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Case Study: Increasing Tobacco Price to Reduce the Burden of Chronic Diseases in Luxembourg

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1. Introduction

The taxation of tobacco products is one of the most effective interventions to reduce their consumption. The World Health Organization (WHO) and other institutions are urging countries to intensify their efforts to combat tobacco consumption through the use of taxes to increase prices, as a measure to effectively reduce the burden related to some of the most common and harmful diseases that are strongly linked to cigarette smoking.[1,2] Along similar lines, the European Commission has recently proposed overhauling the Tobacco Taxation Directive to raise minimum excise rates for tobacco, taking into account that affordability of tobacco products differs between countries with different levels of purchasing power. This would be likely to lead to a significant increase in tobacco prices in Luxembourg. The European Commission has also proposed extending taxes to include e-cigarettes, heated-tobacco and nicotine-pouch products, and to introduce stricter traceability measures to curb illicit trade and support the European Union's Beating Cancer Plan.[3,4] Similarly, the Court of Auditors of the Grand Duchy of Luxembourg have indicated that tobacco prices are very low in Luxembourg and taxes should therefore be increased to align with the health and social costs of tobacco consumption.[5,6]

As shown in the report on prevention, smoking rates in Luxembourg remain high. They also contribute to the large disease burden caused by preventable chronic diseases in the country. Further, taxes on tobacco are low in comparison to the neighbouring nations.[7] This makes cigarettes and other tobacco products very affordable for residents of Luxembourg, as well as for those in France, Belgium and Germany who live near Luxembourg and can purchase their tobacco products there.

In this section, we present results of a modelling exercise that provide evidence of the potential effects of an increase in tobacco prices on smoking prevalence and health status in the elderly resident population in Luxembourg. In particular, we used a dynamic micro-simulation model to predict how cigarette price increases would affect Luxembourg's population aged 50 years and older, over the next 45 years. In this exercise, we estimated the effect of the intervention on the prevalence of chronic respiratory diseases, cancers, cardiovascular disease, diabetes, and stroke, five diseases that are responsible for a large part of the chronic disease burden in Luxembourg and whose development has been linked to smoking.[7,8]

The study examines three scenarios, all starting in 2026 (Table 1). **Option A**, with a 10% annual price rise over 5 years (as an example, this would lead to an increase from €5.09[a] for a pack of cigarettes in Luxembourg to €8.20 after 5 years); **Option B**, with 30% in year one, then 10% per annum for the subsequent 4 years (a pack of cigarettes would increase from €5.09 to €9.69 after 5 years); and **Option C**, where the price increases by 100% in year one and then 10% per annum for the subsequent 4 years (a pack of cigarettes would increase from €5.09 to €14.90 after 5 years).

Table 1. Tobacco price increase scenarios

Scenario	Year 1 Increase	Year 2-5 Increase	Starting Price	Final Price (Year 5)
Option A	10%	10% per annum	€5.09	€8.20
Option B	30%	10% per annum	€5.09	€9.69
Option C	100%	10% per annum	€5.09	€14.90

Note: The prices shown here are only for illustrative purposes. The changes in smoking behaviour in the model are only affected by the price elasticities, not by the price level.

[a] Based on data collected by Tax Foundation Europe for 2023, the average retail selling price per 20-pack of cigarettes in Luxembourg in 2023 was €5.09 (including tax). Source: https://taxfoundation.org/data/all/eu/cigarette-taxes-europe-2024/.

Based on an established microsimulation model developed for Luxembourg, the goal is to provide evidence for the ways in which higher tobacco prices could affect the prevalence of diseases in the short and longer term. To accomplish this, this study makes some key assumptions and has some important limitations, four of which are mentioned below.

First, we assume that residents of Luxembourg would not take advantage of lower prices in neighbouring countries to buy cigarettes, once prices in Luxembourg had exceeded those in other countries because of the price increases. As of now, this is a strong assumption, especially for Option C. However, with the potential harmonisation of prices across the EU as proposed by the European Commission, price differences between countries would become increasingly smaller in the future, leading to overall lesser incentives for cross-border tobacco purchasing. Second, we assume that when people stop smoking cigarettes, they will not take up alternative heated tobacco products or e-cigarettes, or that if they do, this will not affect their health. The current evidence regarding the health effects of these products is less clear than for combustible tobacco such as cigarettes, making projections concerning their health impact very uncertain. Third, the model only simulates the direct impact of the price increase on five specific diseases, ignoring the potential impact of reduced smoking on other diseases. In addition, this case study takes a public health perspective and does not assess the impact of changes in cigarette smoking behaviour and higher prices on tax revenues, direct- or indirect costs of smoking and other effects this intervention may have on the economy.

2. Methodology and data

This section presents the model, the used data sources and price elasticities as well as additional sensitivity analyses carried out to test the robustness of results.

2.1. The model: general structure

Based on a standard theoretical framework,[11] Giordana and Pi Alperin (2023) calibrated a dynamic model that allows the simulation of individual economic decisions and health-related behaviour, and effects on long-term public expenditure on healthcare and on long-term care.[10] This model, adapted to the specificities of healthcare in Luxembourg, links health-related public expenditure to individuals' health status.

More precisely, the model simulates the evolution over time of different health conditions such as diseases (e.g., hypertension, diabetes, Parkinson's, Alzheimer's, cancer, lung disease), limitations in instrumental and non-instrumental daily activities (e.g., difficulties dressing, eating, taking medication, walking 100 meters), and symptoms (e.g., appetite loss, trouble sleeping, energy loss). These variables in turn, depend on individual health-related behaviour (smoking, alcohol drinking, physical exercise, and obesity) as well as individual demographic (age, gender), socio-economic characteristics (educational attainment, income, workforce participation and years of contribution to the pension system) and childhood circumstances (country of birth, parents' longevity, and financial situation during childhood).

In particular, the dynamic model simulates the evolution of the health status of the Luxembourg resident population aged 50 and over during their life cycle. In each simulated period, individuals are characterized by different demographic, health related behaviour, risk of comorbidities, childhood circumstances, health status, and socio-economic characteristics variables. In the transition phase of the model (between periods), some of these variables can change following specific transition rules while others remain constant (for example, gender). Transition rules can be deterministic, purely random, calibrated, restricted to certain conditions (as for example in the case where diseases are chronic) or probabilistic. In the present model, the transition steps are the following:

- The *first* variables to change state are the demographic characteristics of the individuals.
- The *second* set of variables that enter the transition phase are those regarding the health-related behaviour of individuals.
- The *third* set of variables to be estimated are socio-economic. This concerns the fact that active individuals may be forced to reduce their participation in the labour market or to declare themselves as disabled.
- Lastly, the *fourth* set of variables to be estimated refer to health. In this final block, individuals who are at risk of developing diseases and/or limitations in their daily activities are estimated.

The specific estimated equations used in the simulation are detailed in Appendix 2.

2.2. Data

Data from several sources was used to estimate and calibrate the parameters of the model for Luxembourg. The country data from the Survey of Health, Ageing and Retirement in Europe (SHARE) was used to estimate parameters such as individual health status, health-related behaviour, demographic characteristics, socio-economic conditions and childhood circumstances. For the long-term simulations, we used demographic projections published by the European Commission and long-term macroeconomic projections for Luxembourg published by the Central Bank.

To calibrate the smoking prevalence among individuals aged 16 and above by age and gender, we took data from the Survey on Tobacco in Luxembourg, co-hosted by Fondation Cancer and the Directorate of Health/Ministry of Health and Social Security in 2023.[14b]

2.3. Changes to smoking as a result of tobacco price increases

Before a model can assess the impact on health of a reduction in smoking, it is important to establish the extent to which smoking is reduced through price increases. This was accomplished by using price elasticities, which express in relative terms the degree of smoking reduction linked to tobacco price increases. For Luxembourg, price elasticities of smoking prevalence or cigarette consumption have not been estimated. We therefore used price elasticities commonly reported in studies that have estimated them for other high-income countries.

The elasticities used here are 0.1 to 0.35.[15] This is in line with consensus estimates from the economic literature and recent studies from other high-income countries,[15–18] and those used in other modelling studies, for example, in a model for the United Kingdom.[19] We assumed that elasticity changes with age (Table 2), based on evidence that younger people are generally more responsive to price changes than older people. As we are interested in the impact of price increases on the decision to start or stop smoking, it is important to consider that for young people the price is likely to be an important factor in the decision to start smoking, while for older smokers, it is more related to the decision to reduce or stop, which may be more difficult.[20] To deal with the uncertainty around the estimates of elasticity, we also carried out sensitivity analyses using lower and upper bounds of price elasticities (Table 5) and using different elasticities by age and socio-economic status (Table 6). For more details on existing price elasticity estimates, see Textbox 1.

Table 2. Price elasticities of smoking prevalence used in the model, by age group

Age Group	Price Elasticity	Effect of 10% Price Increase
16-24	-0.4	4% reduction in smoking prevalence
25-44	-0.3	3% reduction in smoking prevalence
45-54	-0.3	3% reduction in smoking prevalence
55+	-0.2	2% reduction in smoking prevalence

[b] For more details of the data used and the variables included in the model, see Appendix 1.

Textbox 1. Recent evidence on price elasticities for tobacco demand and smoking participation

In our review of the literature to identify price elasticities of smoking participation (i.e. the decision to smoke), we focused on more recent studies that used advanced quasi-experimental approaches to estimate the impact of such price increases, as well as reviews published during the last decade. A recent narrative review on the economics of tobacco carried out by DeCicca et al. (2022)[9] shows the price elasticity of smoking participation among adults to be between 0.1 and 0.3, indicating that a 10% price increase would reduce smoking (or its prevalence) by 1% to 3%. An umbrella review looked at evidence from meta-analyses on the relationship between price and demand for tobacco, and shows that the elasticity for tobacco products is 0.54, suggesting a 5.4% reduction in demand for tobacco products for each 10% price increase.[11] Because demand is comprised of both the decision to consume tobacco products and the intensity (the amount of tobacco consumed), it is likely that the participation elasticity is somewhat smaller.

Using data from over 30 mostly high and higher-middle income countries, another recent study estimates that a 10% increase in prices would reduce the sales of cigarettes by around 3%. The study also finds that heated tobacco products (HTPs) have a much larger price elasticity of above 1, suggesting that a 10% price increase in these tobacco products would reduce consumption by over 10%. However, the study also finds that while price increases for traditional cigarettes lead to an increase in the consumption of HTPs, this does not seem to be true the other way around, in that price increases for heated tobacco products do not lead to significant increases in cigarette consumption.[8] Using information on cigarette sales across European countries and an instrumental variable strategy, Kohler et al. (2023) estimate a price elasticity of cigarette demand between 0.3 and 0.45; the former when also considering the role of illicit trade, which may increase with higher cigarette prices.[10] Specifically regarding younger populations, a systematic review on price elasticities of cigarette demand among youths in high-income countries identifies price elasticities of smoking participation between 0.3 and 0.56, indicating a somewhat larger elasticity of younger people to price increases compared with adult populations.[13]

2.3.1. Two approaches to calculate changes in smoking prevalence as a result of price increases

Two approaches were applied to estimate the change in smoking prevalence resulting from price increases. The first 'static' approach only models the effect on the population aged 50 and above, whose age-specific smoking prevalence would be reduced by the intervention. However, this ignores the fact that people below the age of 50 will also be affected by the price increase. As the population progresses throughout the simulated period, these younger populations will age until they reach 50 and will become part of the simulated population. For example, a person aged 30 in 2030 will be exposed to the price increase and adjust their smoking behaviour accordingly (the prevalence in this age group will be reduced by 3% for each 10% price increase). Because the decrease in smoking prevalence is expected to be larger for younger populations than older ones, this will lead to an additional decrease in the smoking prevalence in the population aged 50 and above once these younger populations age and become part of the older population group. Therefore, a second, 'dynamic', approach was developed to model the changes in smoking prevalence across age groups, considering the impact the intervention would have on younger groups.

Prevalence in the static approach

Table 3 shows the modelled changes in annual smoking prevalence from the baseline in 2025 to 2070. All the price increase scenarios are expected to lead to reductions in smoking prevalence among men and women. While both Option A and the Option B lead to relatively similar reductions in smoking, Option C leads to larger decreases. The overall prevalence among the population of 50 and above decreases from 18.69% in 2025 to 16.49% in the Option A scenario, to 15.74% in Option B and to 13.11% in the Option C in 2030. Any further changes in prevalence in the subsequent years are only due to population ageing, with a lower prevalence of smoking among older populations leading to a small further decrease in the overall proportion of the population that smokes.

Table 3. Evolution of smoking prevalence under different scenarios from 2025 to 2070 in the static approach (%)

Scenario	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050	2055	2060	2065	2070
Option A	18.7	18.2	17.8	17.4	16.9	16.5	16.3	16.2	16.2	16.1	16.0	15.8	15.7	15.6
Option B	18.7	17.4	17.0	16.6	16.1	15.7	15.6	15.5	15.5	15.4	15.3	15.1	15.0	14.9
Option C	18.7	14.5	14.1	13.8	13.5	13.1	13.0	12.9	12.9	12.9	12.8	12.7	12.5	12.5

Prevalence in the dynamic approach

A slightly different picture is visible from 2035 onwards using the dynamic approach (Table 4). In comparison with the static approach, smoking prevalence decreases further as the effects of the intervention on (formerly) younger age groups are considered. As more and more people that were below the age of 50 in 2030 join the 50 years and above population in the subsequent years, the prevalence decreases further in comparison with the static approach. In the dynamic approach, by 2050 (20 years after the price increase) the prevalence is 0.49 percentage points lower in Option A, 0.67 percentage points lower in Option B and 1.28 percentage points lower in Option C, compared with the static approach.

Table 4. Evolution of smoking prevalence under different scenarios from 2025 to 2070 in the dynamic approach (%)

Scenario	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050	2055	2060	2065	2070
Option A	18.7	18.2	17.8	17.4	16.9	16.5	16.1	15.9	15.8	15.7	15.4	15.0	14.7	14.5
Option B	18.7	17.4	17.0	16.6	16.1	15.7	15.3	15.1	14.9	14.8	14.5	14.0	13.7	13.4
Option C	18.7	14.5	14.1	13.8	13.5	13.1	12.5	12.1	11.9	11.6	11.2	10.6	10.1	9.7

2.4. Sensitivity analyses

2.4.1. Upper and lower bounds of elasticities

Estimates of the price elasticity of tobacco consumption do not exist for Luxembourg, and it is unlikely that the assumed elasticities taken from other countries will be exactly the same. We therefore carried out sensitivity analyses, in which the simulations are based on smoking prevalence estimates calculated using a range of lower and upper bound estimates of elasticities. The goal is to assess how the disease prevalence develops under smaller or larger changes in smoking behaviour following a price increase. Table 5 presents the elasticities that we used.

Table 5. Different levels of price elasticity of smoking prevalence by age

Age Group	Lower Bound	Upper Bound
16-24	-0.1	-0.7
25-34	-0.1	-0.5
35-44	-0.1	-0.5
45-54	-0.1	-0.5
55+	0	-0.4

2.4.2. Different levels of elasticities by age and *by socio-economic status*

Price elasticities may differ according to the socio-economic status of the individuals.[20] We therefore evaluated the different price increase scenarios using elasticities that vary across people's age and socio-economic status, as shown in Table 6. Socio-economic status (SES) is defined by the highest level of education achieved by an individual.

Table 6. Different levels of price elasticity of smoking prevalence by age and by socio-economic status

Age Group	Low SES	Normal SES	High SES
50-54	-0.5	-0.3	-0.1
55+	-0.4	-0.2	0

Note: Low SES level includes Level 0 –pre-primary education– or Level 1 –Primary education of first stage of basic education–. Moderate education level includes Level 2 –Lower secondary or second stage of basic education– or Level 3 –Upper secondary education–. High education level includes Level 4 –Postsecondary non-tertiary education– or Level 5 –First or second stage of tertiary education–.

