et al.* On the vertical axis is the cotinine content of saliva samples taken from smokers, and on the horizontal axis is a measure of the printed nicotine strength of the corresponding cigarettes smoked. Cotinine is a metabolite of nicotine with a long half life. Nicotine has a relativerly short half life, and therefore nicotine samples are not very informative indicator of the amount of nicotine ingested during a given time period. (This relationship is developed fully in the model section below.) There are two notable aspects of this graphic. One is that the gradient increases very slowly – indicating that stronger cigarettes do not necessarily result in substantially more nicotine or cotinine in the body. Second, is the great variation among smokers in the amount of cotinine found in their system.

While smoking cigarettes more intensively yields more of a nicotine boost from a given cigarette, it has been recognized for some time by economists that smokers may also choose to switch to brands that have greater nicotine potential (this assumes that intensity compensation is less than one hundred percent) in the face of tax increases that are uniform across brand strengths. The earliest econometric work to have an impact was done by Evans and Farrelly, 1998; Farrelly and coauthors developed the ideas further in 2004, while Harris had proposed in 1980 that cigarette taxes should reflect the tar and nicotine content of cigarettes.

Understanding the intensity decision is crucial. Why does a smoker in some instances smoke a cigarette very intensively, and in other circumstances at a low level of intensity? The answer provided by the physical sciences indicates that, while more nicotine in the body gives smokers a higher level of satisfaction, nicotine is also accompanied by many nasty toxins that not only cause cancer but also short-term discomfort. Carbon monoxide is one such toxin, and high rates of inhalation result in a concentration of carbon monoxide which, in turn, leads to dizziness and nausea. Accordingly, the intensity decision involves a trade off between getting more nicotine into the system on the one hand as a result of smoking more intensively, and reducing carbon monoxide by smoking less intensively, on the other. This implies that if cigarettes have a low price, smokers should smoke a lot of them at low levels of intensity; but at higher prices they can less afford this low-yield behavior and therefore should inhale a smaller number more intensively.

Before developing a utility-maximizing that incorporates this trade-off, it is instructive to view what Adda and Cornaglia discovered when examining the relationship between cigarettes smoked and cotinine. Figure 2 below is also their figure 2, and supports the pattern in figure 1: when the number of cigarettes increases from a low range of about 7 to a higher range of around 22, cotinine increases by a much lower proportion. Again their data suggest a wide range of individual patterns, but strongly support the tendency to smoke greater numbers of cigarettes at a lower level of intensity.

3 A model of Individual Behavior

Descriptions of the impact and behavior of nicotine in the body are widespread (for example, Benowitz et al, 2002, 2004, 2005). Nicotine induces addiction by impacting specific regions in the brain. Thereafter, nicotine intake that is processed by the lungs, fed into the blood stream and transported to the brain, produces a sense of pleasure. But nicotine has a relatively short life, and so to satisfy the brain nicotine must be ingested on a regular basis. Technically, nicotine has a half life of about one hour, which is to say that half of the nicotine that is inhaled from a cigarette is metabolized (transformed) into another product, cotinine, in that time period. Cotinine is subsequently excreted from the body, at a slow rate. Thus the ability of a given quantity of ingested nicotine to satisfy the pleasure-seeking area of the brain is limited time wise.

It follows that the amount of nicotine inhaled, and exactly when it is inhaled, affects the pleasure obtained throughout a day. There is thus a dynamic associated with smoking, that is distinct from the type of dynamic developed in Becker and Murphy, 1988, who examine the impact on smoking of the possibility of becoming addicted, or the dynamic of Gruber and Koszegi, 2004, who develop a ratonale for tax policies to counter time-inconsistent planning.

3.1 The setup

To formalize this idea, suppose N units of nicotine are ingested at time t_1. Then in the subsequent time interval there is an amount $Ne^{-\delta(t-t_1)}$ of nicotine in the system at any time instant t , where δ is the known decay rate; that is, the decay rate yielding a half life of one hour. A smoker gets positive utility from this nicotine and let this be of the power form $U_p = N^\alpha$ where $\alpha < 1$. It follows that, in the interval $\{t_1, t_2\}$, utility is the integral

$$\int_{t_1}^{t_2} N_{t_i}^{\alpha} e^{-\alpha\delta(t-t_1)} dt \tag{1}$$

If an individual smokes c cigarettes per day, and inhales N units of nicotine from each, starting at instant t_1 and ending at T, then utility is given by the sum of utility in each of the c subperiods

$$U_p = \sum_{i=1..T-1} \left(\int_{t_i}^{t_{i+1}} N_{t_i}^{\alpha} e^{-\alpha\delta(t-t_i)} dt \right), \tag{2}$$

where N_t is the amount of nicotine in the system at the start of each interval. The c intervals are bounded by the $c+1$ points or instants $t_1..t_T$.

The choice of intensity N is determined both by the amount of plesure it yields throughout the day through nicotine, and by the 'up-front' disutility it generates on account of the associated nausea that, in turn, is determined by the degree of inhalation/intensity. Accordingly, defining the disutility associated with this latter impact by $U_d = N^{\phi}$, net utility from daily smoking becomes:

$$U = U_p - U_d = \sum_{i=1..T-1} \left(\int_{t_i}^{t_{i+1}} N_{t_i}^{\alpha} e^{-\alpha\delta(t-t_i)} dt \right) - cN^{\phi}, \tag{3}$$

In intuitive terms, the above states that if, for example, a smoker were to smoke one cigarette each hour, the resulting stock of nicotine in the body yields utility at each subsequent instant throughout the day, but that there is some disutility in the initial phase of each hour on account of the nauseous impact of the carbon monoxide associated with inhalation. It is this negative utility potential of high-intensity smoking that limits the intake of nicotine to a level below its maximum.

