Supplemental Appendix for "Power of Personalized Smoking Cessation: A Quantitative Lifecycle Framework for Policy Evaluation"

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In this Appendix, Section A provides more data on smoking behavior and demographics. Section B shows the model optimization and characterization, followed by an explanation of the algorithm for solving the numerical model in Section C. Section D defines the the death hazard measures, and Section E derives the policy effectiveness measures, CE and IE. Section F presents two robustness analyses, and Section G provides all Appendix Tables and Figures.

A. Data and Evidence

For a general impact of smoking, see Tobacco Use and Dependence Guideline Panel (2008) and WHO Reports (2009, 2011).

The cross-sectional data from PSID (1999-2011) show that the share of current smokers among the US adult population (whites and blacks at age above 18) is 24.6%, the average CPD among smokers is 13.97, and the average expenditure on tobacco is 6.5% of labor income among smokers and 1.6% among the adult population. While the share of smokers does not differ much across genders and races, it varies substantially across education groups (29.9% for non-college but only 9.2% for college-educated). Among the eight demographic groups by gender, race, and education, non-college educated female whites have the largest share of smokers (almost 40%), followed by two non-college male groups (black and white, for which the share of smokers is about 30%).

Regarding smoking intensity measured by CPD, males smoke more than females on average (15.0 versus 11.0), whites smoke more than blacks (16.0 versus 9.8), and the non-college educated smoke more than college educated (14.1 versus 11.1). While the non-college educated male whites have the highest average CPD (17.5), the non-college educated female blacks have the highest smoking expenditure to labor income share (8.6%).

In addition, we look at persistence of smoking activity using the duration of regular smoking for those who ever smoked (but are not smoking currently) from PSID, and find that on average males smoke longer than females (15.1 versus 13.5 years), whites smoke longer than blacks (15.1 versus 13.6 years), and the non-college educated smoke longer than college educated (15.1 versus 13.5 years). All the differences are statistically significant.

B. Model: Optimization and Characterization

To solve the dynamic optimization problem for a smoker, we set up the current-value Hamiltonian for each given value of life expectancy $T \geq 65$ and bequest $a(T)$:

$$\begin{aligned}\mathcal{H}\left(c(t), s(t), x(t), \lambda_k(t), \lambda_a(t), \lambda_h(t), t\right) &= \ln(c(t)) + \alpha I_\alpha \ln\left(\frac{s(t)}{(S_0 k(t))^\nu}\right) + \beta(t)\ln(\widetilde{h}(t)) \\ &\quad + \lambda_k(t)\varsigma\left[s(t) - k(t)\right] \\ &\quad + \lambda_a(t)\left[r(t)a(t) + y\left(\widetilde{h}(t), t\right) - c(t) - p(t)s(t) - x(t)\right] \\ &\quad + \lambda_h(t)\{\Phi(t)x(t)^\epsilon - [\widetilde{\delta} + \widetilde{\gamma}(t)(s(t) + q\overline{s}(t))]\}\widetilde{h}(t)^\mu\end{aligned}$$

where λ_k,λ_a, and λ_h are the costate variables associated with smoking habit evolution, asset accumulation, and health capital evolution equations (2), (5), and (7). For the remainder of the Appendix, we will suppress time index t whenever that does not cause confusion.

Applying the Pontryagin Maximum Principle in optimal control theory, we can obtain three FOCs with respect to c, s, and x, and three Euler equations (EE) with respect to k, a, and $\widetilde{h}$ as below:

FOCs:

$$\begin{aligned} c:&\quad \tfrac{\partial \mathcal{H}}{\partial c} = \tfrac{1}{c} - \lambda_a = 0 \\ s:&\quad \tfrac{\partial \mathcal{H}}{\partial s} = \tfrac{\alpha}{s} + \lambda_k\varsigma - \lambda_a p - \lambda_h\widetilde{\gamma}(t)\widetilde{h}(t)^\mu = 0 \\ x:&\quad \tfrac{\partial \mathcal{H}}{\partial x} = -\lambda_a + \lambda_h\Phi(t)\epsilon x^{\epsilon-1}\widetilde{h}(t)^\mu = 0\end{aligned}$$