2.5. Definition of the diseases considered

The model simulates the evolution of the prevalence of different tobacco-related diseases: cancer, chronic respiratory diseases, cardiovascular disease, stroke and diabetes. Table 7 presents the questions in SHARE that were used to identify individuals with the specified conditions. Respondents were specifically asked to only mention diseases for which they were receiving care at the time or were still suffering from.[c,d]

Table 7. Definition of diseases in SHARE

Disease	SHARE variable	Definition of SHARE variable
Cancer	PH006_D	Has a doctor ever told you that you had (do you currently have) any of the conditions? Cancer or malignant tumour, including leukaemia or lymphoma, but excluding minor skin cancers
Chronic respiratory diseases	PH006_D	Has a doctor ever told you that you had (do you currently have) any of the conditions? Chronic lung disease such as chronic bronchitis or emphysema
Stroke	PH006_D	Has a doctor ever told you that you had (do you currently have) any of the conditions? A stroke or cerebral vascular disease
Diabetes	PH006_D	Has a doctor ever told you that you had (do you currently have) any of the conditions? Diabetes
Cardiovascular disease	PH006_D	Has a doctor ever told you that you had (do you currently have) any of the conditions? A heart attack including myocardial infarction or coronary thrombosis or any other heart problem including congestive heart failure

[c] See questionnaire: https://share-eric.eu/fileadmin/user_upload/Questionnaires/Q-Wave_6/w6_lu_de_capi_main.pdf
[d] See Appendix 3 for the disease prevalence in the underlying SHARE data.

3. Results

This section first presents the results of the static approach that was used to calculate reductions in smoking prevalence. While the model simulates effects up to the year 2070, in the following presentation and discussion we focus on the more immediate first 20 years after the interventions start. This serves two purposes: first, it aligns more closely with the time horizon of decision-makers by focusing on the more immediate effects. Second, as time progresses, the uncertainty in the simulation increases. The full simulation results are presented in Appendix 5.2.

3.1. Disease prevalence reductions over time

The model predicts reductions in disease prevalence across all scenarios. Table 8 shows the evolution of prevalence in the different scenarios and in parenthesis, the percentage change compared with the benchmark prevalence. The largest and most immediate reductions appear for chronic respiratory diseases and cardiovascular disease. These are also maintained over time. No strong effects are visible for cancer and diabetes. Below, we discuss the change in disease prevalence due to the tobacco price increase for each disease and compare the results with international evidence. Please see Figure 3 to Figure 11 in Appendix 5.3.

Table 8. Simulated disease prevalence over 20 years for the Luxembourg population aged 50 and above. The relative reductions in prevalence compared with the benchmark prevalence are shown in percentages in parentheses

Disease	Scenario	Benchmark (2025)	1 Year (2026)	2 Years (2027)	3 Years (2028)	4 Years (2029)	5 Years (2030)	10 Years (2035)	15 Years (2040)	20 Years (2045)
CVD	Option A	8.2	7.6 (-7.6%)	7.6 (-7.4%)	7.5 (-8.6%)	7.5 (-8.2%)	7.5 (-8.5%)	7.5 (-8.8%)	7.7 (-6.1%)	7.7 (-5.7%)
	Option B	8.2	7.4 (-9.5%)	7.4 (-9.7%)	7.3 (-10.6%)	7.4 (-10.1%)	7.3 (-10.5%)	7.4 (-9.9%)	7.6 (-7.9%)	7.6 (-7.3%)
	Option C	8.2	6.9 (-16.4%)	6.9 (-16.2%)	6.8 (-16.8%)	6.9 (-15.8%)	6.9 (-16.3%)	7.0 (-15.3%)	7.1 (-13.0%)	7.1 (-13.4%)
Cancer	Option A	7	7.0 (0.3%)	7.0 (-0.1%)	7.0 (0.0%)	7.0 (-0.1%)	7.0 (0.1%)	7.0 (-0.1%)	6.9 (-1.6%)	7.0 (-0.9%)
	Option B	7	7.0 (-0.3%)	7.0 (-0.1%)	7.0 (-0.3%)	7.0 (0.1%)	7.0 (0.0%)	6.9 (-1.1%)	6.9 (-2.3%)	6.9 (-1.6%)
	Option C	7	6.9 (-2.0%)	6.9 (-1.7%)	7.0 (-1.0%)	7.0 (-1.0%)	7.0 (-1.0%)	6.8 (-3.4%)	6.7 (-4.6%)	6.7 (-4.0%)
Chronic respiratory disease	Option A	7.4	7.3 (-1.3%)	7.2 (-3.4%)	7.2 (-4.0%)	7.0 (-5.6%)	7.0 (-6.3%)	7.0 (-5.9%)	7.0 (-6.4%)	6.9 (-7.2%)
	Option B	7.5	7.1 (-5.2%)	6.9 (-7.1%)	6.9 (-7.8%)	6.8 (-9.6%)	6.7 (-10.6%)	6.7 (-10.0%)	6.7 (-10.7%)	6.6 (-11.4%)
	Option C	7.5	6.3 (-15.1%)	6.3 (-16.0%)	6.2 (-16.8%)	6.1 (-18.0%)	6.1 (-18.8%)	6.1 (-17.8%)	6.1 (-17.8%)	6.1 (-18.4%)
Diabetes	Option A	11.1	11.1 (0.0%)	11.1 (-0.1%)	11.1 (-0.1%)	11.1 (-0.1%)	11.1 (-0.1%)	11.1 (0.1%)	11.1 (-0.2%)	11.1 (-0.1%)
	Option B	11.1	11.0 (-0.4%)	11.0 (-0.4%)	11.0 (-0.4%)	11.0 (-0.4%)	11.0 (-0.3%)	11.1 (-0.1%)	11.0 (-0.3%)	11.0 (-0.3%)
	Option C	11.1	10.9 (-1.6%)	10.9 (-1.5%)	10.9 (-1.6%)	10.9 (-1.5%)	10.9 (-1.4%)	10.9 (-1.3%)	10.9 (-1.6%)	10.8 (-2.0%)
Stroke	Option A	2.4	1.2 (-50.4%)	1.0 (-55.5%)	1.0 (-55.9%)	0.9 (-63.6%)	1.2 (-50.8%)	1.5 (-37.3%)	1.4 (-41.5%)	1.6 (-32.2%)
	Option B	2.3	0.9 (-60.9%)	0.8 (-65.7%)	0.8 (-66.1%)	0.6 (-75.5%)	0.9 (-59.7%)	1.3 (-44.2%)	1.3 (-42.5%)	1.6 (-29.2%)
	Option C	2.4	0.3 (-86.5%)	0.2 (-91.6%)	0.2 (-91.6%)	0.2 (-89.9%)	0.6 (-74.7%)	1.0 (-55.7%)	1.1 (-53.2%)	1.4 (-40.9%)

3.1.1. Cardiovascular disease

Active smoking and exposure to second-hand smoke are significant contributors to cardiovascular disease development and mortality.[21–23] Our model indicates that the price increase leads to a rapid reduction in the prevalence of cardiovascular disease. In particular, Option B and Option C considerably reduce the prevalence in year five (2030), by 10.5% (Option B) and 16.3% (Option C). Over the longer term, the prevalence remains reduced at similar levels. The rapid decrease in cardiovascular disease risk has been confirmed in international studies, which show that heavy smokers who quit smoking have a 40% lower risk of CVD 5 years after quitting compared with current smokers.[24] The rapid reduction in risk is related to the immediate adverse impact tobacco smoking has on cardiovascular health, as well as the rapid reduction of the cardiovascular disease risk after smoking cessation.[24]

3.1.2. Cancer

Smoking is one of the leading causes of cancers, especially of the throat and lung.[9] We find a delayed but statistically significant reduction in overall cancer prevalence in Option C (see Figure 12 in the appendix), but not in the other scenarios. In Option C, cancer prevalence is reduced by 0.3 percentage points, or 4%, after 20 years, due to the reduction in smoking. Other studies tend to show a relatively strong impact of smoking cessation on cancer risk and mortality. A recent study looking at the United States found that smoking cessation reduced cancer related mortality by half after 10 years, and after 30 years led to a rate of cancer mortality similar to people who had never smoked.[21] However, in terms of cancer incidence, a study from Korea found that former smokers had a 6% lower risk of a cancer diagnosis six years after they had stopped smoking—a finding that appears more in line with the reductions observed in our model.[25] While it is difficult to directly compare our results with these studies, they indicate that reductions in smoking prevalence can have a substantial preventative effect for cancer. In future analyses, it would be important to investigate the direct impact on throat and lung cancer. This was not possible in our analysis, due to low case numbers in the underlying data.

3.1.3. Chronic respiratory disease

Smoking is the leading cause of chronic obstructive pulmonary disease (COPD) and other chronic respiratory diseases.[26,27] Our findings suggest that an increase in tobacco prices would significantly and immediately reduce the burden of chronic respiratory diseases in Luxembourg. Depending on the scenario, the prevalence is reduced by 6.3% (Option A) to 18.8% (Option C) 5 years after the first price increase. The reduction in prevalence also remains substantive 20 years after the price increase.

These findings align with international evidence. For example, Wu et al. (2022) found that comprehensive tobacco control policies, including price increases, reduced COPD related hospitalisations in Beijing by 14.7% shortly after their introduction.[28] Two studies from Sweden and Norway found significant reductions in COPD prevalence following reductions in smoking rates and intensity.[27,29,30]

3.1.4. Diabetes

Smoking has been identified as associated with the development of diabetes, specifically type 2 diabetes.[9] However, recent evidence suggests that there may not be a causal relationship between type 2 diabetes and smoking.[31] The results of our model indicate only a minor impact of smoking cessation on the prevalence of diabetes (consisting of any type of diabetes), even in Option C.

3.1.5. Stroke

Smoking is an important risk factor for the incidence of strokes, even at low levels of daily cigarette consumption. Smoking cessation can significantly reduce the stroke risk.[9,32–34] In our model, the reduction in the extent of strokes is immediate and large. While important reductions in stroke risk have been found in other studies, the very large effect observed in our study is likely to be the result of a very small sample size of stroke cases in the Luxembourg SHARE data. While a reduction in stroke risk is almost certain when smoking rates are reduced,[34,35] the impact on stroke incidence will probably be smaller than modelled here. These results should therefore be interpreted with caution.

3.2. Dynamic approach

Overall, the results are not sensitive to the consideration of the smoking behaviour of younger generations. The simulated prevalence of the five diseases of interest does not, apart from a few exceptions, significantly change in any of the price increase scenarios in comparison to the static approach (see Figure 3 to Figure 11 in Appendix 5.3).

Even if the differences in prevalence resulting from the implementation of the three scenarios are not statistically significant, the reduction in prevalence when accounting for the behaviour of younger generations is greater in absolute terms, except for cancer and stroke. One possible explanation is that to not smoke or to stop smoking at a younger age prevents diseases more effectively than quitting at an older age. According to existing literature, quitting smoking at a younger age leads to a considerably longer lifespan than quitting later or never, due to much lower chance of developing certain diseases.[36]

3.3. Sensitivity analyses

To analyse the sensitivity of the results to the assumptions about the price elasticity of smoking prevalence, we carried out the simulations using different elasticity values. First, we considered lower and higher values of the elasticity by age as described in Table 5. Second, we considered values of the price elasticity of smoking prevalence that varies by age and socio-economic status, as shown in Table 6. We used educational attainment as a proxy for socio-economic status.

The analysis confirms the effectiveness of the three scenarios (see Figure 16 to Figure 26 in the appendix). In fact, only the lower bounds of the estimated prevalence of certain health outcomes under the three scenarios are not statistically significant. This is the case for:

- the lower bounds of chronic respiratory disease (in the initial periods) and stroke (in 2055 and 2060) under Option A;
- the lower bounds of chronic respiratory disease (in 2026 and 2027) and cancer (in 2035, 2040 and 2045) under the Option B; and
- the lower bounds of diabetes (up to 2040), and stroke (in 2055 and 2060) under Option C.

Apart from that, the reductions are similar to the initial simulated prevalence rates or are statistically significantly different from zero. As expected, the lower bound price elasticities lead to smaller reductions in disease prevalence and the upper bound elasticities to larger reductions. Nonetheless, the results show that even under more conservative assumptions about the price elasticity of cigarette smokers in Luxembourg, the reductions in disease prevalence are still considerable.

Considering different elasticities by socio-economic status (proxied by educational attainment) does does not lead to qualitatively different results (see Figure 33 to Figure 31 in the appendix). Most of the residents of Luxembourg aged 50 and over have a moderate level of education (as measured in the SHARE survey in 2015), leading to mostly non-significant changes in the simulated prevalence of smoking and the resulting disease prevalences in comparison with the previous analyses.

4. Summary and discussion

Price increases are considered as one of the most efficient ways to decrease tobacco use and the resulting harms to health. Our model investigates the extent to which reductions in tobacco consumption could affect the prevalence of smoking-related diseases in Luxembourg. We simulated the effect of three hypothetical price increases on the prevalence of smoking and the resulting changes in the prevalence of chronic respiratory disease, cancer, cardiovascular disease, diabetes and stroke among the population aged 50 years and above. The results show that substantial reductions can be expected for chronic respiratory and cardiovascular diseases. These reductions would start appearing almost immediately after implementing the first price increases and remain even after 20 years from the first increase. Of the three modelled price increase scenarios, Option C would be likely to lead to the largest reductions in the disease burden, but Option A and Option B result in important health benefits.

4.1. Limitations of the analysis

This analysis has several limitations. Most importantly, the model was originally developed to simulate long-term trends in Luxembourg's public expenditure on healthcare and on long-term care giving the population ageing, using data from the Survey of Health, Ageing and Retirement in Europe. To model the health impact of cigarette price increases this poses several challenges that have resulted in data related limitations of this study. A limitation is that the SHARE data only includes people 50 years and above. Therefore, the results are only representative for the older population residing in Luxembourg, hence results for the entire population may differ. While we did consider the impact of smoking reductions in younger age groups in the dynamic approach, we could not explore the impact on diseases in the population below the age of 50. Clearly this also precluded the consideration of the effects on children, both through the reductions in maternal smoking during pregnancy and the reductions in exposure to second-hand smoking. Research has shown that price increases decrease maternal smoking and have positive health effects for children, both in the short and medium term.[15,40]

Another data limitation is that we could not distinguish between different cancers, thus preventing any exploration of the direct impact of the intervention on smoking-related cancers, such as lung cancer. Similarly, the number of stroke cases in the data is very low, complicating the modelling of changes in stroke prevalence and possibly leading to overestimating the impact on strokes.

In addition, the data was taken from waves 5 and 6 of the SHARE survey, which took place in 2013 and 2015, respectively. These were chosen as they were the last for which the sample had been refreshed and included individuals of every age from 50 and above. While there are later waves, they do not contain information for every age, given that SHARE is a longitudinal survey that follows the same people over time. Accordingly, without constant refreshing of the sample, later waves do not contain younger age groups as respondents grow older. To have up to date and comprehensive smoking data, we integrated data from the Survey on Tobacco in Luxembourg. However, while this allowed for the use of up to date and more comprehensive information on smoking, it required additional calibration of the model requiring assumptions about smoking behaviours introducing additional uncertainty. Optimally, more comprehensive smoking information would have already been included in the SHARE data.

Further, the underlying elasticities of how price changes affect smoking are not known for Luxembourg. We used elasticities published in international literature to inform our model. We carried out extensive sensitivity analyses to identify if much lower or higher elasticities would lead to substantially different results. Overall, even when using very conservative elasticities of a 1% decrease in smoking prevalence per 10% price increase, the results show mostly significant, albeit smaller, reductions in the prevalence of chronic respiratory and cardiovascular disease, even in the most conservative price increase scenario.

Also related to price elasticities is the potential change in consumption patterns of other tobacco products apart from cigarettes that have become increasingly popular in recent years, and for which the health effects are less well established. The current analysis assumes that people will not substitute cigarette smoking with the consumption of other alternative products, in particular heated tobacco products (HTPs) or e-cigarettes. We did not consider these other products due to the less-established evidence linking them to health outcomes and a lack of information in the SHARE data. HTPs are likely to be less problematic than cigarettes, but may still harm health and could be a gateway to nicotine addiction and later cigarette smoking. However, they may also help current smokers to quit cigarette consumption, which is why the overall health effects of HTPs remain unclear and are likely to be country dependent.[16,37] With regard to cross-price elasticities between the two products, recent evidence indicates that price increases in cigarettes lead to increases in the consumption of alternative tobacco products, but price increases in HTPs do not result in higher cigarette smoking rates.[16]

Another simplification is that changes in the intensity of smoking due to a price increase are ignored. We assume that the price increase only affects the decision whether to smoke, but not if people reduce the amount of tobacco they consume if they continue to smoke. We made this decision because the main goal of public health interventions is usually to prevent smoking initiation and to promote smoking cessation. Further, smokers may compensate for reductions in the number of cigarettes by smoking more high-tar cigarettes or smoking cigarettes longer or harder, making any interpretation of changes in smoking intensity more difficult.[15] Overall, the omission of smoking intensity changes likely led to an underestimation of the overall health impact of tobacco price increases in the presented results. Similarly, we do not consider the effects of the reduced exposure to second-hand smoking of non-smokers, pregnant women and children.[38,39]

Regarding the model, the chosen approach has the advantage of using estimated associations of health behaviours, socio-economic and demographic characteristics, and health outcomes based on data from Luxembourg. However, the underlying regression models cannot establish causal relationships, potentially introducing biases in the estimated results.