3.2 Optimization and solution algorithm

For a given set of relative prices between cigarettes and other goods, the consumer must choose the optimal number of cigarettes, the optimal spacing during the day of such cigarettes, and the optimal intensity with which to smoke them. The solution strategy is sequential: optimize on the timing of each cigarette, conditional upon a given number of cigarettes purchased; then the optimal intensity can be chosen; finally, relative prices determine the quantity of cigarettes purchased.

Formally, in terms of equation (2), the smoker first chooses the set $\{t_1, t_2..t_{T-1}\}$, conditional upon the number of cigarettes smoked. The choice of this timing vector can be separated from the choice of intensity, since the maximand can be written as:

$$Max_{\{\bar{t}_i, N;\ c\}} \quad U = N^{\alpha} \sum_{i=0..T-1} \left(\int_{t_i}^{t_{i+1}} e^{-\alpha\delta(t-t_i)} dt \right) - cN^{\phi} = N^{\alpha} V - cN^{\phi}. \tag{4}$$

Thus, total positive utility is the product of the level of nicotine intake raised to the power of α, and the utility that accrues during the day to smoking each cigarette at unit intensity $N = 1$. The unit normalization on N can be thought of as one milligram of nicotine per cigarette, a close approximation to median smoker behaviour. This program can be integrated with respect to t, and then a set of choices for the c time period boundaries t_i may be obtained from the gradient vector $\partial U_p / \partial t_i = 0$. Integrating yields

$$U = N^{\alpha} \sum_{i=0..T-1} \frac{e^{-\alpha\delta(t_{i+1}-t_i)} - 1}{-\alpha\delta} - cN^{\phi}. \tag{5}$$

Differentiating this with respect to each t_i yields conditions that are complex in the extreme. To see this, suppose an individual smokes 30 cigarettes per day. The choice of when to smoke the second or third cigarette will have consequences on the utility obtained from every subsequent cigarette - because nicotine decay is incomplete from interval to interval. Postponing the time of the next cigarette means that more nicotine is carried to all subsequent time intervals. Consequently, the choice of, say t_2, influences the utility obtained in all 30 time intervals. Accordingly, to reduce the dimensionality of the problem to manageable proportions, the search algorithm is based on an approximate set of first order conditions in making the timing choices.

Since the decay rate of nicotine is moderate, a very good numerical approximation to the full underlying first order conditions can be obtained by limiting attention to the impact of the choice of any t_i on a small number of intervals. In particular, focussing on the utility obtained in the intervals on either side of any t_i, and two further future periods, means that an approximate first order condition can be obtained by differentiating

$$Z = N^{\alpha}_{t_{i-1}} \frac{e^{-\alpha\delta(t_i - t_{i-1})} - 1}{-\alpha\delta} + N^{\alpha}_{t_i} \frac{e^{-\alpha\delta(t_{i+1} - t_i)} - 1}{-\alpha\delta} + N^{\alpha}_{t_{i+1}} \frac{e^{-\alpha\delta(t_{i+2} - t_{i+1})} - 1}{-\alpha\delta} + N^{\alpha}_{t_{i+2}} \frac{e^{-\alpha\delta(t_{i+3} - t_{i+2})} - 1}{-\alpha\delta}, \tag{6}$$

with respect to t_i, using the relations

$$N_{t_i} = N_{t_{i-1}} e^{-\delta(t_i - t_{i-1})} + N; \quad \frac{\partial N_{t_i}}{\partial t_i} = N_{t_{i-1}}(-\delta) e^{-\delta(t_i - t_{i-1})}; \quad \frac{\partial N_{t_{i+1}}}{\partial N_i} = e^{-\delta(t_{i+1} - t_i)}. \tag{7}$$

This yields, after some rearranging of terms:

$$\begin{aligned} \frac{\partial Z}{\partial t_i} &= N^{\alpha}_{t_{i-1}} e^{-\alpha\delta(t_i - t_{i-1})} \\ &\quad - N^{\alpha}_{t_i} e^{-\alpha\delta(t_{i+1} - t_i)} + \left(e^{-\alpha\delta(t_{i+1} - t_i)} - 1\right) N^{\alpha}_{t_i} N_{t_{i-1}} e^{-\delta(t_i - t_{i-1})} \\ &\quad - \left(e^{-\alpha\delta(t_{i+2} - t_{i+1})} - 1\right) N^{\alpha-1}_{t_{i+1}} N e^{-\delta(t_{i+1} - t_i)} - \left(e^{-\alpha\delta(t_{i+3} - t_{i+2})} - 1\right) N^{\alpha-1}_{t_{i+2}} N e^{-\delta(t_{i+2} - t_i)} \end{aligned} \tag{8}$$

The solution algorithm starts by allocating the cigarettes evenly over the whole day, thus determining a starting set of t_i values. The vector $\partial Z/\partial t_i$ is then computed at each such value of t_i, and the t_i that corresponds to the largest gradient is adjusted. If that gradient is negative its t_i value is reduced, if positive, the value is increased. Each time a value of t_i is modified the new value of U_p is calculated, a new gradient vector is calculated and some t_i is again adjusted. The routine stops when $dU_p < 0.001$. Since the numerical value of utility typically falls in the range $\{50, 150\}$, this criterion means that the value of the objective function is changing by less than one in one hundred thousand at the final iteration.