EEs:

$$\begin{aligned} k:&\quad \rho\lambda_k - \dot{\lambda}_k = -\tfrac{\alpha\nu}{k} - \lambda_k\varsigma \\ a:&\quad \rho\lambda_a - \dot{\lambda}_a = \lambda_a r \\ h:&\quad \rho\lambda_h - \dot{\lambda}_h = \tfrac{\beta(t)}{h} + \lambda_a\tfrac{\partial y}{\partial h} + \lambda_h\{\Phi(t)x^\epsilon - [\widetilde{\delta}(t) + \widetilde{\gamma}(t)(s + q\overline{s})]\}\mu\widetilde{h}(t)^{\mu-1}\end{aligned}$$

Totally differentiating the three FOCs and manipulating them produces equations (10) and (11), and the following conditions for the dynamic optimization problem:

$$\frac{s}{c} = \frac{\alpha + \lambda_k\varsigma s}{p + \widetilde{\gamma}(t)/(\Phi(t)\epsilon x^{\epsilon-1})} \tag{A1}$$

$$\dot{\lambda}_k = \frac{\nu\alpha}{k} + (\rho + \varsigma)\lambda_k \tag{A2}$$

$$\frac{\Phi(t)\epsilon x^{\epsilon-1}}{\widetilde{\gamma}(t)}\left[\frac{\nu\alpha\varsigma c}{k} - \frac{\alpha c}{s}\left(\rho + \varsigma + \frac{\dot{s}}{s}\right) + p(r+\varsigma)\right] + \left[r + \frac{\dot{\Phi}(t)}{\Phi(t)} - (1-\epsilon)\frac{\dot{x}}{x} + \varsigma\right] = \frac{\dot{\widetilde{\gamma}}(t)}{\widetilde{\gamma}(t)} \tag{A3}$$

Note that (A2) is a first-order differential equation depending only on $\{k\}$. Thus, the general solution is $\lambda_k(\{k\}, t)$ and a higher habit stock k lowers the shadow value of the habit, λ_k. This and (A1) imply (13).

Similar conditions can be derived for smokers with life expectancy $T < 65$. As such, combining (11) and (A3) yields

$$\frac{\Phi(t)\epsilon x^{\epsilon-1}}{\widetilde{\gamma}(t)}\left[\frac{\nu\alpha\varsigma c}{k} - \frac{\alpha c}{s}\left(\rho + \varsigma + \frac{\dot{s}}{s}\right) + p(r+\varsigma) + \widetilde{\gamma}(t)\widetilde{h}^\mu\left(\frac{\beta(t)c}{\widetilde{h}} + \theta w \cdot \mathbf{1}_{t\leq 65}\right)\right] + \varsigma = \frac{\dot{\widetilde{\gamma}}(t)}{\widetilde{\gamma}(t)} \tag{A4}$$

which can be manipulated to yield (12).

A nonsmoker's problem is simpler than a smoker's; the current-value Hamiltonian for given T and $a(T)$ can be written as:

$$\begin{aligned}\mathcal{H}\left(c(t), x(t), \lambda_a(t), \lambda_h(t), t\right) &= \ln(c(t)) + \beta(t)\ln(\widetilde{h}(t)) \\ &\quad + \lambda_a(t)\left[r(t)a(t) + y\left(\widetilde{h}(t), t\right) - c(t) - x(t)\right] \\ &\quad + \lambda_h(t)\{\Phi(t)x(t)^\epsilon - [\widetilde{\delta} + \widetilde{\gamma}(t)q\overline{s}(t)]\}\widetilde{h}(t)^\mu\end{aligned}$$

from which one can derive FOCs and EEs and characterize the dynamic path of all variables accordingly.