4.2. Other considerations

Other considerations for the implementation of tobacco price increases via tobacco tax increases are important in Luxembourg. First, its geographic nature, as a small country surrounded by three neighbours, could partly reduce the effectiveness of price increases if they were to lead to higher prices than in neighbouring countries. In that case, Luxembourg residents could buy cheaper tobacco products across the border. The current analysis assumes that prices in Luxembourg would remain below prices in neighbouring countries, removing the potential incentive for cross-border shopping for cigarettes. In addition, the analysis here only investigated a price increase, irrespective of how this could be achieved. Normally, this would be the result of an increase in taxes on tobacco—and specifically cigarettes. It would be important to consider the extent to which taxes would need to be increased to achieve the desired increase in prices, as an increase in taxes may not be completely passed on to the consumer, if it is partly absorbed by cigarette producers or retailers. However, research has shown that tax increases tend to be almost completely passed through to consumers, at least on average, meaning that consumer prices rise proportional to the tax increase.[15] Irrespectively, companies who sell both low-priced and higher priced premium cigarettes may still aim to maintain profits by increasing prices less for premium cigarettes while increasing prices more for lower-end non-premium cigarettes, which on average may lead to a more tamed price response of consumers.[16,41]

Further, our analysis considers only the public health perspective, where higher tobacco prices are very likely to have important benefits. In terms of its economic effects, a discussion about the increase of tobacco prices, probably through an increase in taxes on tobacco products, will also need to consider the economic impact on healthcare expenditure and productivity due to changes in the disease burden of the population and longer life expectancies, as well as changes in tax revenues based on tobacco products (and products that are bought instead of tobacco) and other economy-wide costs and benefits.[15,42–45]

4.3. Future research directions

Several measures should be taken in future to further the evidence on the relationship between prices and smoking behaviours in Luxembourg. First, existing price elasticities come from countries that do not necessarily face the same reality as Luxembourg, where its small size makes it possible for residents to buy tobacco in neighbouring countries and vice versa. To better understand the price sensitivity of Luxembourg residents and cross-border shoppers, it will be important to estimate Luxembourg-specific price elasticities of cigarette demand and smoking. Similarly, studies on the cost-of-illness of tobacco related diseases in Luxembourg are missing, limiting the possibility to better understand the wider societal economic burden of smoking in the country. Regarding future modelling analyses, they would profit form the use of more recent data covering the entire population of Luxembourg. Similarly, more detailed and comprehensive data on smoking behaviours included in population-based survey data, such as SHARE, would further decrease the uncertainty in the modelling results.

Key messages

- An increase in tobacco prices is likely to reduce smoking in Luxembourg.
- Substantial reductions in cardiovascular and chronic respiratory disease can be expected shortly after an increase in prices.
- The largest increase in prices yields the greatest health benefits, but smaller increases are also likely to improve health.
- From a public health perspective, making tobacco products more expensive is highly effective in changing smoking behaviour and preventing smoking related diseases.

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Appendix 1. Data

In this chapter, we provide a brief overview of the various data sources employed to estimate and calibrate the model parameters and the different simulated scenarios. Secondly, we present all the variables used in this project.

1.1. Data sources

To estimate and calibrate the parameters of the model for Luxembourg, several data sources are used: data from the SHARE survey, demographic data and projections from Eurostat, long-term macroeconomic projections from the European Commission, as well as data provided punctually by the CNS and the General Inspectorate of Social Security. In addition, the Cancer Foundation survey served the calibration of smoking prevalence by age.

Survey of Health, Ageing and Retirement in Europe (SHARE)

SHARE is a multidisciplinary, cross-national panel survey. It collects data on individuals aged 50 years or older and their partners (of whatever age) through more than seven hundred questions on health (e.g., physical health, mental health, health behaviour, healthcare), socio-economic conditions (e.g., education level, living conditions, employment status, income, pensions), and social and family networks (e.g., intergenerational support, volunteering).[e] SHARE is unique in covering a wide range of health related variables, which is a key advantage to estimate the parameters of our model. In particular, we use data from Waves 5 and 6, Release 9.0.0, collected in Luxembourg in 2013 and 2015, respectively. [12,13]

SHARE results for Luxembourg are representative of the resident population, by gender and age. However, it does not cover the population living in specialized institutions or nursing homes, nor does it cover non-residents who cross the border every day to work in Luxembourg and therefore benefit from the Luxembourg Social Security system. The sample includes 1563 respondents, 54.51% are women. Individual sample weights ensure that results are representative of the target population. However, they do not consider the distribution of different diseases across the population.

The SHARE data is used to estimate parameters such as the individual health status, health-related behaviour, demographic characteristics, socio-economic conditions, and childhood circumstances.

European Commission and Luxembourg Central Bank

We rely on Eurostat (2024) population projections reflecting a set of assumptions on future age-specific fertility rates, age-specific mortality rates, and international net migration levels. For the purpose of our simulation, we use the EUROPOP2023 baseline scenario.[46] To build indicators of longevity, we also use Eurostat projections on the evolution of life expectancy by age and gender.[f]

Finally, the long-term simulations use demographic projections from EUROPOP2023.[46]

1.2. Variables in the model

To simulate the impact of an increase in tobacco prices on the health of Luxembourg residents, we first defined all the variables that the microsimulation model simulates over time. More precisely, this section describes five vectors of variables: demographic characteristics, childhood circumstances, health behaviour, socio-economic characteristics, and health-related variables. Compared with Giordana and

[e] See Börsch-Supan et al. (2013) for a detailed description of SHARE.[13]
[f] Available at https://ec.europa.eu/eurostat/web/main/data/database.

Pi Alperin's original model10, some of the health behaviour variables were redefined to align with objectives of the analysis. We adjusted the definition of the variables measuring smoking and alcohol consumption habits as well as the one capturing the frequency of physical activity.

Demographic characteristics vector

The demographic characteristics vector includes the individual's age and gender, as well as the size of their household. These variables are described in Table 9.

Table 9. Variables included in the Demographic characteristics vector

Vector	Variables	Definition
Demographic characteristics	Age	Measured in years for individuals aged 50 years old and more
	Gender	Two categories: man or woman
	Household size	Number of individuals living in the same household regardless of family ties

Source: SHARE, Wave 6.

Childhood circumstances vector

The childhood circumstances vector comprises three variables: the country of birth, parents' longevity and financial situation during childhood. These variables are described in Table 10.

Table 10. Variables included in the Childhood circumstances vector

Vector	Variables	Definition
Childhood circumstances	Country of birth	Luxembourg; France, Belgium or Germany; other country
	Parents' longevity	Parents' longevity proxies for parental health, following Jusot et al. (2013). Own calculations based on SHARE. Survey participants report whether their parents are still alive at the time of the survey or their parents' age at death
	Financial situation during childhood	Identifies individuals who report they grew up (from birth to age 15) in a poor family or one whose financial situation was poor at one time. Variable with four categories

Source: SHARE, Wave 6.

Health behaviours vector

The health behaviour vector includes four binary variables. These are smoking consumption, alcohol consumption, physical inactivity, and dietary behaviour. Table 11 provides definitions of these variables.

Table 11. Variables included in the Health behaviours vector

Vector	Variables	Definition
Health behaviours	Smoking	Smokers are those individuals who currently smoke or smoked for at least 5 years[g]
	Alcohol consumption	Individuals who drink more than nine units of alcoholic beverages during the last 7 days and, in the last three months and for at least once a month, they consumed six or more units of alcoholic beverages on one occasion
	Physical inactivity	Individuals who do not engage in vigorous physical activity - such as sports, heavy housework, or a job that involves physical labour - or who only engage in activities that require a moderate level of energy - such as gardening, cleaning the car, or doing a walk - less than once a week
	Dietary behaviour	Individuals who have a Body Mass Index[h] of 30 or more

Source: SHARE, Wave 6.

Socio-economic conditions vector

The socio-economic conditions vector comprises four variables: individual's level of education, household disposable income, participation in the workforce, and years of contribution to the pension system. These variables are described in Table 12.

Table 12. Variables included in the Socio-economic conditions vector

Vector	Variables	Definition
Socio-economic conditions	Educational attainment	Reflects the highest level reached according to the 1997 version of the International Standard Classification of Education (ISCED). Level 0: Pre-primary education; Level 1: Primary education or first stage of basic education; Level 2: Lower secondary or second stage of basic education; Level 3: (Upper) secondary education; Level 4: Post-secondary non-tertiary education; Level 5: First or second stage of tertiary education
	Household equivalent disposable income	Combination between the total income received by all household members in last month and the household size
	Workforce participation	Binary variable indicating whether the individual is economically active
	Years of contribution to the pension system	

Source: SHARE, Wave 6.

[g] In our sample, individuals who currently do not smoke but used to smoke had smoked for less than five years.
[h] BMI is calculated by dividing an individual's weight in kilograms by the square of their height in meters.

Health-related variables vector

The vector including the health-related variables is the largest. The model simulates sixty-two individual health variables over time, including diseases, limitations in instrumental and non-instrumental daily activities, and symptoms of several conditions. For the sake of simplification, we will refer to all of these variables as a “disease”. Additionally, these variables can be regrouped into nine health conditions reflecting various aspects of mental and physical health, as well as limitations in daily activities. These nine conditions are depression, orientation, memory, permanent health conditions, non-permanent health conditions, eyesight, hearing, limitations in instrumental and non-instrumental daily life activities, and mobility. Table 13, Table 14 and Table 15 describe, respectively, health conditions related to mental health, physical health and limitations in daily activities.

Table 13. Health conditions and variables measuring mental health

Conditions	Variables	Definition
Depression scale EURO-D	Depression	Binary variable that indicates whether the individual has been sad or depressed in the last month
	Pessimism	Binary variable that refers to the individual’s hope for the future
	Suicidality	Binary variable that gives information on suicidal feelings
	Guilt	Binary variable that indicates whether the respondents tend to blame themselves or feel guilty about anything
	Sleep	Binary variable that indicates whether a person has trouble with sleeping
	Interest	Binary variable that refers to changes in the general interest in things
	Irritability	Binary variable that indicates whether the individual has been irritable recently
	Appetite	Binary variable that refers to changes in the individual´s appetite
	Fatigue	Binary variable that indicates whether the individual had too little energy to do the things she/he wanted to do in the previous month
	Concentration	Binary variable that gives information on difficulties with the concentration on a television program, film, radio program or reading
	Enjoyment	Binary variable that indicates if the individual has enjoyed doing something recently
	Tearfulness	Binary variable that indicates if the individual has cried last month
Cognitive tests: Orientation	Orientation_Day	The respondent answered correctly the day of the month
	Orientation_Month	The respondent answered correctly the month
	Orientation_Year	The respondent answered correctly the year
	Orientation_Week	The respondent answered correctly the day of the week
Cognitive tests: Memory	Ten words_First trial	The interviewer read a list of words. The respondent recalled as many of the words he/she could immediately after listening to them
	Ten words_delayed trial	The interviewer read a list of words. The respondent recalled as many of the words he/she could ten minutes after the interviewer read them

Source: SHARE, Wave 6.

In each simulation period, we also measure the global health status of each individual using the sixty-two previously described health variables grouped into nine health conditions. To do this, we follow the multidimensional approach in Pi Alperin (2016)[47], which employs fuzzy set theory to aggregate the nine health conditions reflecting various aspects of mental and physical health, as well as limitation in daily activities into a single indicator of health status. Thus, the general health status indicator for each individual can take any value between 0 (absolutely healthy) and 1 (absolutely non-healthy in all sixty-two variables).

In particular, the health status indicator is calculated as the average of the nine health conditions, with equal weighting assigned to each. This assumes that each condition is equally important for health status.

Table 14. Health conditions and variables measuring physical health

Conditions	Variables	Definition
Permanent health conditions*	Hypertension	High blood pressure or hypertension
	Hypercholesterol	High blood cholesterol
	Diabetes	Diabetes or high blood sugar
	Pneumonia	Chronic lung disease such as chronic bronchitis or emphysema
	Parkinson	Parkinson's disease
	Alzheimer	Alzheimer's disease, dementia, organic brain syndrome, senility or any other serious memory impairment
	Anxiety	Other affective or emotional disorders, including anxiety, nervous or psychiatric problems
	Rheumatism	Rheumatoid Arthritis
	Arthritis	Osteoarthritis, or other rheumatism
	Kidney	Chronic kidney disease
Non-permanent health conditions*	Heart attack	A heart attack including myocardial infarction or coronary thrombosis or any other heart problem including congestive heart failure
	Stroke	A stroke or cerebral vascular disease
	Cancer	Cancer or malignant tumour, including leukaemia or lymphoma, but excluding minor skin cancers
	Ulcer	Stomach or duodenal ulcer, peptic ulcer
	Cataracts	
	Hip fracture	
	Other fractures	
Eyesight	Farsighted	How good is your eyesight for seeing things at a distance, like recognizing a friend across the street
	Near-sighted	How good is your eyesight for seeing things up close, like reading ordinary newspaper print
Hearing	Hearing	How is your hearing (with or without hearing aid)

Note: *Has a doctor ever told you that you had/ Do you currently have any of the permanent o non-permanent conditions? Permanent and non-permanent health conditions are binary variables while the eyesight and hearing are five-modality response variables.

Source: SHARE, Wave 6.

Table 15. Health conditions and variables measuring activities in daily life

Conditions	Variables	Definition
Instrumental and non-instrumental daily activities	Dressing	Dressing, including putting on shoes and socks
	Movement	Walking across a room
	Bathing	Bathing or showering
	Eating	Eating, such as cutting up your food
	Bed	Getting in or out of bed
	Toilet	Using the toilet, including getting up or down
	Map	Using a map to figure out how to get around in a strange place
	Meal	Preparing a hot meal
	Shop	Shopping for groceries
	Telephone	Making telephone calls
	Medicines	Taking medications
	Work	Doing work around the house or garden
	Money	Managing money, such as paying bills and keeping track of expenses
	Cleaning	Doing personal laundry
Mobility index	Walking	Walking 100 meters
	Sitting	Sitting for about two hours
	Chairs	Getting up from a chair after sitting for long periods
	Stairs	Climbing several flights of stairs without resting
	Stairs 2	Climbing one flight of stairs without resting
	Stooping	Stooping, kneeling, or crouching
	Arms	Reaching or extending your arms above shoulder level
	Objects	Pulling or pushing large objects like a living room chair
	Weights	Lifting or carrying weights over 10 pounds/5 kilos, like a heavy bag of grocers
	Coins	Picking up a small coin from a table

Note: Please tell me if you have any difficulty with these activities because of a physical, mental, emotional or memory problem, excluding any difficulties you expect to last less than three months.

Source: SHARE, Wave 6.

Appendix 2. Methodology used for modelling diseases

In this chapter, we explain the econometrics underlying the microsimulation model. In particular, the function governing the probability of having each disease depends on individuals' health behaviour and health status, which are both likely influenced by other individual characteristics such as demographics, socio-economic characteristics and childhood circumstances. Therefore, to estimate the parameters in the system of equations, we adopt a similar procedure to Trannoy et al. (2010) and Lazar (2013).[48,49] The procedure is explained in what follows.

2.1. Estimation of health behaviours and general health status

We specify health behaviour as a function of age *a*, gender g, and other individual characteristics. In the following system of equations, we consider four types of nonmutually exclusive health behaviour *s* (smoking, alcohol drinking, physical inactivity, and dietary behaviour proxied by the residuals of the obesity model[i]), with $hb^s \in \{0,1\}$:

$$Pr(hb^s = 1 \mid DEM_{a,g}, SEC_{a,g}, C) = F_s(-u_t^s < DEM_t\beta_1^s + SEC_t\beta_2^s + C\beta_3^s + U^s\beta_u^s - \zeta^s), \quad (1)$$

$$s \in \{Smoke, Alcohol, PhIn, Obesity\},$$

where, *PhIn* refers to *physical inactivity*. Each *s* in the system of Equations (1) includes the same variables included in the demographic vector DEM (Table 1), in the socio-economic characteristics vector SEC (Table 2) and the childhood circumstances vector C (see Table 4). However, following Trannoy et al. (2010), the matrix U^s varies across equations and incorporates estimated residuals from other equations in the system following a recursive order:

$$U^{Alcohol} = [\hat{u}^{Smoke}]$$

$$U^{PhIn} = [\hat{u}^{Smoke}, \hat{u}^{Alcohol}]$$

$$U^{Obesity} = [\hat{u}^{Smoke}, \hat{u}^{Alcohol}, \hat{u}^{PhIn}],$$

where, $\hat{u}^s$ is the deviance residual obtained from probit regressions of the system of Equations (1) for each *s* among smoking, alcohol drinking, physical inactivity, and obesity. These residuals provide an estimate of the risk of being affected by the health behaviour after accounting for other determinants (demographic, socio-economic and childhood circumstances).