The smoking day is specified to lie between 7:30 am and 10:00 pm. This is broken into 145 units of 6 minutes each, on the grounds that it takes about 6 minutes to smoke a cigarette (a smoker typically inhales ten to twelve times, with 30-35 second breaks between puffs - see Hammond *et al*). The solution algorithm yields integer values for the t_i vector in the range $\{1..145\}$.

While a sufficient condition for this mechanism to attain a maximum is that the function be negative semi definite in the time choices, we cannot demonstrate that it has this property because of the complexity of the associated Hessian described above. The function will also attain a maximum if it has a unique optimum and positive first derivatives everywhere in the t_i space. While the order of the problem prevents establishing this in the general case, I have explored exact solutions to the maximand where there are a small number of intervals. In such cases the numerical solutions obtained from the solution algorithm match the analytical solutions, and the 3D images of the function indicate that it has a unique maximum.

It is straightforward to show by contradiction that the first cigarette of the day should be at the first feasible moment, regardless of the number of cigarettes smoked. To illustrate, suppose just one cigarette is smoked in the day in time period 2 and that utility accrues in the interval $\{2..145\}$. Since some small amount of nicotine remains in the body after period 145, it is clear that by shifting the smoking choice from t_2 to $t_1$will increase utility. The same argument applies to any number of cigarettes smoked. This observation has implications for the Fagerstrom test of addiction (Fagerstrom, 1978).

3.3 Optimizing on intensity

An optimal value of intensity N^* is obtained from equation (4) above:

$$\begin{aligned} \partial U/\partial N &= \alpha N^{\alpha-1}V - c\beta N^{\beta-1} = 0 \\ N^* &= V^{1/(\beta-\alpha)}\left(\frac{\alpha}{c\beta}\right)^{1/(\beta-\alpha)}. \end{aligned} \tag{9}$$

For intensity to be increasing in the number of cigarettes (and so match the stylized observations), a sufficient pair of conditions is that $\phi > \alpha$ and that the second term in equation (10) dominate (because $\frac{\delta V}{\delta c} > 0$). Conditional upon this set of functions, the observed intensity 'facts' yield tight limits on the parameters. Values in the neighbourhood of $\{\alpha = 0.3, \phi = 2.5\}$ yield intensity outcomes that fall in the observed range of 0.8 mg to 1.4 mg of nicotine per cigarette. Such values also ensure that the model predicts nicotine/cotinine levels that increase much less than in proportion to the number of cigarettes smoked. That the ϕ should be so much larger than the β value is readily intuited: disutility from nausea is specified to last for six minutes, whereas the utility from nicotine lasts several hours (though declining exponentially). The smoker is therefore trading off two impacts that have very different durations.

3.4 Prices quantities and demand functions

To this point the choices of optimal timing and intensity are conditioned on a given quantity consumed. The link between a chosen quantity and a given price can be established easily by invoking a quasi-linear utility structure:

$$W = U(c) + \theta y, \tag{10}$$

where c is the number of cigarettes, and y is other goods. Normalizing the price of y at one and defining p as the price of cigarettes the optimality condition is

$$\frac{U_c'}{p} = \theta. \tag{11}$$

Any change in price, tax-induced or otherwise, requires a new quantity of cigarettes such that marginal utility divided by price is restored to the initial value θ. A demand function is obtained as follows: Numerically, the value of utility is obtainable for any quantity of cigarettes purchased (maximizing simultaneously on timing and intensity), and a marginal utility schedule drops out of this.[1] Elasticity values follow immediately.

The utility function used here always results in some positive number of cigarettes being smoked, because the marginal utility of smoking tends to infinity as the amount of nicotine in the body becomes small. The use of continuing smokers renders the model output comparable to the results of Adda and Cornaglia. At the same time, it must be recognized that in the econometric literature, the impact of prices is normally examined through some variant of a two-step model of the type developed by Cragg, 1971, involving a participation decision followed by a conditional quantity decision (see also Jones, 2000).

[1] In fact I regress the utility values obtained in the optimization on a polynomial in c in order to get smoothness in U and differentiability for the marginal utilities.

4 Results on Intensity Compensation

Some outputs for this model are provided in figures 3, 4, and 5 for a median smoker - one who smokes 18 cigarettes per day. Figures 3 is an optimal nicotine path, figure 4 the resultant positive utility path and figure 5 the implied cotinine path. Period 75 corrersponds to 7:30 am; period 220 is sleep and end of utility; period 240 is midnight. Consider first figure 3. The pattern is of the expected inventory-management type: the smoker optimizes by boosting his stock of nicotine early in the day, maintains it a relatively smooth level, and smokes little at the end of the day. A low rate of smoking late in the day ensures that he does not 'waste' the nicotine by having too large a quantity in his blood stream at the time of sleep. Experimentation with the number of cigarettes indicates that individuals who smoke few cigarettes spread them evenly, but that heavy smokers build up their nicotine stock strongly at the start of the day[2] . Figure 4 plots the resultant utility corresponding to figure 3.

Figure 5 is the cotinine time path. Since cotinine has a half life of approximately 20 hours, the decay rate is much less than for nicotine. It thus has a 24-hour cycle (in contrast to nicotine, where the nicotine from the preceding day has metabolized before the start of the 'smoking day'), and the end-of-day value must equal the start-of-day value in a steady state. Defining the decay rate of cotinine by γ then the cotine path is defined by

$$Cot_t = Cot_{t-1}e^{-\gamma t} + \theta N_{t-1} \tag{12}$$

The cotinine scale is normalized to reflect a unit transformation of nicotine into cotinine ($\theta = 1$). The value of computing the cotinine path lies primarily in being able to assess if different smoking patterns throughout the day yield broadly similar cotinine samples for individuals who smoke differently. For example, if some individuals are subject to work-place regulations, while others are not, if they smoke the same number of cigarettes, will their cotinine samples reflect this?