C. Algorithm for Solving the Numerical Model

Although we cannot solve analytically the entire dynamic path of $\left\{c(t), s(t), x(t), k(t), a(t), \widetilde{h}(t)\right\}_{t=t_0}^{T}$, (10), (11), (12), together with the three evolution conditions (2), (5), and (7), and the initial conditions can be used to solve numerically for the dynamic path above.

The algorithm for solving the numerical model is as follows. We discretize the life span so that one year corresponds to one period; and we set $t_0 = 18$ so that individual choice starts at age $t_0 + 1 = 19$.

In the first step, for each given T, we choose $\{c(19), s(19), x(19)\}$ to achieve highest lifetime utility, subject to the terminal health condition (i.e., $\widetilde{h}(T) = \underline{h}$); that is, the resulting path of $\{s(t), x(t)\}$ ensure a life expectancy of T. Note that once $\{c(19), s(19), x(19)\}$ is chosen, the entire path of $\{c(t), s(t), x(t), k(t), a(t), \widetilde{h}(t)\}_{t=19}^{T}$ can be pinned down using the discrete-time approximations of (2), (5), (7), (10), (11), and (12). The optimal bequest $a(T)$ – the terminal value of the asset path is also determined. In the second step, we repeat the first step for different values of T, and choose the T that achieves the highest $V(T; \mathcal{T}, I_\alpha(t_0))$ – this determines the optimal dynamic path of $\{c(t), s(t), x(t), k(t), a(t), \widetilde{h}(t)\}_{t=19}^{\tilde{T}}$ as well as the optimal life expectancy, $\tilde{T}$.

For a nonsmoker, we set $s(t) = k(t) = 0$ for all t, while the path of other variables can be solved for using the same method as for a smoker's problem.

When a smokers receives a cessation treatment at age t_p, whether counseling (which affects α_τ) or counseling plus medication (which affects both α_τ and σ_τ), she reoptimizes, taking $\{k(t_p), a(t_p), \widetilde{h}(t_p)\}$ and $\{\breve{\alpha}_\tau, \breve{\sigma}_\tau, T_k\}$ as given. First, for each value of the *remaining* life years, T_r, she chooses $\{c(t_p), x(t_p)\}$ to maximize the *remaining* lifetime utility conditional on quitting at t_p, subject to the terminal health condition (i.e., $\widetilde{h}(t_0 + T_r) = \underline{h}$); that is, the resulting path of $\{x(t)\}$ ensures a remaining life expectancy of T_r. As above, the path of $\{c(t), x(t), a(t), \widetilde{h}(t)\}_{t=t_p}^{t_p+T_r}$ can be determined using the discrete-time approximations of (5), (6),(10), and (11), and the new optimal bequest, $a(t_p + T_r)$, can also be determined. In the second step, we repeat the first step for different values of T_r and choose the T_r that achieves the highest *remaining* lifetime utility, denoted as $V_r(\breve{T}_r; \mathcal{T}, I_\alpha(t_p) = 0)$. In the third step, we compare $V_r(\breve{T}_r; \mathcal{T}, I_\alpha(t_p) = 0)$ and the remaining life time utility in the benchmark case without treatment/quit; if the former is larger, the smoker quits at t_p, otherwise she remains addicted with $\{\alpha, \sigma\}$ unchanged.