Then, based on a linear regression of the logit transform of the health indicator *Z*, we estimate the parameters in vectors β^z in the following equation:

$$Z^* = DEM_t\beta_1^z + SEC_t\beta_2^z + C\beta_3^z + U^z\beta_u^z + u^z, \quad (2)$$

where, Z is the logistic transformation of the health status indicator and vectors DEM, SEC and C are the same as in Equation (1). However, matrix U^z includes $\hat{u}^{Smoke}, \hat{u}^{Alcohol}, \hat{u}^{PhIn}$ and $\hat{u}^{Obesity}$ are the same as estimated in Equation (1).

[i] For the sake of simplification, we will refer to it as "obesity".

2.2. Estimating the conditional probability of having each disease

In a second step, we estimate probit regressions for each of the sixty-two diseases included in the health status indicator to obtain the probability of being affected by each disease for every individual, conditioning on his/her individual characteristics (health behaviour, risk of comorbidities, demographic and socio-economic characteristics, childhood circumstances, and health status).

Following Giordana and Pi Alperin (2023), in Equation (3), binary variable $I_{a,g}^{i}$ indicates whether disease i affects an individual of age a and gender g. The probability that $I_{a,g}^{i} = 1$ depends on the individuals' health behaviour (vector $hb_{a,g}$), risk of comorbidities (vector O^i), demographic and socio-economic characteristics and childhood circumstances (vector X), and health status (variable Z). In total, the empirical model consists of sixty-two equations, one for each disease, limitation in instrumental and non-instrumental daily activities, and symptoms considered in the model. Each equation contains the same set of vectors with the same variables with a few exceptions. Multimorbidity [j] vector O^i varies across equations and incorporates deviance residuals estimated from probit regressions of Equation (3) for specific equations in the system.[k] For instance, vector O^{Stroke} includes deviance residuals resulting from the estimation of Equation (3) for hypertension and diabetes diseases. Therefore, the estimation approach assumes a specific recursive structure based on the causal relationships identified by medical research. Thus,

$$Pr(I_{a,g}^{i} = 1 \mid X_{a,g}, Z_{a,g}, hb_{a,g}, O_{a,g}^{i}) =$$

$$= F_i(-u_{a,g}^{i} < X_{a,g}\beta_X^i + Z_{a,g}\beta_Z^i + O_{a,g}^{i}\beta_O^i + hb_{a,g}\gamma^i - \zeta^i).\ \forall i \in \Phi \quad (3)$$

We assume that $u_{a,g}^{i}$ is a normally distributed random variable representing the source of risk with cumulative distribution function F_i and ζ^i a structural parameter. This parameter helps fine tuning the classification of individuals as being affected or not by condition i and is estimated in a separate step using a grid search algorithm that minimizes a linear combination of classification errors (for more details, see Giordana and Pi Alperin, 2023)[10].

2.3. Survival probability

In each period, the survival probability of individuals varies across gender, age and time, as we constrain the population to follow the baseline scenario of EUROPOP2023 projections. For each year t, the probability of survival until $t + 1$ for an individual of gender g, age a and general health status Z is:

$$sp_{a,g,z}^{t} = \Pr\left(1 + Z_{a,g} - \frac{N_{a+1,g}^{t+1}}{n_{a,g}^{t}} < \epsilon\right), \quad (4)$$

where, ϵ is random draw from a uniform distribution in the interval [0,1], $N_{a+1,g}^{t+1}$ is the number of individuals of gender g and age $a + 1$ who are alive in year $t + 1$ (according to Luxembourg's population projections), and $n_{a,g}^{t}$ is the number of individuals of gender g and age a in the target population. Therefore, Equation (4) implies that an individual's survival probability increases with his/her health status and with the projected growth of his/her population subgroup.

[j] Diseases such as diabetes, high cholesterol, which are risk factors for other diseases included in the analysis.

[k] The sum of squares of deviance residuals is the generalization for probit models (and other generalized linear models) of the sum of raw residuals in the linear model. For a more detailed definition of deviance residuals, see Section 8.7.3 in Cameron and Trivedi (2005)[50]. For an application of this approach based on Frisch and Waugh (1933)[51], to the estimation of the contribution of different risk factors to individual health outcomes, see Jusot et al. (2013) and Deutsch et al. (2018).[52,53]

Appendix 3. Disease and health behaviour prevalences

This chapter presents the prevalence of the diseases and health behaviours used in the model.

3.1. Prevalence of diseases

The prevalence of the diseases included in the microsimulation model, are those measured in SHARE Wave 6 collected in 2015. Table 16 shows the prevalence rates of the five diseases of interest for this analysis: chronic respiratory disease, cancer, diabetes, stroke, and cardiovascular disease.

Table 16. Prevalence rates of diseases

Diseases	Total prevalences for individuals 50+ (%)
Chronic respiratory disease	7.45
Cancer	7.02
Diabetes	11.07
Stroke	2.35
Cardiovascular disease	8.21

Source: SHARE, Wave 6.

3.2. Prevalence of health behaviours and obesity

The prevalence of the alcohol consumption, physical inactivity and obesity variables, are based on data from SHARE Wave 6 collected in 2015. Table 17 shows the prevalence of these three variables.

Table 17. Prevalence rates of health-related variables

Health behaviour	Women (%)	Men (%)	Total (%)
Alcohol consumption	1,96	13,08	7,3
Physical inactivity	25,93	21,2	23,66
Obesity	21,12	25,09	23,03

Source: SHARE, Wave 6.

Appendix 4. Calibration of the smoking variable

For this analysis, the definition of the smoking behaviour variable was aligned with the one used for the estimation of the price elasticity of smoking prevalence.

In addition, we calibrated the prevalence of smoking using the results of the "*Fondation Cancer DISA: Le tabagisme au Luxembourg – Bilan 2023*". Table 18 compares the prevalence rates from the Cancer Foundation and SHARE surveys, based on the smoking definition presented in Table 11. The major differences in smoking prevalence between these two surveys concern men aged 50-54 and women aged 75 and over. For the other age intervals, the prevalence rates are similar, indicating that the chosen definition for identifying individuals currently at risk of smoking aligns with the Cancer Foundation survey results and the price elasticity of smoking prevalence used in this analysis.

Table 18. Comparison between smoking prevalence in SHARE and Cancer Foundation surveys

	Cancer Foundation Survey		SHARE Survey	
Gender	**Age**	**Smoking prevalence**	**Age**	**Smoking prevalence**
Men	16-24	36	-	-
	25-34	40	-	-
	35-44	39	-	-
	45-54	25	50-54	10.73
	55-64	23	55-64	22.54
	65-74	13	65-74	16.77
	75+	10	75+	8.89
Women	16-24	35	-	-
	25-34	31	-	-
	35-44	33	-	-
	45-54	20	50-54	20.72
	55-64	20	55-64	18.50
	65-74	15	65-74	15.45
	75+	19	75+	5.53

Note: *ILRES 2023 smoking question: Are you currently smoking?

Smoking was the only variable calibrated in the model. No other variables were calibrated with external sources to avoid manipulating the original data.

Appendix 5. Additional results

5.1. Smoking prevalences used in simulation

Table 19. Change in smoking prevalence under different scenarios from 2025 to 2030, by age group and gender

		Prevalence					
Gender	**Age**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Option A							
Men	50-54	25.0	24.3	23.5	22.8	22.1	21.5
	55-64	23.0	22.5	22.1	21.6	21.2	20.8
	65-74	13.0	12.7	12.5	12.2	12.0	11.8
	75+	10.0	9.8	9.6	9.4	9.2	9.0
Women	50-54	20.0	19.4	18.8	18.3	17.7	17.2
	55-64	20.0	19.6	19.2	18.8	18.4	18.1
	65-74	15.0	14.7	14.4	14.1	13.8	13.6
	75+	19.0	18.6	18.2	17.9	17.5	17.2
Option B							
Men	50-54	25.0	22.8	22.1	21.4	20.8	20.1
	55-64	23.0	21.6	21.2	20.8	20.3	19.9
	65-74	13.0	12.2	12.0	11.7	11.5	11.3
	75+	10.0	9.4	9.2	9.0	8.8	8.7
Women	50-54	20.0	18.2	17.7	17.1	16.6	16.1
	55-64	20.0	18.8	18.4	18.1	17.7	17.3
	65-74	15.0	14.1	13.8	13.5	13.3	13.0
	75+	19.0	17.9	17.5	17.2	16.8	16.5
Option C							
Men	50-54	25.0	17.5	17.0	16.5	16.0	15.5
	55-64	23.0	18.4	18.0	17.7	17.3	17.0
	65-74	13.0	10.4	10.2	10.0	9.8	9.6
	75+	10.0	8.0	7.8	7.7	7.5	7.4
Women	50-54	20.0	14.0	13.6	13.2	12.8	12.4
	55-64	20.0	16.0	15.7	15.4	15.1	14.8
	65-74	15.0	12.0	11.8	11.5	11.3	11.1
	75+	19.0	15.2	14.9	14.6	14.3	14.0

5.2. Simulated disease prevalences for the Luxembourg population aged 50 and older

Table 20. All simulated disease prevalences for the Luxembourg population aged 50 and older in the static approach

Disease	Year	Option A	Option B	Option C
Chronic respiratory disease	2025	7.45	7.47	7.46
	2026	7.35	7.08	6.33
	2027	7.20	6.94	6.27
	2028	7.15	6.89	6.21
	2029	7.03	6.75	6.12
	2030	6.98	6.68	6.06
	2035	7.01	6.72	6.13
	2040	6.97	6.67	6.13
	2045	6.91	6.62	6.09
	2050	6.96	6.71	6.17
	2055	7.00	6.74	6.20
	2060	6.98	6.76	6.22
	2065	7.05	6.81	6.30
	2070	7.09	6.84	6.32
Cancer	2025	7.02	7.02	7.02
	2026	7.04	7.00	6.88
	2027	7.01	7.01	6.90
	2028	7.02	7.00	6.95
	2029	7.01	7.03	6.95
	2030	7.03	7.02	6.95
	2035	7.01	6.94	6.78
	2040	6.91	6.86	6.70
	2045	6.96	6.91	6.74
	2050	6.90	6.84	6.63
	2055	6.88	6.81	6.56
	2060	6.88	6.82	6.54
	2065	6.84	6.74	6.52
	2070	6.84	6.79	6.55
Diabetes	2025	11.07	11.07	11.07
	2026	11.07	11.03	10.89
	2027	11.06	11.03	10.90
	2028	11.06	11.03	10.89
	2029	11.06	11.03	10.90
	2030	11.06	11.04	10.91

	2035	11.08	11.06	10.93
	2040	11.05	11.04	10.89
	2045	11.06	11.04	10.85
	2050	11.02	11.01	10.76
	2055	10.98	10.96	10.63
	2060	10.93	10.86	10.49
	2065	10.77	10.74	10.32
	2070	10.76	10.71	10.30
Stroke	2025	2.36	2.33	2.37
	2026	1.17	0.91	0.32
	2027	1.05	0.80	0.20
	2028	1.04	0.79	0.20
	2029	0.86	0.57	0.24
	2030	1.16	0.94	0.60
	2035	1.48	1.30	1.05
	2040	1.38	1.34	1.11
	2045	1.60	1.65	1.40
	2050	1.90	1.86	1.57
	2055	2.01	2.05	1.69
	2060	2.11	2.08	1.69
	2065	2.00	1.96	1.58
	2070	1.91	1.90	1.51
Cardiovascular disease	2025	8.21	8.21	8.21
	2026	7.59	7.43	6.86
	2027	7.60	7.41	6.88
	2028	7.50	7.34	6.83
	2029	7.54	7.38	6.91
	2030	7.51	7.35	6.87
	2035	7.49	7.40	6.95
	2040	7.71	7.56	7.14
	2045	7.74	7.61	7.11
	2050	7.66	7.53	6.97
	2055	7.72	7.59	6.97
	2060	7.69	7.55	6.91
	2065	7.69	7.53	6.84
	2070	7.74	7.60	7.04

5.3. Relative change in disease prevalence in static and dynamic scenarios

Option A price increase scenario

Figure 1. Cardiovascular disease prevalence differences between static and dynamic approaches in Option A relative to the benchmark (risk ratios) between 2025 and 2070

Figure 2. Cancer prevalence differences between static and dynamic approaches in Option A relative to the benchmark (risk ratios) between 2025 and 2070

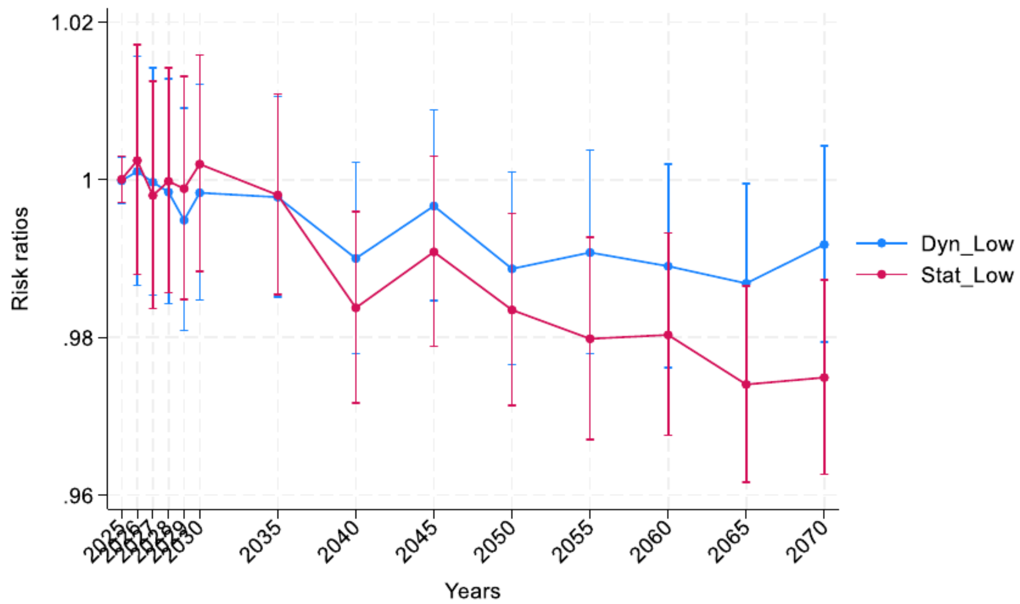


Figure 3. Chronic respiratory disease prevalence differences between static and dynamic approaches in Option A relative to the benchmark (risk ratios) between 2025 and 2070

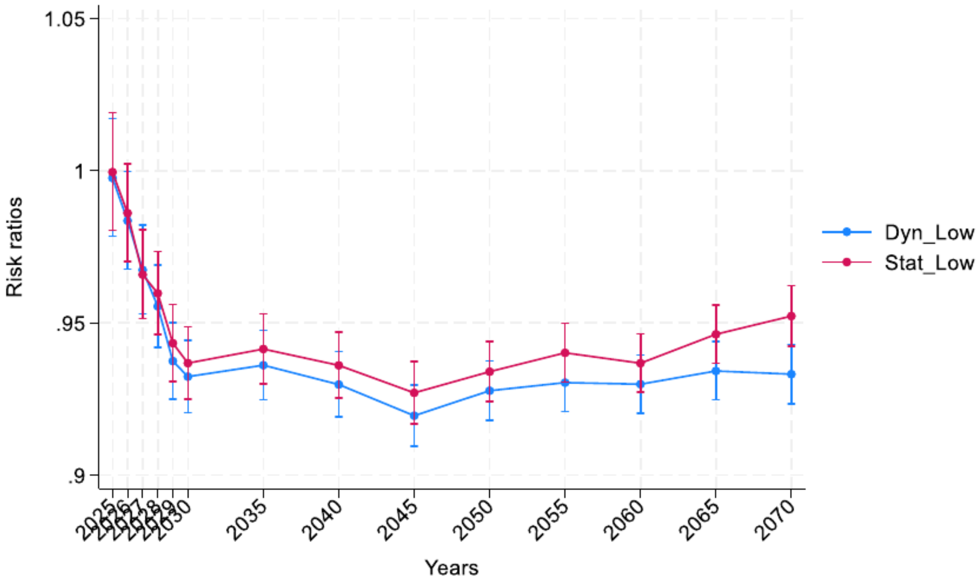


Figure 4. Diabetes prevalence differences between static and dynamic approaches in Option A relative to the benchmark (risk ratios) between 2025 and 2070