[2] For example, an individual smoking 5 cigarettes has a timing pattern on the 145-unit range of $\{1, 28, 58, 88, 117\}$, while an individual smoking 30 cigarettes has a pattern of $\{1, 2, 3, 9, 15, 21, 26...136, 141\}$.

Experiments, not reported here, indicate that cotinine samples are a good indicator of total nicotine ingested, even with different intake patterns - on account of the long half life of cotinine.

The principal results of this paper are contained in figures 6 and 7 and table 1. Figure 6 plots the relationship between intensity and the number of cigarettes, conditional on the parameterization adopted for the utility functions and on the half life of nicotine. The graphic indicates that individuals facing high prices, and choosing to smoke few cigarettes should inhale at a rate of 1.35 on a scale normalized at 1 for a median smoker. In contrast, at low a low price and a higher quantity, smokers may inhale as little as 0.85 units of nicotine per cigarette. Figure 7 indicates that cotinine concentrations increase at a much slower rate than the number of cigarettes. This pattern is consistent with figure 2 above. In sum, the model appears to predict well, in the sense that it replicates established patterns.

To compute the degree of compensatory behavior in response to different prices, the implicit demand function described above is tabulated in columns 1 and 2 of table 1. The quantities are derived from the marginal utility conditions, and the demand curve is anchored by assuming a price of 40 cents per cigarette for a median smoker ($q = 18$). At each quantity the model computes an optimal intensity, and this is contained in column 3. Total nicotine intake is the product of quantity and intensity and given in column 4. To the degree that the median smoker actually inhales 1 milligram of nicotine per cigarette, then these numbers can be interpreted as milligrams of nicotine in total. If compenation were 'full' or 'complete' the final column should have entries that are all more or less equal - at least for some considerable range of the values. With zero intensity compensation, the numbers in the final column should be strictly proportionate to the number smoked in column 2. In contrast to these extremes, the calibrated model produces a substantial degree of intensity compensation, though by no means full. For example, if the price increases from 33.2 cents to 43.4 cents (an increase of 27% based on an 'arc' calculation), quantity demanded falls from 22 to 16 cigarettes (a decline of 32%, calculated similarly). However nicotine intake decreases by just 21%. At this point on the demand curve therefore, the model suggests that intensity compensation offsets about one third of the quantity impact. Calculations at the less elastic segments of the demand curve (where a higher quantity is purchased) suggest that more of the quantity reduction is offset by intensity compensation.

To conclude: intensity compensation is significant, and therefore important; but it also indicates that tax policy is not neutral: higher prices reduce quantity purchased, and this in turn reduces nicotine intake.

5 Caveats on Adda and Cornaglia

5.1 Estimates are 'Local'

The initial set of estimates reported by AC in their table 2 indicate exceedingly high response elasticities on the part of smokers in both the number of cigarettes they purchase and in their intensity responses. For example the initial intensity elasticity, with respect to a 1% increase in tax lie in the range $\{0.34, 0.55\}$. To illustrate the implications, consider their first estimate of 0.47%. Since a 1% increase in tax corresponds to a 0.15% increase in price (AC footnote 8), the intensity price elasticity is therefore in excess of three ($0.47/0.15 = 3.1$). If this estimate is applicable to the present time, then it would imply that intensity of smoking should have increased by about 200% in the last decade. In table 2 below are presented data on prices and quantities for cigarettes in the US between 1997 and 2006. Prices increased by exactly two thirds. If the intensity elasticity is in the region of three, it follows that smokers should be inhaling three times as much nicotine as in 1997. This is simply not within the bounds of possibility.

By the same token the price elasticities of quantity purchased in table 2 are well in excess of unity. For example the first price elasticity, while not statistically significant, is -1.33 ($= -0.20/0.15$). And these elasticities capture only the impact of price changes on the quantity of cigarettes purchased by continuing smokers. In contrast, there is a widespread concensus in the econometric literature that elasticities capturing *both* the incidence/participation decision and the conditional quantity decision are about half of this value (Chaloupka and Warner, 2000) - implying that AC's conditional quantity elasticity is a multiple of the concensus estimates. Moreover, the only significant elasticities in this table have values of -0.49 and -0.73. If the latter were correct it would imply a conditional quantity elasticity of $-4.9 \quad (= -0.73/0.15)$. This is at least ten times the magnitude of the accepted estimates.

In fact it is easy to see that the AC results imply that *price reductions* would the most effective way to reduce nicotine intake: Using the identity that total nicotine ingested is

$$Total\ nicotine = population * smoker\ share\ of\ population * cigarettes\ per\ smoker * intensity, \tag{13}$$

and taking logs and totally differentiating with respect to price yields the result that

$$\%\Delta Total\ cotinine/\%\Delta p = \%\Delta prevalence/\%\Delta p + \%\Delta cigs/smoker/\%\Delta p + \%\Delta intensity/\%\Delta p. \tag{14}$$

Assuming that the first term is negative (AC do not estimate it), despite the accepted wisdon that the first two terms should add to about -0.5, the price elasticities in the preceding paragraph suggest that

$$\%\Delta Total\ nicotine/\%\Delta p \approx small\ neg - 1.33 + 3.1 = 1.77 + small\ neg = pos. \tag{15}$$

If a reduction in total nicotine is required, clearly the price should *fall*, reflecting an underlying positively sloped demand curve for nicotine. It would be prudent to revisit these estimates before basing actual policy on them.