D. Death Hazard Measures

Assuming that the mortality rate at age t, $d(t)$, is the inverse of health status (Hall and Jones, 2007), given that health evolution is an exponential process, we have

$$d(t) = \frac{1}{h(t_0) e^{-\int_{t_0}^{t} \{\delta + \gamma(t')[I_\alpha(t') \cdot s(t') + q\bar{s}(t')]\}/h(t')^{1-\mu} dt'}} \tag{A5}$$

where an adolescent smoker ($I_\alpha(t_0) = 1$) may quit at $t_q \in (t_0, T)$ after which $I_\alpha(t) = 0$ for $t \geq t_q$. Then the overall death hazard at age t is

$$DH(t; \delta, I_\alpha(t_0)) \equiv \frac{d(t)}{prob_{suv}(t)} = \frac{e^{\int_{t_0}^{t} \{\delta + \gamma(t')[I_\alpha(t') \cdot s(t') + q\bar{s}(t')]\}/h(t')^{1-\mu} dt'}}{h(t_0) \cdot prob_{suv}(t)} \tag{A6}$$

where $prob_{suv}(t)$ denotes the survival probability at age t. The death hazard from smoking alone is then $DH(t; 0, 1)$ (i.e., by setting $\delta = 0$).

E. Policy Effectiveness Measures

Mathematically, with health perception consistency ($\tilde{h} = h$), the Consumption Equivalent (CE) is determined by

$$\int_{t_0}^{T} e^{-\rho(t-t_0)}[\ln(c(1+CE)) + \alpha \ln\left(\frac{s}{(S_0 k)^{\nu}}\right) + \beta(t)\ln\left(\tilde{h}\right)]dt + e^{-\rho(T-t_0)}\bar{U}(a(T)) = \check{V} \tag{A7}$$

where $\check{V}$ is the lifetime utility when the individual is covered by a particular policy. Denote by V_0 the untreated lifetime utility in the absence of a policy intervention or voluntary take-up:

$$V_0 \equiv \int_{t_0}^{T} e^{-\rho(t-t_0)}[\ln(c) + \alpha \ln\left(\frac{s}{(S_0 k)^{\nu}}\right) + \beta(t)\ln\left(\tilde{h}\right)]dt + e^{-\rho(T-t_0)}\bar{U}(a(T)) \tag{A8}$$

We thus obtain

$$CE = \exp\left[\frac{\rho\left(\check{V} - V_0\right)}{1 - e^{-\rho(T-t_0)}}\right] - 1 \tag{A9}$$

Similarly, the Income Equivalent (IE) is determined by

$$\int_{t_0}^{T} e^{-r(t-t_0)}\left[c\left(1+CE\right) + x + ps\right]dt = \int_{t_0}^{T} e^{-r(t-t_0)} y\left(1+IE\right)dt \tag{A10}$$

Applying (A9) and manipulating, we obtain

$$IE = CE \cdot \frac{\int_{t_0}^{T} e^{-r(t-t_0)} c dt}{\int_{t_0}^{T} e^{-r(t-t_0)} y dt} = \frac{\int_{t_0}^{T} e^{-r(t-t_0)} c dt}{\int_{t_0}^{T} e^{-r(t-t_0)} y dt}\left\{\exp\left[\frac{\rho\left(\check{V} - V_0\right)}{1 - e^{-\rho(T-t_0)}}\right] - 1\right\} \tag{A11}$$

F. Robustness Analyses

We conduct two sets of robustness analyses, with one considering the net deadweight cost of medical treatment and the other a lump-sum tax imposed on all agents to finance the government subsidy. The results are summarized in Table A9.

In the benchmark case, the cessation treatment cost includes the monetary cost of treatment incurred by smokers and the government, plus the time cost for smokers. However, the monetary cost is eventually paid to hospitals, pharmaceutical companies, and medical professionals; thus, the total cost to the society is not as large. We thereby reevaluate the policies by only considering the deadweight cost. To do this, we add back the total monetary cost of treatment as a lump-sum transfer to subsidized smokers at age 37 or 52. The results of policy evaluation are very close to the benchmark values. The income effect generated from the lump-sum transfer may either have a positive effect on health due to a larger health care budget, or a negative effect on health due to more cigarettes purchased. The overall effect turns out to be small but positive.

One may argue, on the contrary, that government subsidy should be financed by taxation. We thus reevaluate the policies by considering a lump-sum tax on all agents (both smokers and nonsmokers). Because the amount of subsidy is modest, alternative financing (via income tax or cigarette tax) would not change the results much. One can see that the results of policy evaluation are quantitatively even closer to the benchmark values, for the reasons discussed above.