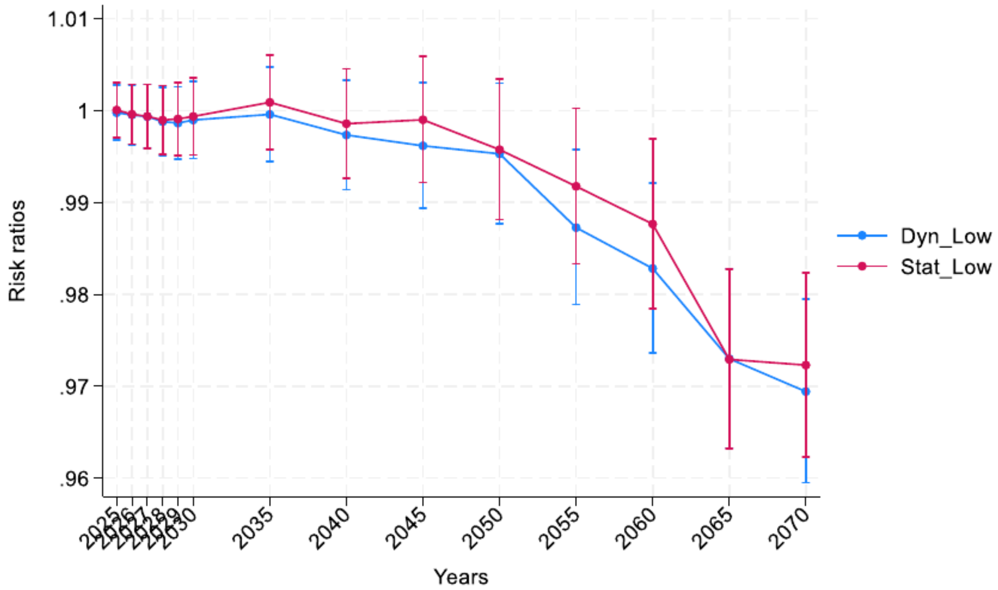


Figure 5. Stroke prevalence differences between static and dynamic approaches in Option A relative to the benchmark (risk ratios) between 2025 and 2070

Option B price increase scenario

Figure 6. Cardiovascular disease prevalence differences between static and dynamic approaches in Option B relative to the benchmark (risk ratios) between 2025 and 2070

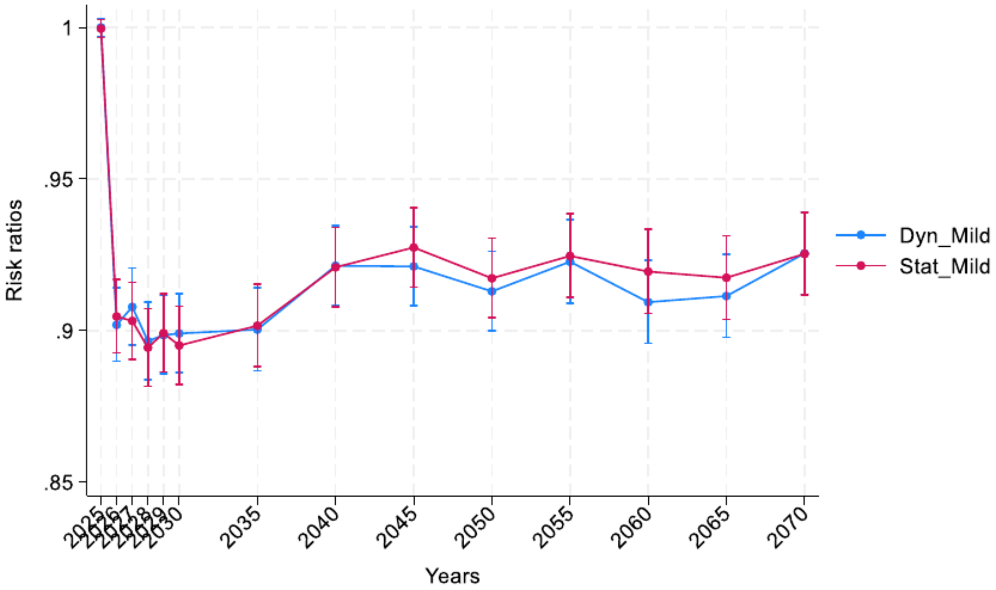


Figure 7. Cancer prevalence differences between static and dynamic approaches in Option B relative to the benchmark (risk ratios) between 2025 and 2070

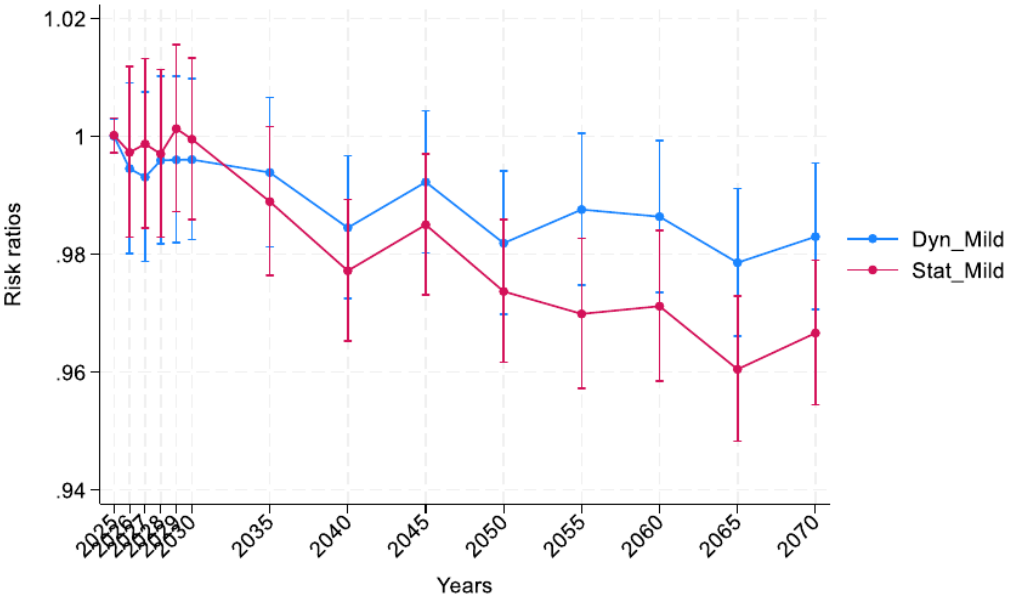


Figure 8. Chronic respiratory disease prevalence differences between static and dynamic approaches in Option B relative to the benchmark (risk ratios) between 2025 and 2070

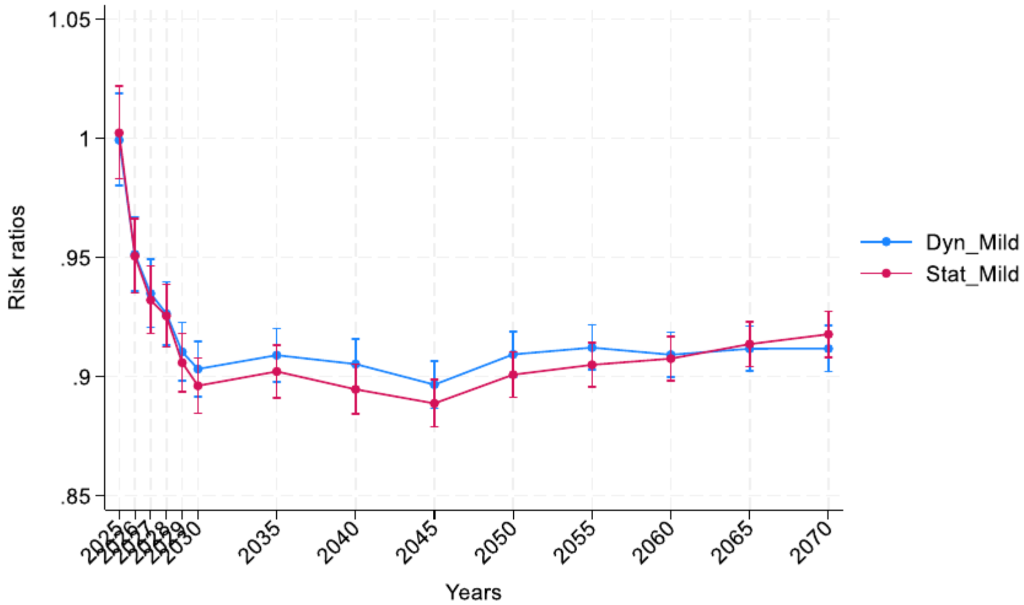


Figure 9. Diabetes prevalence differences between static and dynamic approaches in Option B relative to the benchmark (risk ratios) between 2025 and 2070

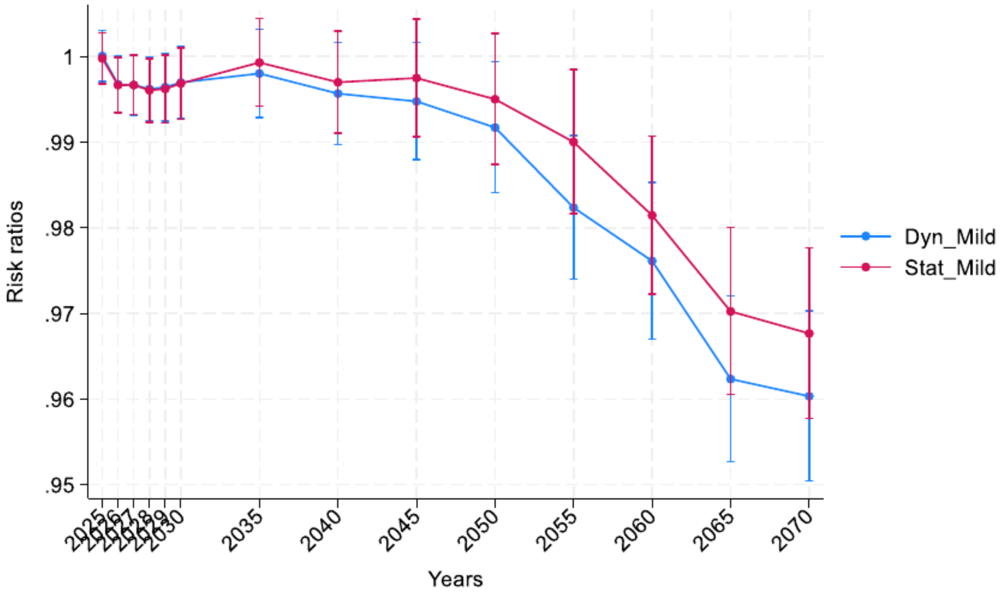
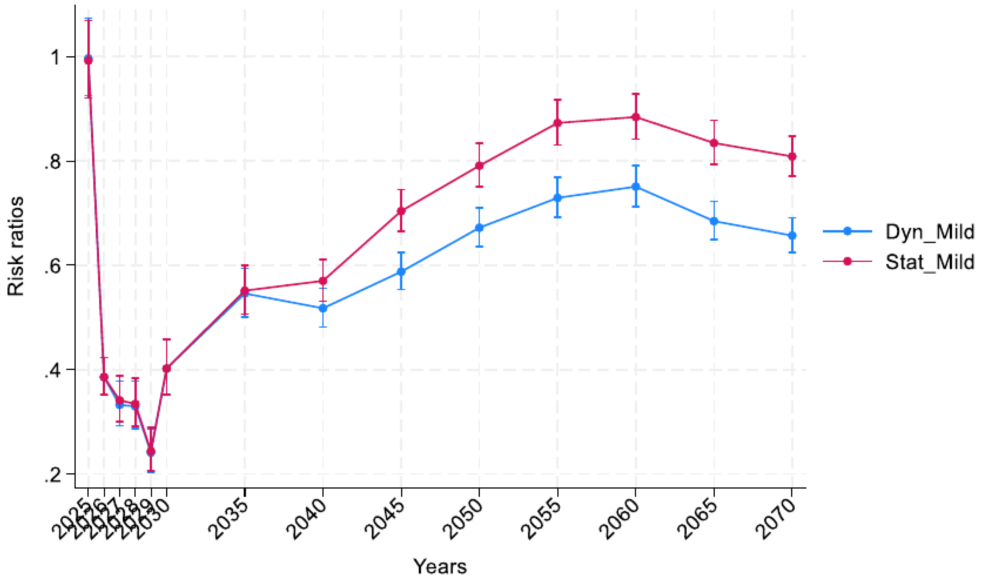


Figure 10. Stroke prevalence differences between static and dynamic approaches in Option B relative to the benchmark (risk ratios) between 2025 and 2070



Option C price increase scenario

Figure 11. Cardiovascular disease prevalence differences between static and dynamic approaches in Option C relative to the benchmark (risk ratios) between 2025 and 2070

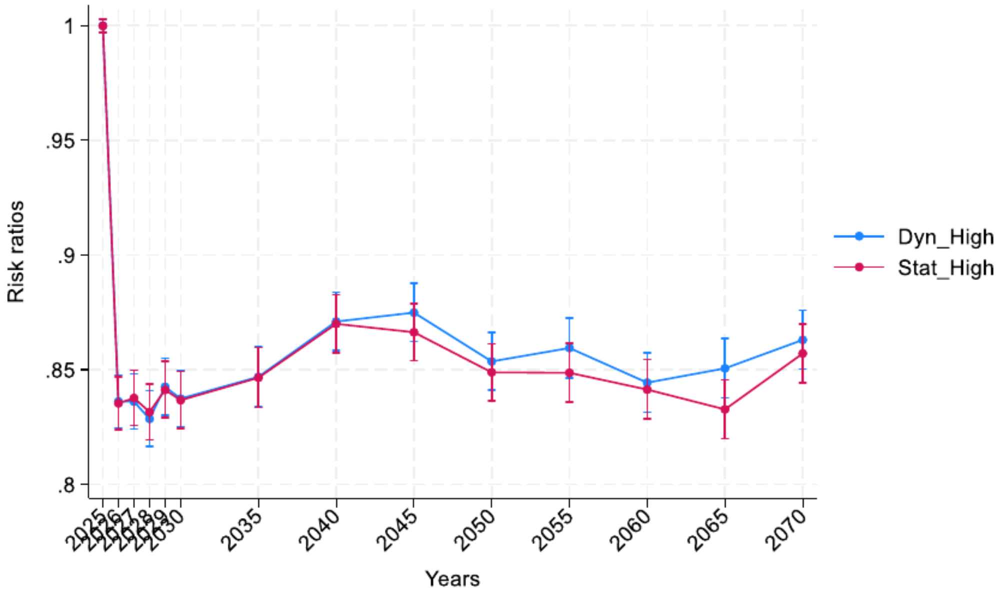


Figure 12. Cancer prevalence differences between static and dynamic approaches in Option C relative to the benchmark (risk ratios) between 2025 and 2070

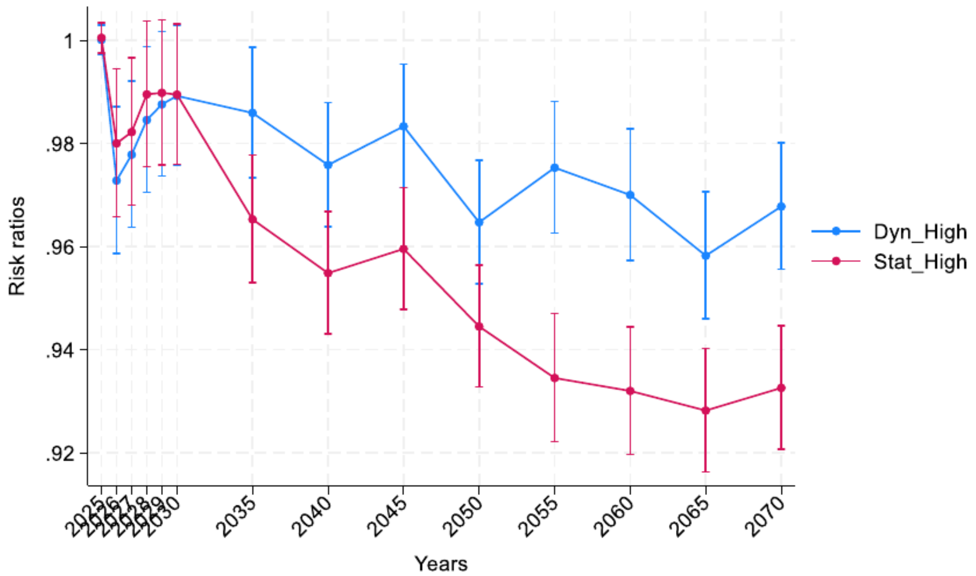


Figure 13. Chronic respiratory disease prevalence differences between static and dynamic approaches in Option C relative to the benchmark (risk ratios) between 2025 and 2070