It should be borne in mind that prices in the period of their first set of estimates were in the region of $1.50 per pack, whereas in 2008 *Tobaccofreekids* reported an average price in the range of $4.50. Gospodinov and Irvine (2008) have cautioned against using estimates based on prices that are a fraction of current prices in the formation of public policy. And indeed, the AC estimates in table 3, based on 1999-2000 data, are much smaller than those reported in table 2.

A further consideration in formulating policy here is that, in recent years, the US is unique in the way taxes should be interpreted: since the *Master Settlement Agreement* in November 1998 between the states and the tobacco companies, cigarette prices have increased dramatically in order to generate sufficient revenues to pay the amounts agreed under the *Settlement*. The subsequent higher prices *de facto* incorporate higher taxes under another name.

5.2 The Disutility of Intensity

The second area of disagreement with AC concerns their utility function. They specify $U = U(nicotine, intensity, other goods)$, in their equation (1): nicotine produces positive utility, intensity negative utility. If nicotine is the product of the number of cigarettes c times intensity i, then $n = c.i$. AC then rewrite U as $U = ((c.i), i, q)$. While the nicotine production function is constrained to have constant marginal products and increasing returns to scale, there is evidence that this is a reasonable local assumption (for example, Chaiton *et al*, 2005, or Hammond, Fong *et al* 2005). However, their intensity term is now playing two roles: it is both the intensity associated with *each* cigarette, and is also the variable that generates *daily* disutility, governed by the same function U. Given that the disutility is primarily attributable to the dizzyness and nausea associated with carbon monoxide intake, the amount of such disutility during the day is obviously a function of the number of cigarettes *i.e.* a function of $c.i$ rather than simply i. But once correctly specified, the utility function is not so useful because both the pleasure-yielding nicotine and disutility-yielding intensity each enter in the same fashion. In contrast, if the production function were specified in, for example, Cobb-Douglas form with known exponents then meaningful comparative results are obtainable. AC's comparative static results therefore need redevelopment.

In the model developed in this paper the tradeoff between additional nicotine produced by higher intensity and the disutility associated with that same intensity is resolved by recognizing the different time dimensions associated with each impact: the marginal utility of the addional nicotine produced lasts for several hours, while the marginal disutility effect is experienced only while the cigarette is being smoked. Nonetheless our underlying production structure is similar to AC: total nicotine is the product of the number of cigarettes and intensity.

6 Conclusions

Tobacco-smoking is reckoned to be one of the major causes of premature death in both the developed and less-developed world. It is a principal cause of premature death in perhaps 300,000 Americans each year. Understanding the impact of policies that limit tobacco use and the inhalation of cancer-causing toxins is therefore vital. The likelihood that smokers will increase their smoking intensity in response to tax-induced price increases, or tobacco bans in public places, should be accounted for in the decision to adopt deterrent policies. The overiding objective of this paper has been to draw upon the established toxicological literature with a view to understanding behaviour from an economic or incentive-driven standpoint. Developing and calibrating a theoretical model provides an alternative vehicle to econometric estimation. At the present time there is a shortage of both theory-based models and econometric modelling based on recent data.

The principal result of this paper is that while intensity is indeed likely to rise as a rational response to tax-induced price increases on the part of smokers who continue to smoke, such compensation just partially offsets the impact of price on the reduction in quantity. Our estimate of the compensatory intensity offset on a median smoker is that s/he will reduce nicotine intake by about two thirds of the percentage quantity reduction: that is, increased intensity may offset one third of the price impact on quantity. Furthermore, there is a substantial literature detailing the impact of prices on prevalence, and a significant component of the impact of taxes falls here (e.g. Chaloupka and Warner, 2000). In sum, while intensity compensation constitutes an important reaction on the part of smokers, it is not sufficient to offset the greater part of the prevalence and conditional quantity reductions brought on by tax increases. In view of the efforts in recent years of tobacco manufacturers to increase the ‘palatability’ of inhaled smoke (Hoffman and Hoffman, 1997), that is to faciltate greater intensity, tobacco policy might productively orient itself in this direction. As part of this conclusion, the results of Adda and Cornaglia should be interpreted with care: their extraordinarily high intensity elasticity estimates may have the implication that cigarettes should be subsidized rather than taxed.

The conclusion that tax policy is far from being neutral should not be interpreted to mean that indefinite price increases will reduce consumption, despite the fact that there is considerable evidence that the health costs per pack are a multiple of the current price (e.g. Gruber and Koszegi, 2004, or Viscusi and Hersch, 2007). In most of Europe and Canada cigarette prices are almost twice the US price, as of 2008. Such high prices are an invitation to illegal supply: for example, legal shipments have declined by about one third in Canada between 2005 and 2007, while consumer surveys show little change in actual use. If governments wish to reduce tobacco consumption further in the US it will be necessary to rely on a broad range of measures in addition to price increases.

Finally, since time plays a key role in the theoretical model developed here, the approach should should furnish a productive vehicle for analyzing the impact of tobacco control measures which have a time dimension - in particular, restrictions against smoking in public or work places. There is every reason to believe that such measures also increase the intensity with which cigarettes consumed outside of the restricted periods are smoked.