G. Appendix Tables and Figures

Supplementary tables and figures are provided in this appendix.

Table A1. Smoking Behavior by Demographics

gender	race	education	share of smokers (%)	smoking expenditure share (%)	CPD of smokers
female	black	noncollege	23.9	8.6	8.60
female	white	noncollege	39.5	7.8	13.55
female	black	college	11.1	5.0	12.85
female	white	college	11.6	3.2	9.27
male	black	noncollege	31.2	6.7	10.55
male	white	noncollege	29.2	6.2	17.64
male	black	college	14.1	2.0	9.63
male	white	college	7.9	2.3	12.74
all			24.6	6.5	13.97

Table A2. Numerical Example on Lifecycle Smoking Intensity

	age				
individual CPD by age	18	37	52	61	69
1 (never quit light smaller die 72)	4	3.9	3.8	3.7	3.6
2 (quit at 37, die 74)	8	0	0	0	0
3 (quit at 52, die at 69)	12	11	0	0	0
4 (quit at 65, die the same year)	20	19	18	16	0
5 (die at 61)	30	29	28	0	0
average CPD conditional on being alive	14.8	12.6	10.0	4.9	1.8
average CPD conditional on active smokers being alive	14.8	15.7	16.6	9.9	3.6

Table A3. Gains in Life Years by Demographic Groups

by demographics				gain in LY at age 37	gain in LY at age 52
gender	race	education	θ		
female	black	noncollege	0.63	10.81	4.49
female	white	noncollege	0.79	10.76	5.20
female	black	college	1.13	12.09	5.71
female	white	college	1.13	11.65	5.76
male	black	noncollege	0.77	8.66	2.29
male	white	noncollege	1.10	9.47	3.17
male	black	college	1.36	10.15	4.28
male	white	college	1.46	10.85	4.44

Notes: Gains in life years (LY) of smokers who are treated and quit at age 37 and 52 under policy S are reported for each demographic group (along with work efficiency θ).

Table A4. CE and IE of Subsidized Smokers (Net of Voluntary Take-up) by Demographics (%)

					Consumption Equivalent (CE)						Income Equivalent (IE)					
					treated at age 37			treated at age 52			treated at age 37			treated at age 52		
demographics			%	θ	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$
female	black	noncollege	5	0.63	1.20	1.08	1.20	1.62	1.47	1.62	0.74	0.66	0.74	1.26	1.14	1.26
female	white	noncollege	45	0.79	2.75	2.28	2.74	5.93	5.16	5.93	1.92	1.57	1.91	4.63	4.01	4.62
female	black	college	0	1.13	1.93	1.71	1.93	4.29	4.07	4.28	1.31	1.15	1.31	3.24	3.07	3.24
female	white	college	5	1.13	3.54	2.86	3.53	7.37	6.47	7.36	2.54	2.03	2.53	5.60	4.90	5.60
male	black	noncollege	7	0.78	4.56	4.17	4.55	0.42	0.39	0.42	2.24	2.04	2.24	0.24	0.21	0.24
male	white	noncollege	34	1.10	3.92	3.46	3.91	1.02	0.83	1.02	2.07	1.83	2.06	0.71	0.57	0.71
male	black	college	1	1.36	3.91	3.58	3.90	0.33	0.29	0.33	2.15	1.97	2.15	0.26	0.23	0.26
male	white	college	3	1.46	3.84	3.29	3.83	0.95	0.79	0.95	2.15	1.83	2.14	0.76	0.63	0.76