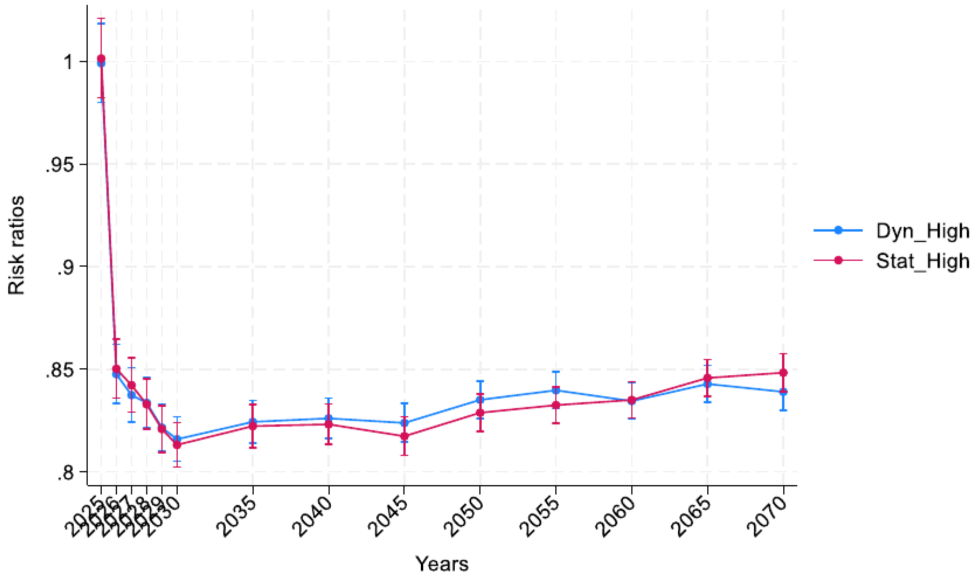


Figure 14. Diabetes prevalence differences between static and dynamic approaches in Option C relative to the benchmark (risk ratios) between 2025 and 2070

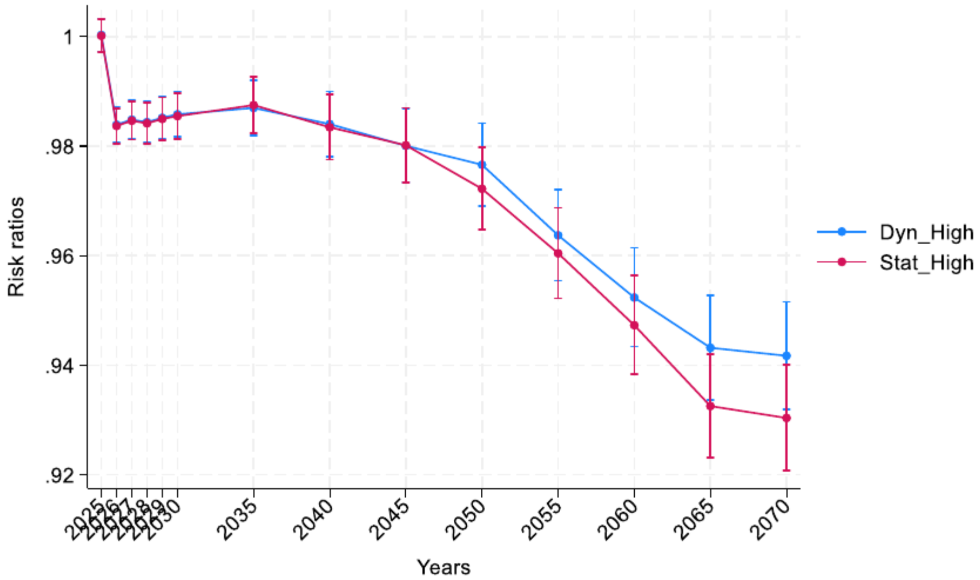
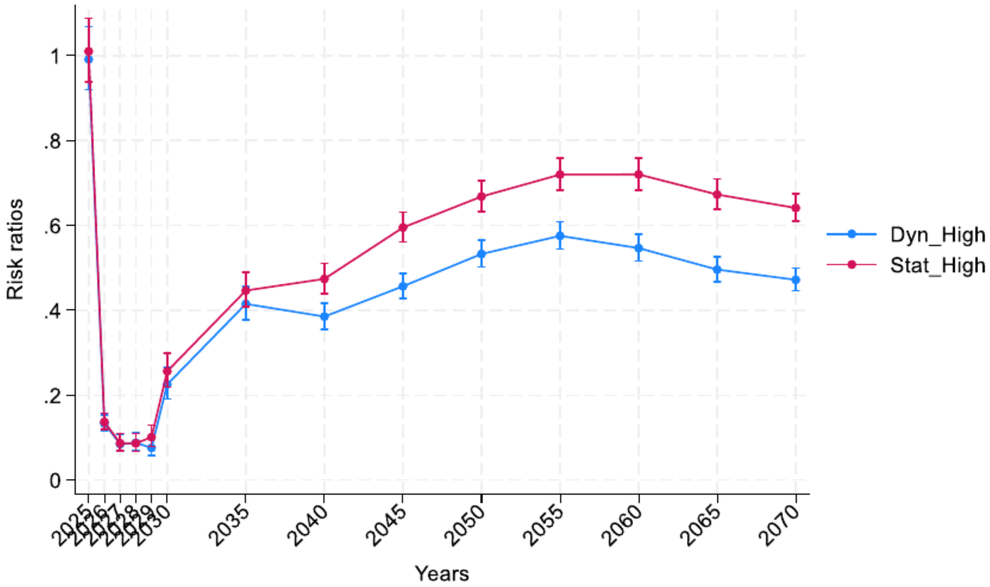


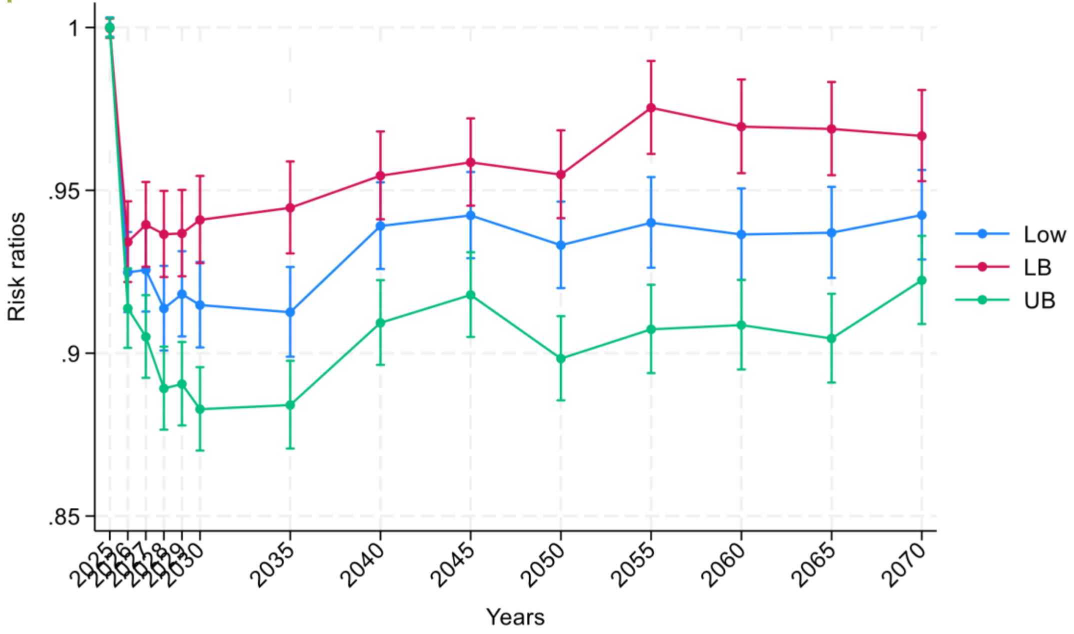
Figure 15. Stroke prevalence differences between static and dynamic approaches in Option C relative to the benchmark (risk ratios) between 2025 and 2070



5.4. Sensitivity analyses

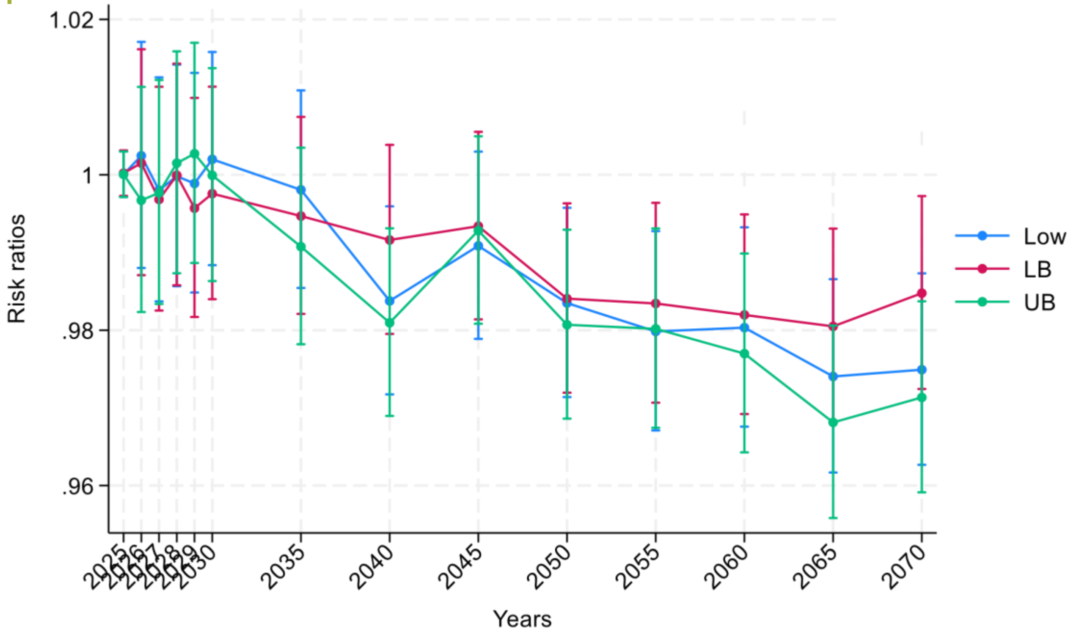
Lower and upper bounds for Option A

Figure 16. Cardiovascular disease prevalence in Option A (low), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



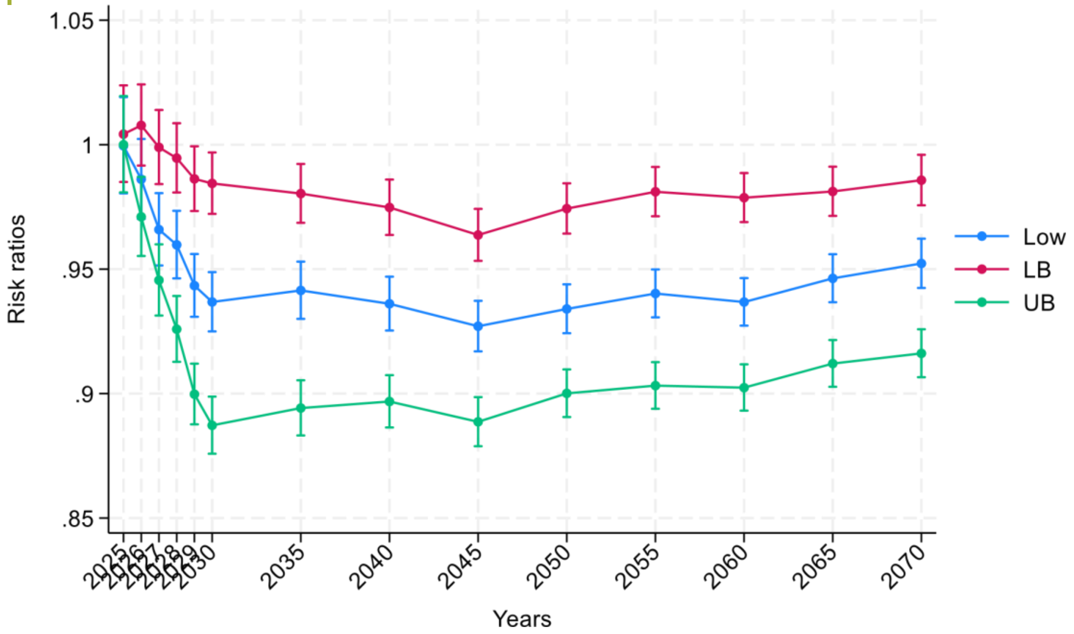
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 17. Cancer prevalence in Option A (low), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



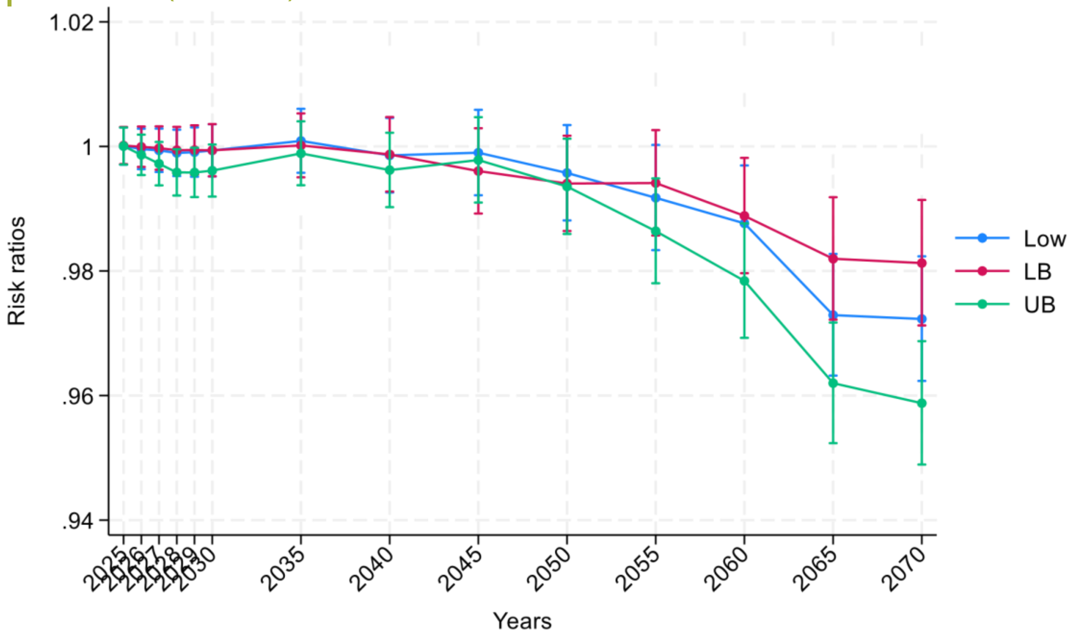
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 18. Chronic respiratory disease in Option A (low), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