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Table 1. Prices and nicotine compensation			
Price/stick in cents	Daily quantity	Intensity (mg/stick)	Total nicotine intake
0.161	32	0.875	28.00
0.195	30	0.893	26.78
0.229	28	0.912	25.54
0.264	26	0.936	24.33
0.298	24	0.959	23.01
0.332	22	0.986	21.70
0.366	20	1.016	20.31
0.400	18	1.052	18.93
0.434	16	1.092	17.47
0.468	14	1.139	15.94
0.502	12	1.1960	14.36
0.536	10	1.267	12.67
0.571	8	1.36	10.88

Table 2. Real price and quantity of cigarettes sold, US, 1997-2006.		
	Cigarettes (billion)	Cigarette real price index
1997	480	100.0
1998	465	108.1
1999	435	138.5
2000	430	149.0
2001	425	156.3
2002	415	167.5
2003	400	166.1
2004	388	164.4
2005	376	167.2
2006	371	167.5

Source: Quantity: US Department of Agriculture (www.ers.usda.gov/briefing/tobacco), "The changing tobacco user's dollar". Prices from BLS, series CUUROOOOSEGA01 and CUUROOOOSA0.

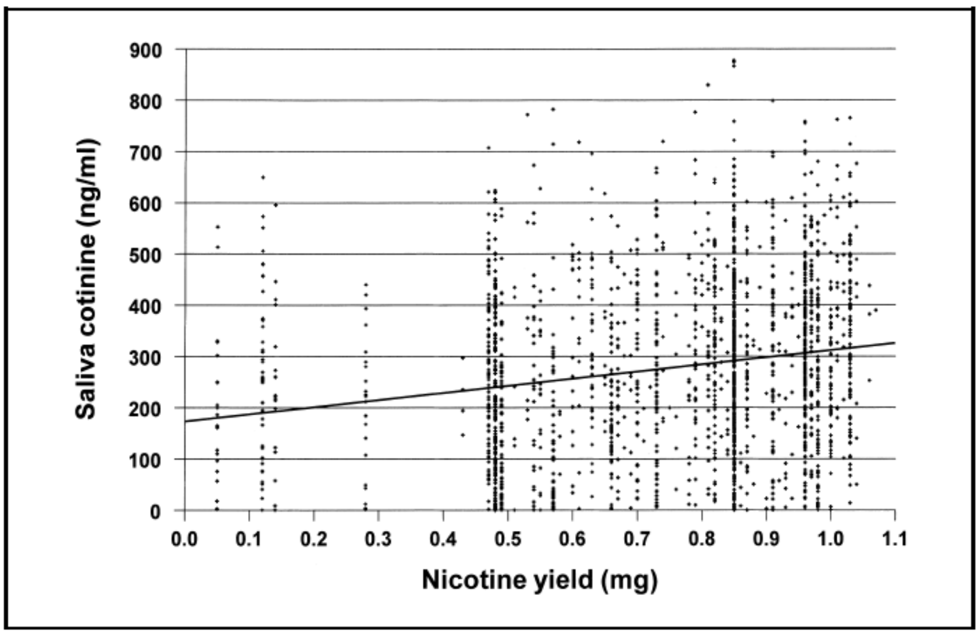

Fig. 1. Scatterplot relating cigarette nicotine yields and saliva cotinine concentrations in 2031 smokers participating in the 1998 Health Survey of England. Cotinine = 173.5 + 138.7 (nicotine yield); r = .19; r^2 = .034.

Figure 1: Source: Jarvis, Boreham *et al*, 2001.