Table A5. Policy Effectiveness without Considering Voluntary Take-up

	treated at age 37			treated at age 52		
	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$
expected CE of a subsidized smoker (%)	4.21	3.76	4.20	4.44	3.96	4.44
expected IE of a subsidized smoker (%)	2.53	2.23	2.53	3.39	3.02	3.39
expected transfer to a subsidized smoker (%)	2.37	2.11	2.36	3.27	2.91	3.27
cost/effectiveness ratio (C/E)	1/30.32	1/32.74	1/36.99	1/40.68	1/44.18	1/49.66
cost/effectiveness ratio (C/E), transfer-based	1/28.37	1/30.86	1/34.61	1/39.22	1/42.67	1/47.88

Table A6. Counterfactual Experiments

	treated at age 37				treated at age 52			
	b.m.	$q = 0$	$\tilde{\gamma} = \gamma$	$\chi = 0$	b.m.	$q = 0$	$\tilde{\gamma} = \gamma$	$\chi = 0$
$LEgain$ of a quitter (years)	10.08	10.27	9.68	10.62	4.87	5.74	4.74	4.91
quit rate (%)	31.7	22.8	26.3	40.8	35.6	50.3	48.0	52.1
CE of a quitter (%)	13.26	13.59	15.06	14.80	12.44	12.85	10.57	11.37
CE of subsidized - net (%)	3.26	1.75	3.01	4.59	3.57	5.13	4.09	4.73
C/E ratio - net	1/28.79	1/14.85	1/28.59	1/40.50	1/40.20	1/60.29	1/47.67	1/53.14

Notes: Table reports the effectiveness of policy P when each of the channels, second-hand smoke, limited health knowledge, and under valuation of health is shut down. The columns "b.m" report the corresponding measures from the benchmark policy experiments.

Table A7. Cessation Treatment Parameterization (Age 45)

A. Calibrated Parameters

Voluntary take-up	H1	H2	H3
45-37 ratio of taste response to counseling $\varpi_{\tau,\text{ratio}}$	1.06	1.22	0.31
45-37 ratio of habit survival response to medication $\varkappa_{\tau,\text{ratio}}$	n.a.	0.30	1.97
Policy-induced treatment			
change in 45-37 ratio of taste response to counseling $\triangle\varpi_{\tau,\text{ratio}}$	-0.11	-0.09	0.59
change in 45-37 ratio of habit survival response to medication $\triangle\varkappa_{\tau,\text{ratio}}$	n.a.	0.00	0.03

B. Model Fit

	data			model		
Voluntary take-up	H1	H2	H3	H1	H2	H3
quit rate ratio at age 45 to 37 after counseling	1.17	1.13	0.89	1.17	1.25	1.06
quit rate ratio at age 45 to 37 after counseling&medication	1.17	0.99	1.10	1.17	0.85	1.05
Policy-induced treatment						
quit rate ratio at age 45 to 37 after counseling	1.17	1.13	0.89	1.20	1.18	0.89
quit rate ratio at age 45 to 37 after counseling&medication	1.17	0.99	1.10	1.20	1.03	1.07

Table A8. Summary of Policy Comparison (Age 45)

	treated at age 45		
	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$
% subsidized	10	10	12.2
expected gain in life years $LEgain$ (years)	7.63	7.58	7.64
quit rate (%)	31.7	28.3	31.5
VSL gain of a quitter (2009 US$)	162,458	150,735	163,311
VSL gain of of a quitter (%)	9.77	9.17	9.82
expected CE of a quitter (%)	11.10	10.43	11.16
expected IE of a quitter (%)	8.27	7.68	8.31
expected transfer to a quitter (%)	8.08	7.52	8.12
expected CE of a subsidized smoker - net (%)	2.78	2.22	2.78
expected IE of a subsidized smoker - net (%)	2.09	1.64	2.08
expected transfer to a subsidized smoker - net (%)	1.97	1.56	1.97
cost/effectiveness ratio (C/E) - net	1/25.02	1/24.08	1/30.52
cost/effectiveness ratio (C/E) - net, transfer-based	1/23.63	1/22.87	1/28.83