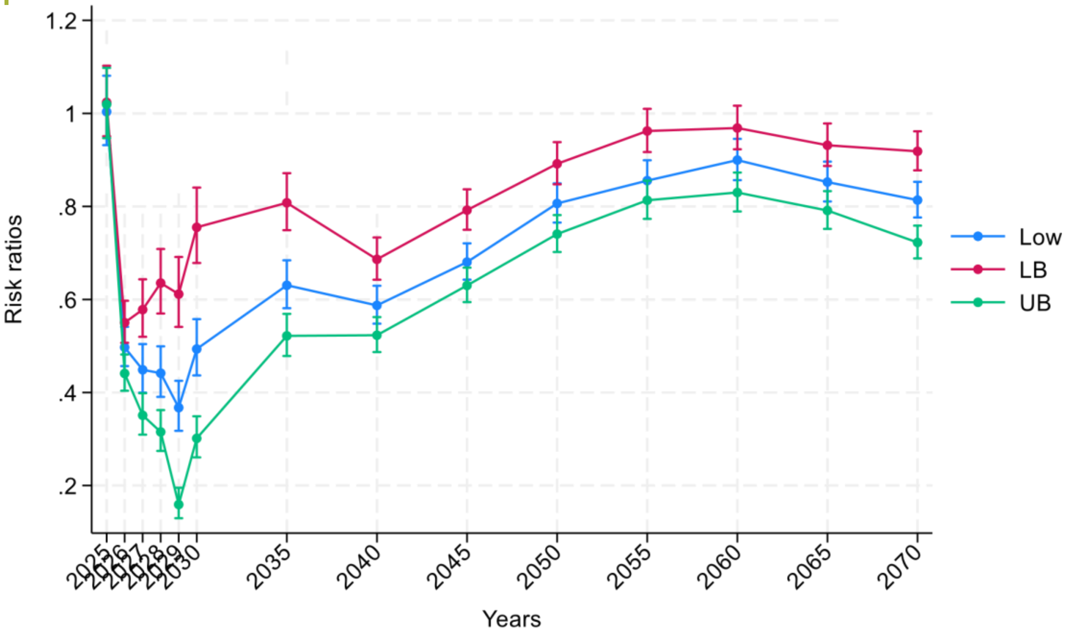
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 19. Diabetes prevalence in Option A (low), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

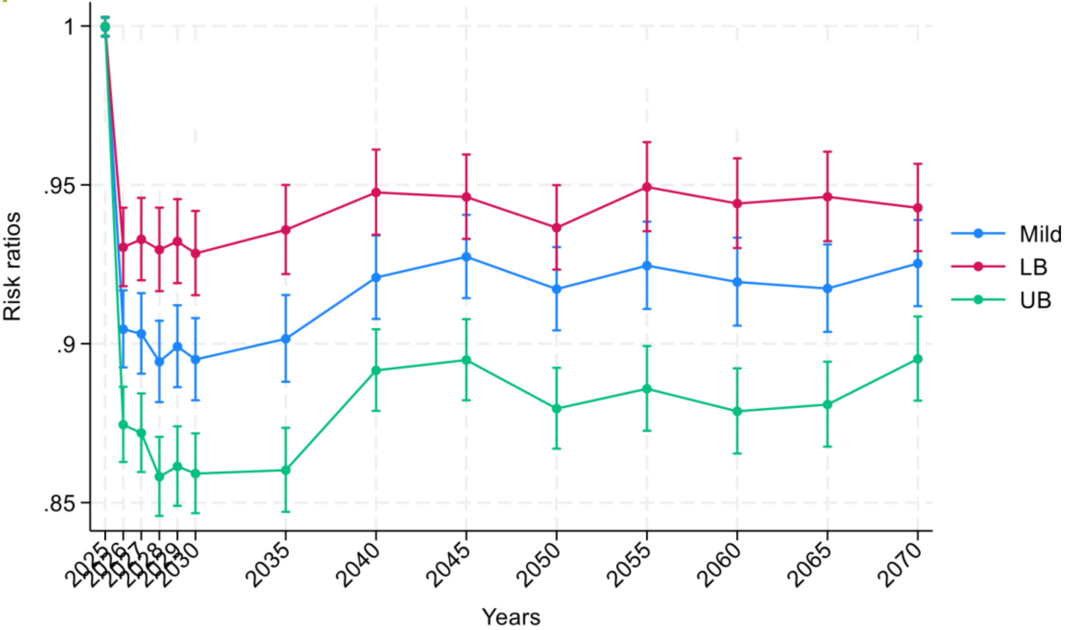
Figure 20. Stroke prevalence in Option A (low), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

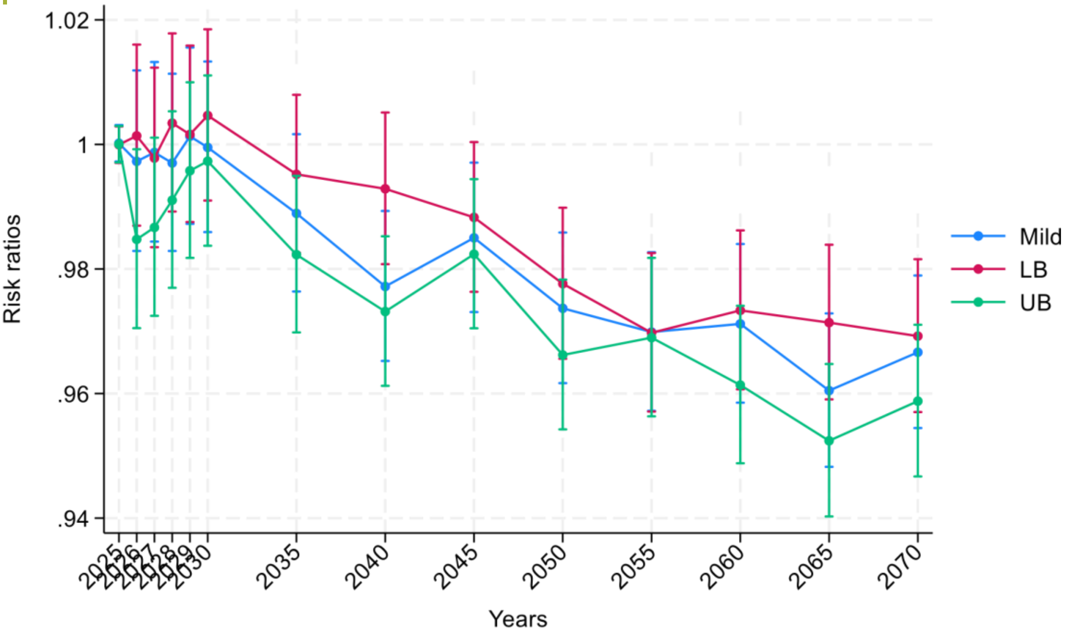
Lower and upper bounds for Option B scenario

Figure 21. Cardiovascular disease prevalence in Option B (mild), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



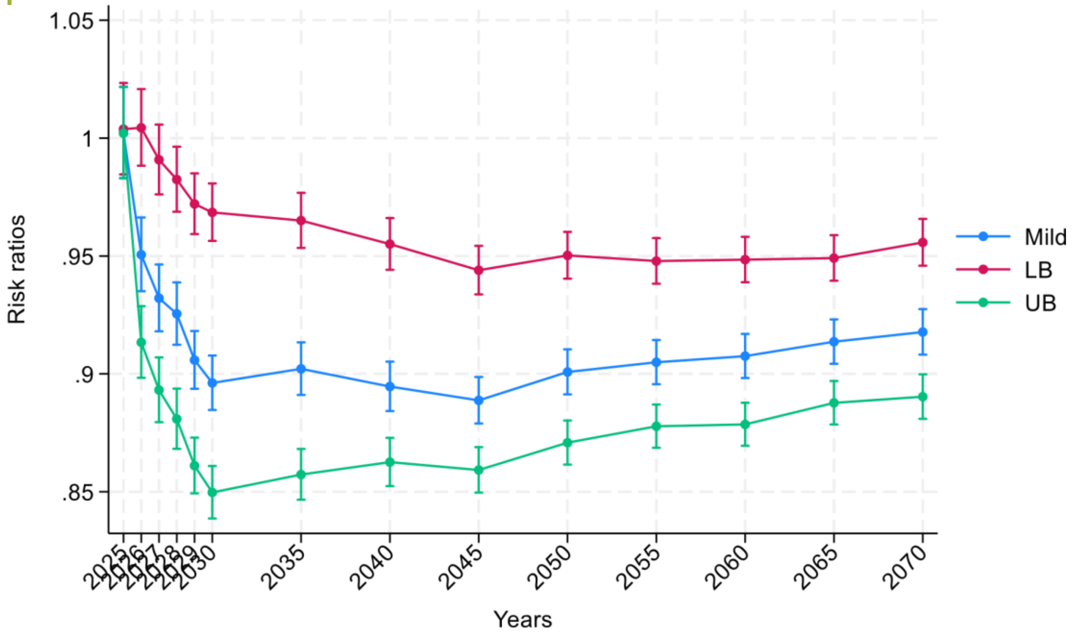
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 22. Cancer prevalence in Option B (mild), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



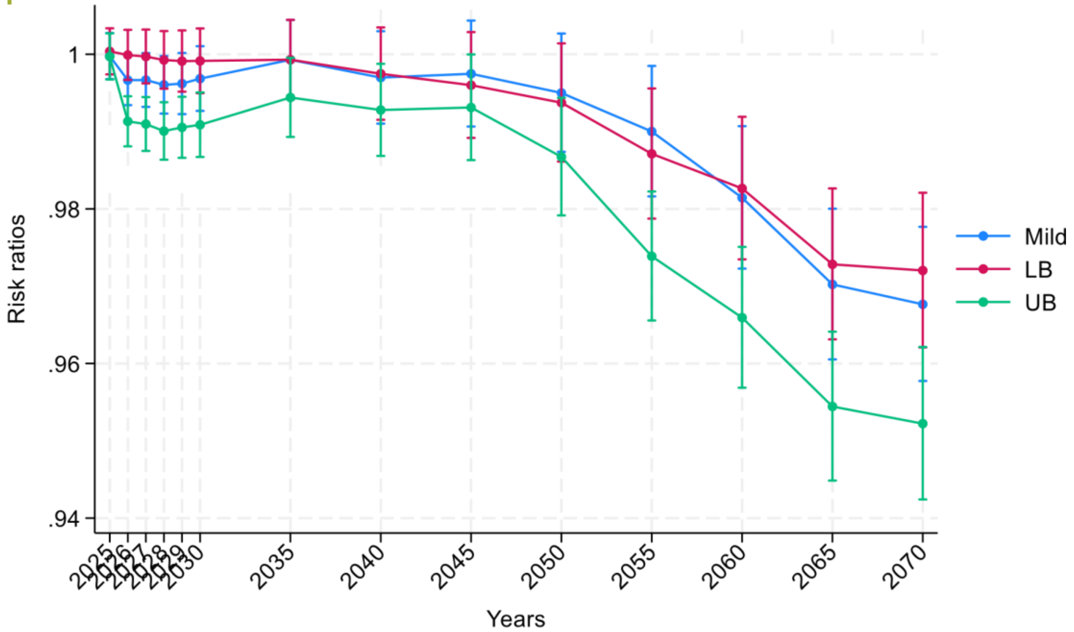
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 23. Chronic respiratory disease in Option B (mild), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



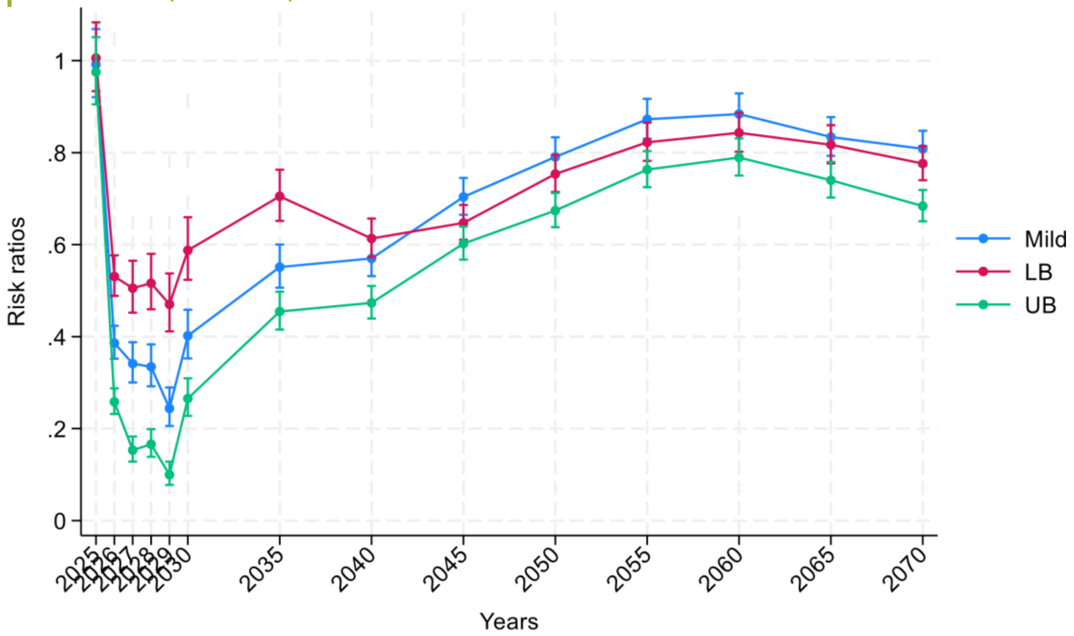
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 24. Diabetes prevalence in Option B (mild), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

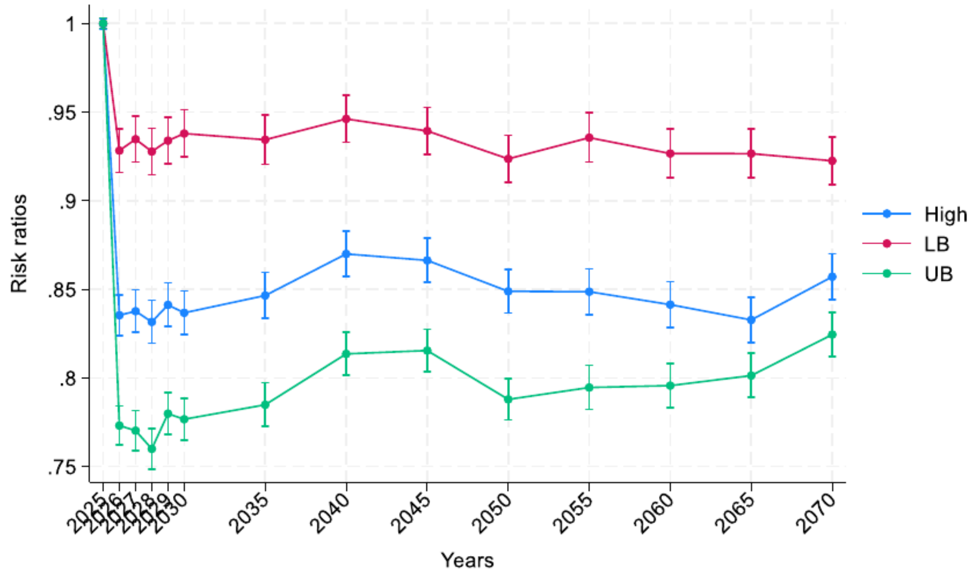
Figure 25. Stroke prevalence in Option B (mild), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

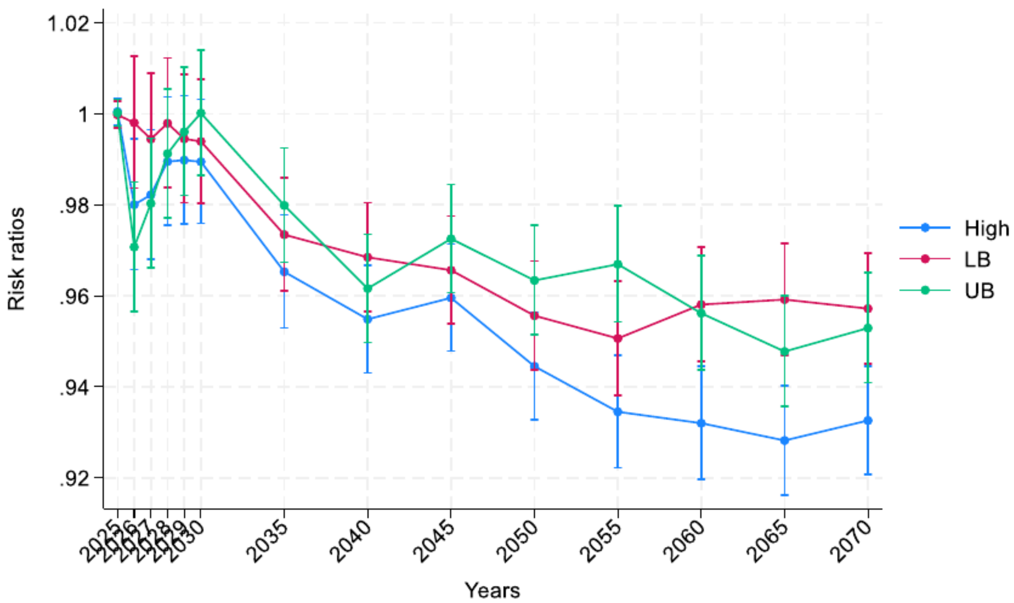
Lower and upper bounds for Option C scenario