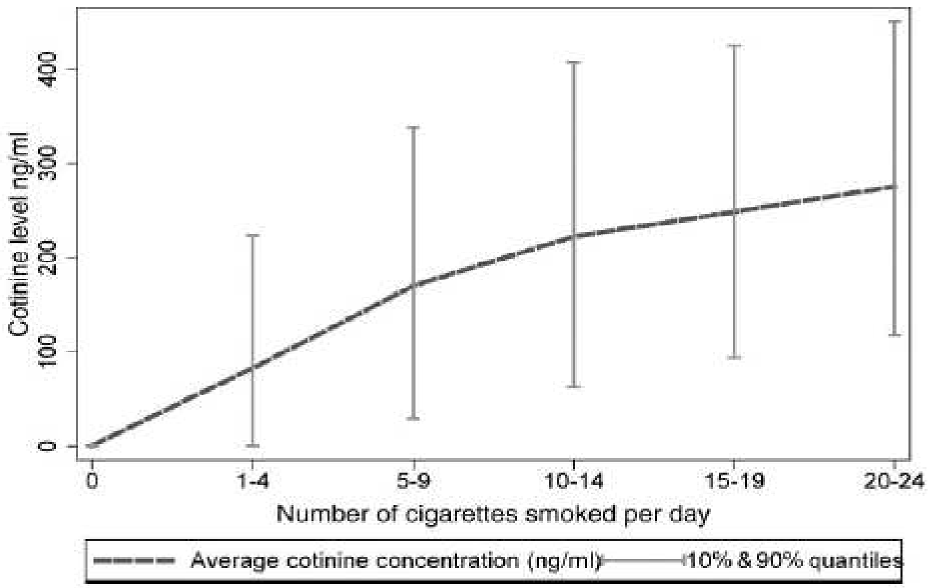

Figure 2: Source: Adda and Cornaglia, 2006

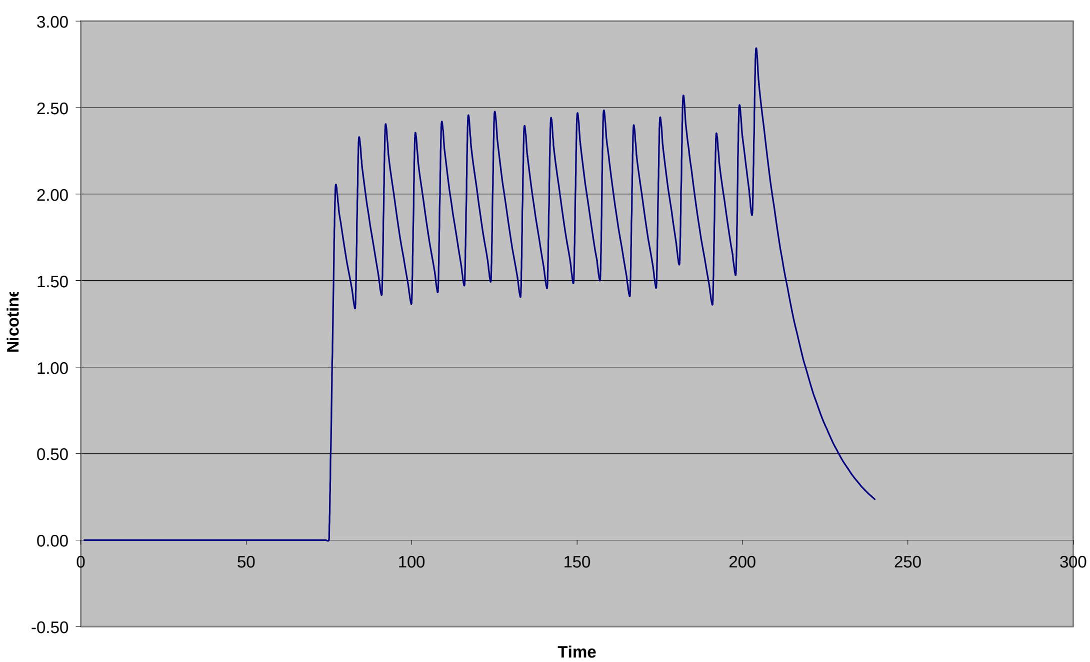

Figure 3: Optimal nicotine path for 18 cigarettes

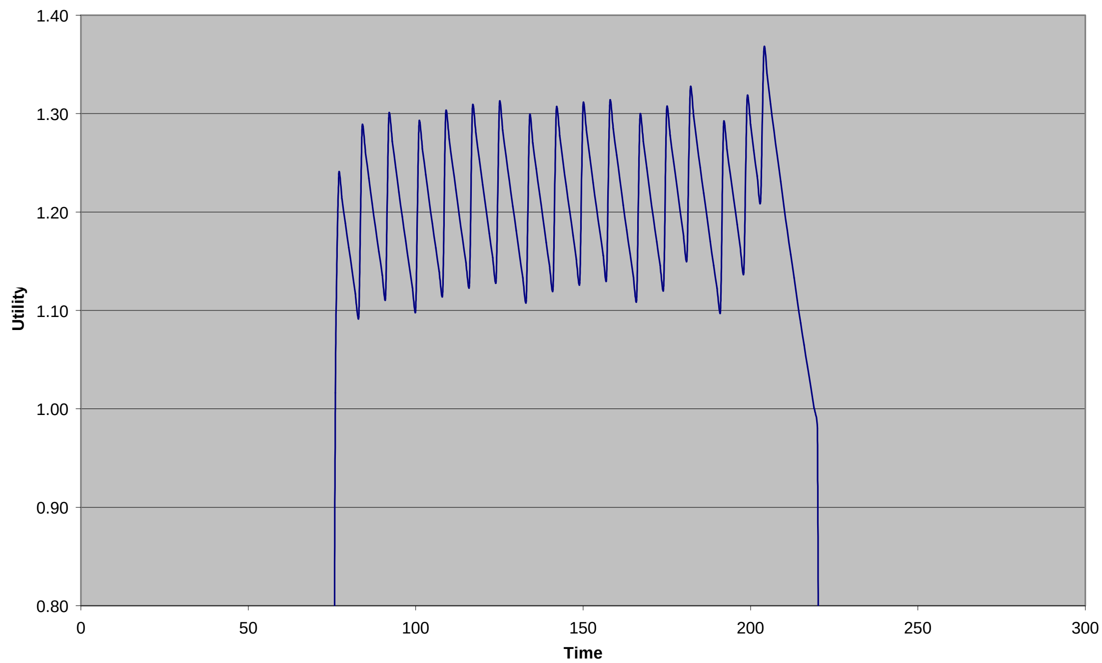

Figure 4: Optimal utility path for 18 cigarettes

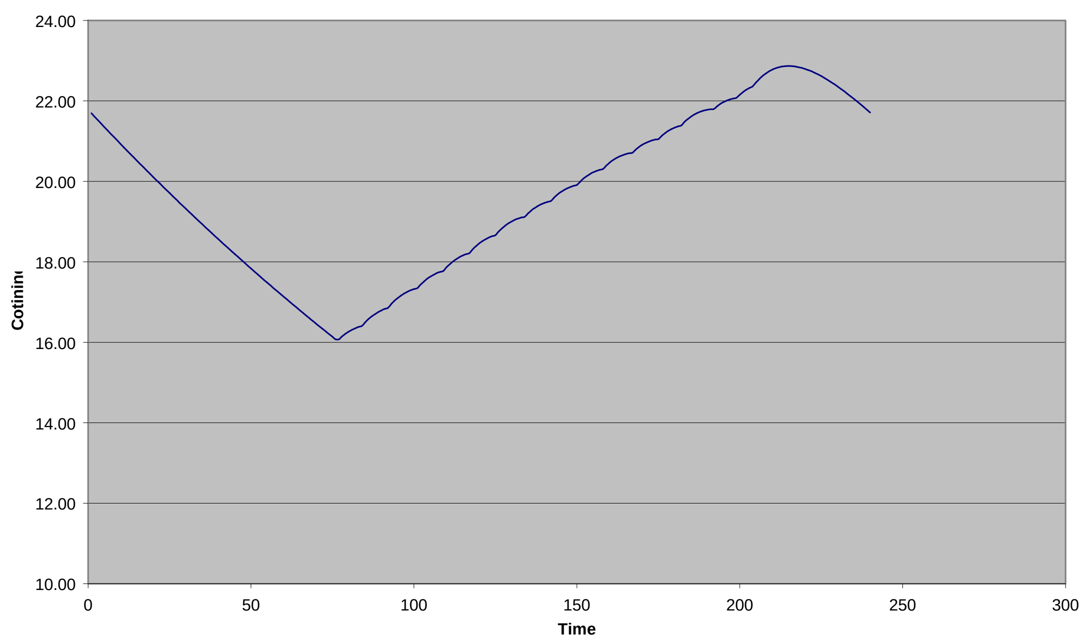