Table A9. Robustness Analyses

	treated at age 37			treated at age 52		
cost/effectiveness ratio (C/E) - net	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$	$\boldsymbol{S}$	$\boldsymbol{S'}$	$\boldsymbol{P}$
benchmark	1/23.61	1/24.54	1/28.79	1/32.94	1/34.72	1/40.20
1. net deadweight cost of treatment	1/23.63	1/24.56	1/28.82	1/32.96	1/34.74	1/40.22
2. subsidy financed by lump-sum tax	1/23.60	1/24.53	1/28.78	1/32.93	1/34.71	1/40.19

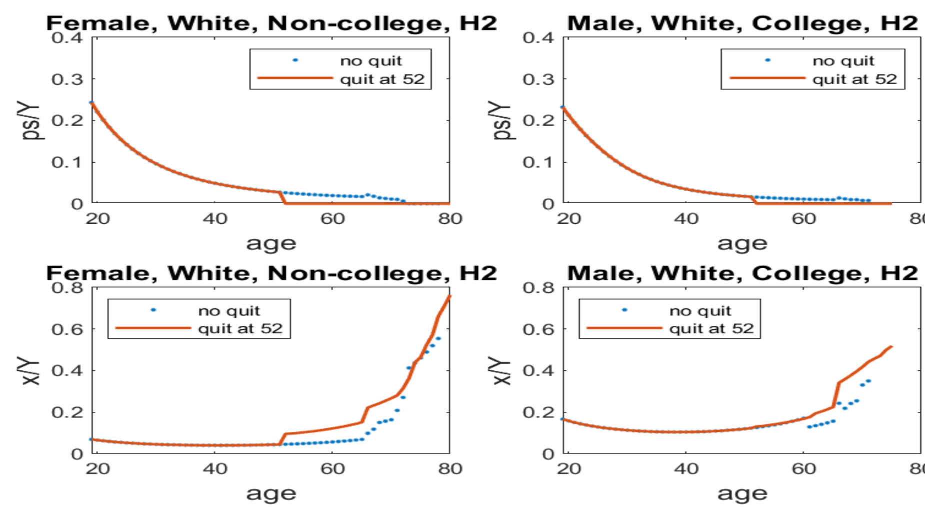

Figure A1. Lifecycle Profile of Smoking and Health Investment when Quitting at Age 52

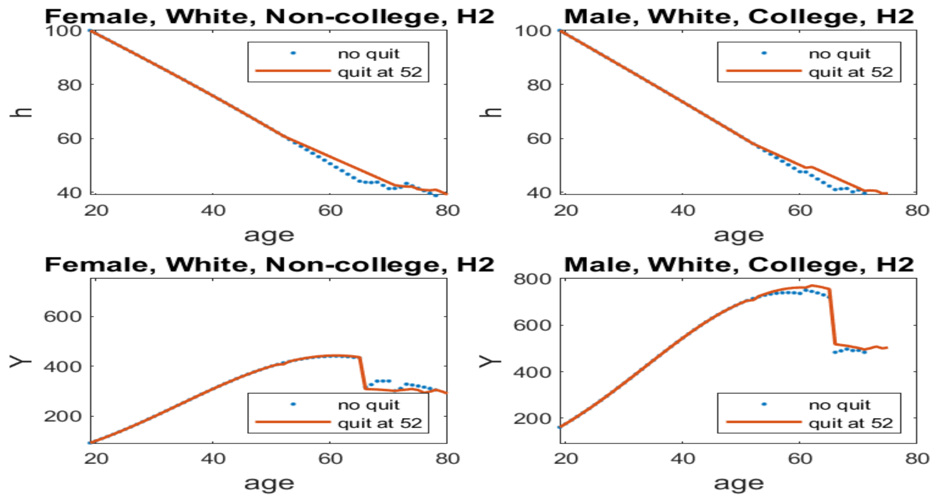

Figure A2. Lifecycle Profile of Health Capital and Labor Income when Quitting at Age 52

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