Figure 26. Cardiovascular disease prevalence in Option C (high), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



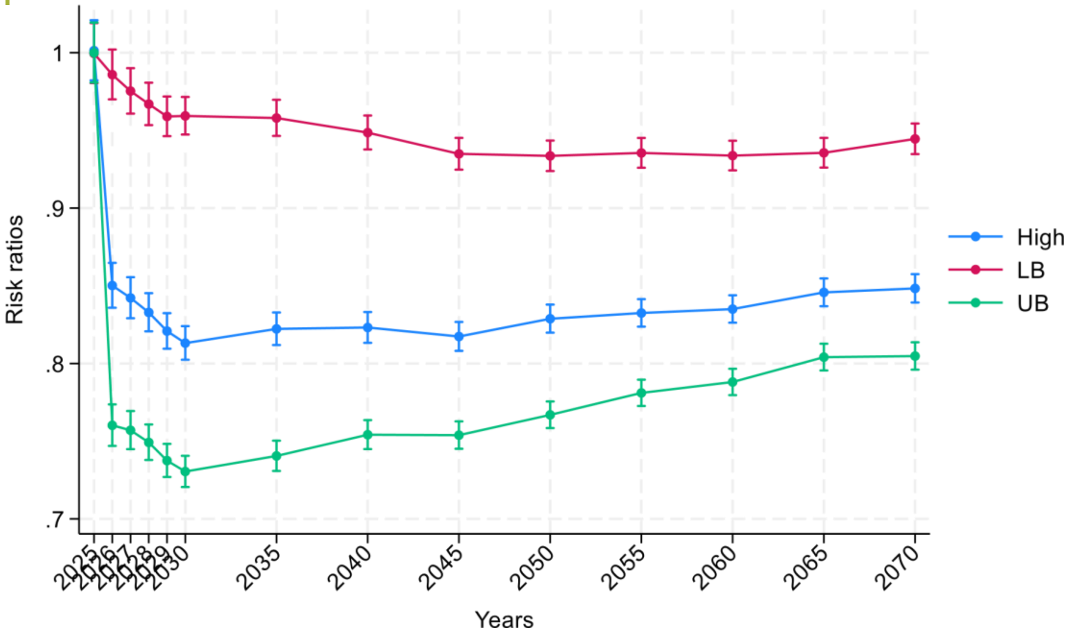
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 27. Cancer prevalence in Option C (high), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



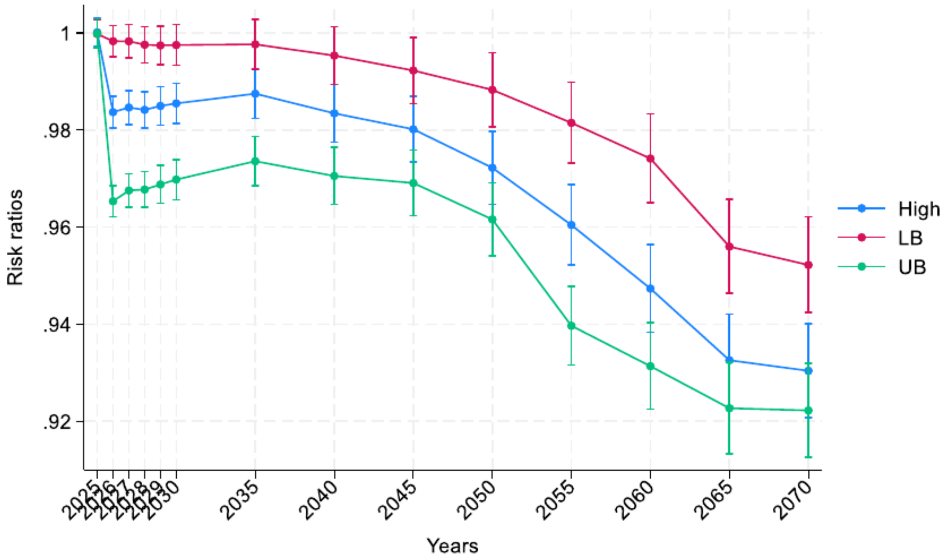
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 28. Chronic respiratory disease in Option C (high), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



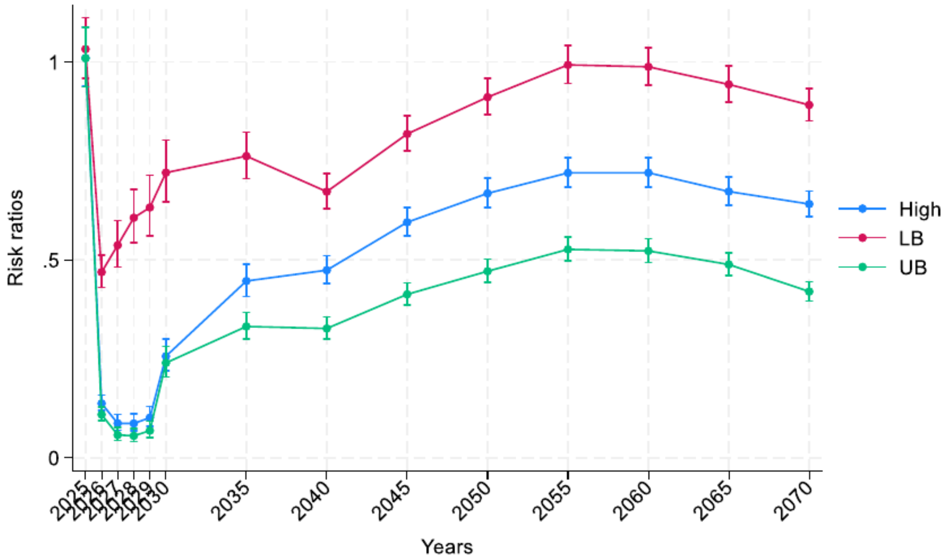
Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 29. Diabetes prevalence in Option C (high), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Figure 30. Stroke prevalence in Option C (high), lower and upper bound scenarios relative to the benchmark (risk ratios) between 2025 and 2070



Note: The blue line represents simulations results based on the standard price elasticities, the red line based on the lower bounds and the green line the upper bounds.

Results based on different elasticities by education status

Figure 31. Cardiovascular disease prevalence in the Option A (low), Option B (mild) and Option C (high) price increase scenarios relative to the benchmark (risk ratios) between 2025 and 2070, using elasticities by age and education

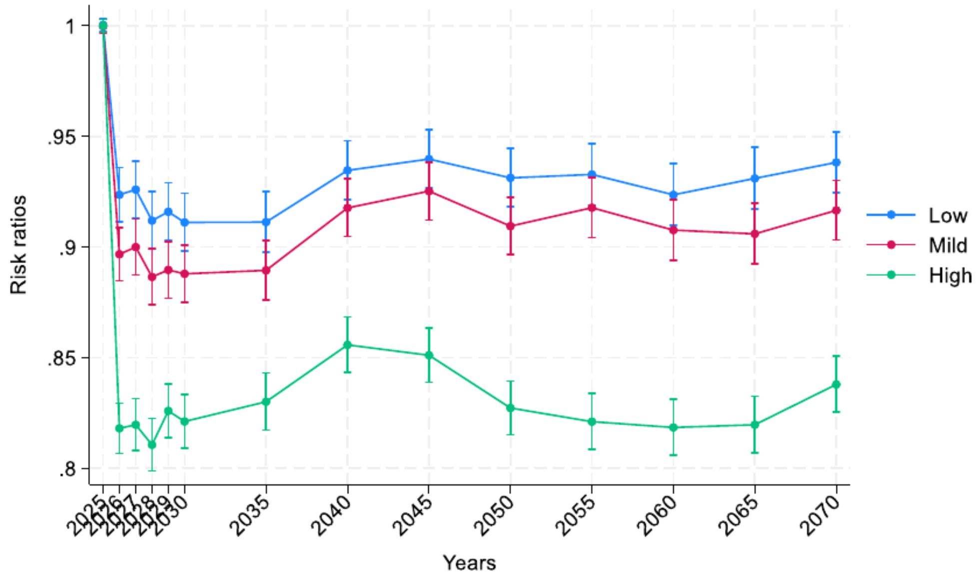


Figure 32. Cancer prevalence in Option A (low), Option B (mild) and Option C (high) price increase scenarios relative to the benchmark (risk ratios) between 2025 and 2070, using elasticities by age and education

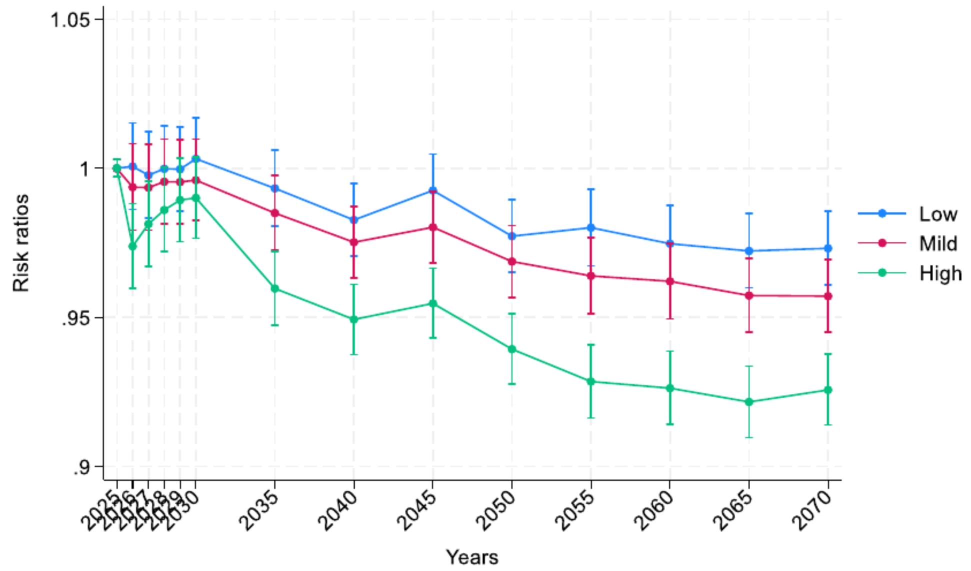


Figure 33. Chronic respiratory disease prevalence in Option A (low), Option B (mild) and Option C (high) price increase scenarios relative to the benchmark (risk ratios) between 2025 and 2070, using elasticities by age and education

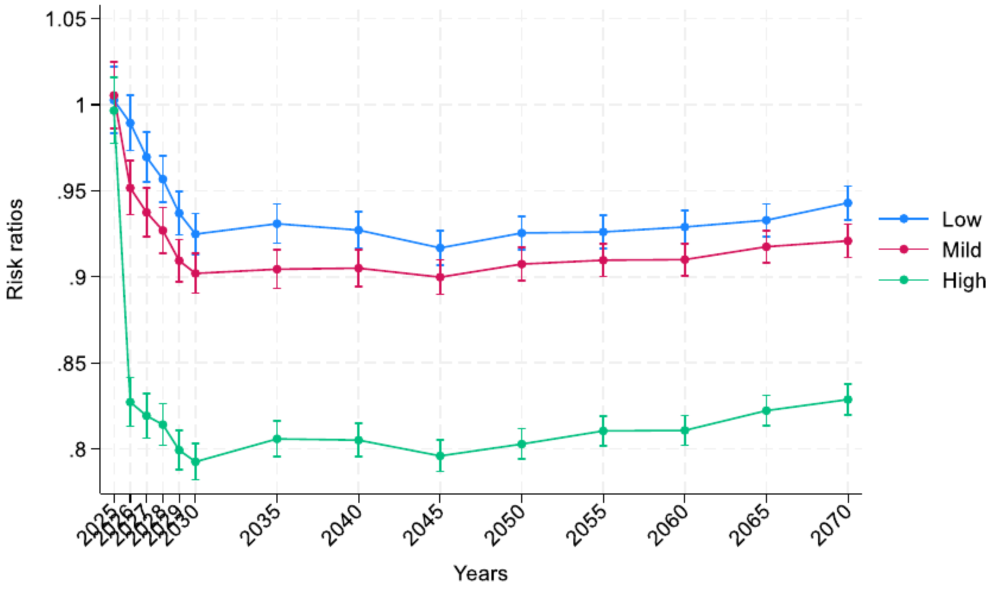


Figure 34. Diabetes prevalence in the Option A (low), Option B (mild) and Option C (high) price increase scenarios relative to the benchmark (risk ratios) between 2025 and 2070, using elasticities by age and education

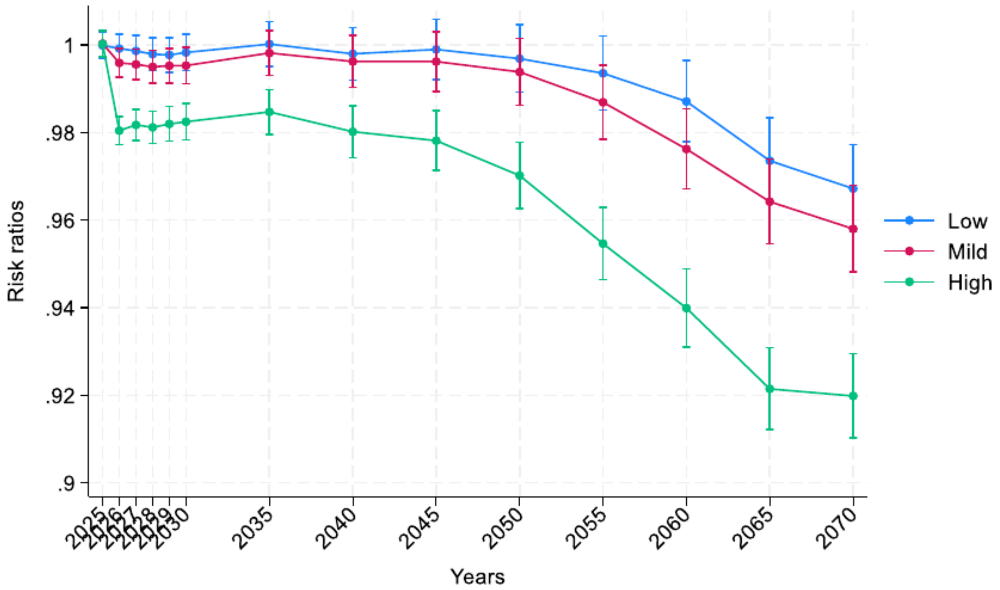
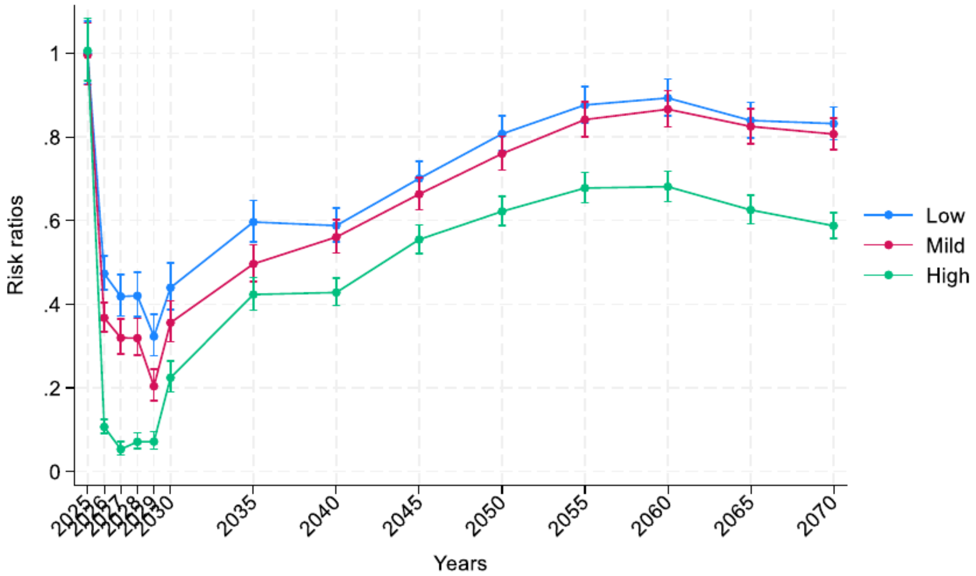


Figure 35. Stroke prevalence in the Option A (low), Option B (mild) and Option C (high) price increase scenarios relative to the benchmark (risk ratios) between 2025 and 2070, using elasticities by age and education



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