Figure 5: Cotinine path corresponding to optimal nicotine path for 18 cigarettes

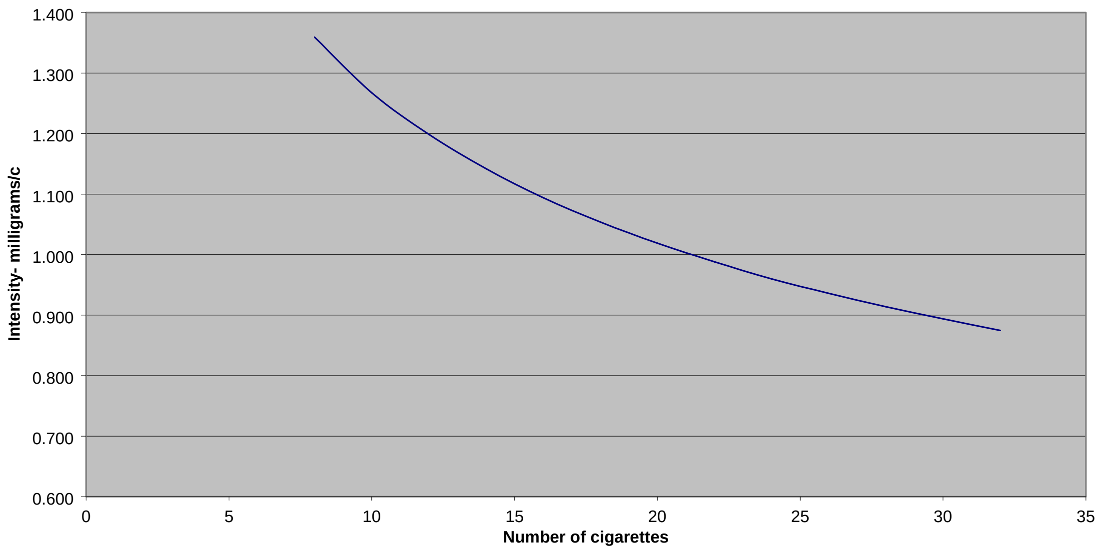

Figure 6: Optimal intensity as a function of number of cigarettes

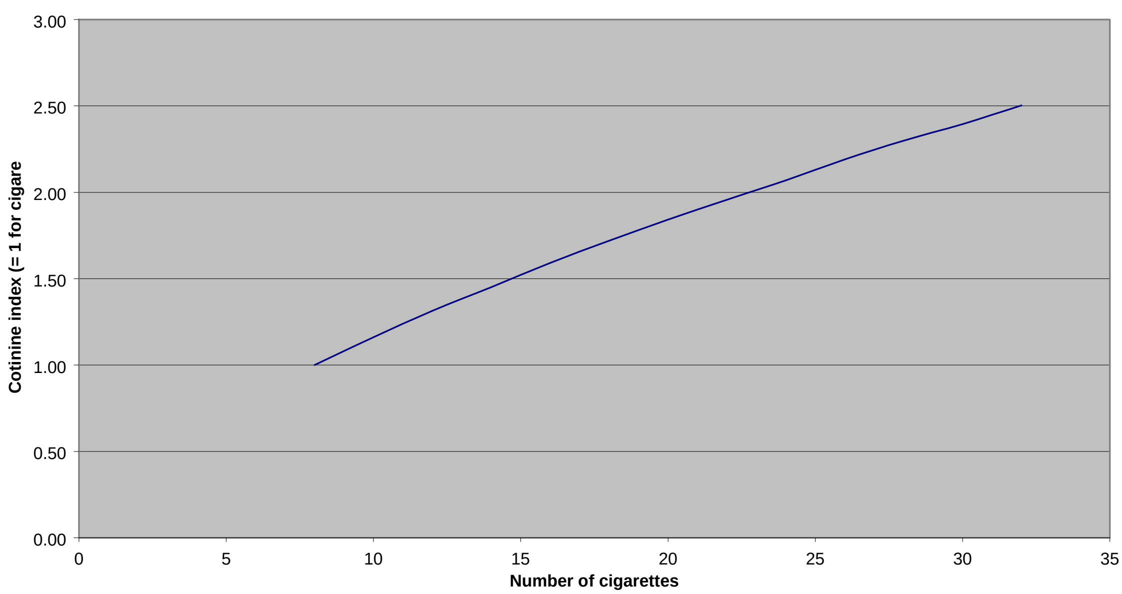

Figure 7: Cotinine as a function of number of cigarettes