Preventive Medicine Reports 28 (2022) 101896

Contents lists available at ScienceDirect

Preventive Medicine Reports

journal homepage: www.elsevier.com/locate/pmedr

The health and economic impact of the Tobacco 21 Law in El Paso County, Texas: A modeling study

Whitney Garney [a], Sonya Panjwani [a,b,*], Laura King [c], Joan Enderle [c], Dara O'Neil [c], Yan Li [d,e]

[a] Department of Health and Kinesiology, Texas A&M University, 4243 TAMU, College Station, TX 77843, USA
[b] Weitzman Institute, Community Health Center, Inc., 631 Main Street, Middletown, CT 06457, USA
[c] American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231, USA
[d] Department of Population Health Science and Policy, Icahn School of Medicine at Mount Sinai, 1770 Madison Avenue, New York, NY 10035, USA
[e] Department of Obstetrics, Gynecology, and Reproductive Science, Icahn School of Medicine at Mount Sinai, 1176 Fifth Avenue, New York, NY 10029, USA

ARTICLE INFO

Keywords:
Smoking
Cardiovascular disease
Health policy
Health care costs
Tobacco21 law

ABSTRACT

In December 2019, the US federal Tobacco 21 (T21) law passed to raise the minimum legal purchase age for tobacco products from 18 to 21 years. Preliminary evidence suggests that the T21 law will restrict youth access to tobacco products, leading to decreases in tobacco use over their lifetime. This study expands the science through the use of systems modeling by linking decreases in youth tobacco use in El Paso County, Texas, due to the T21 law implementation, to potential cardiovascular health (CVH) benefits and health care cost reductions. Using a smoking behavior and cardiovascular disease agent-based model, we projected the T21 law's long-term effects on smoking prevalence and CVH outcomes in El Paso County, Texas. The estimated smoking prevalence in El Paso County, Texas, decreased by 2.7% among 18–24 year olds and by 5.2% among 25–44 year olds in 20 years with T21 law implementation ($p < 0.01$ for both population groups). By reducing tobacco use, the T21 law could prevent 5.4 coronary heart disease events per 1,000 adults and 6.1 S events per 1,000 adults over a lifetime. The model estimated a reduction in lifetime health care costs from $42,929 per person without T21 law to $41,985 per person with the policy. This study provides further evidence for policymakers and communities to understand the potential health and economic impacts of the federal T21 law at the local level. Results emphasize the need for comprehensive policy implementation and enforcement to produce its intended impact on health outcomes.

1. Introduction

Smoking is the leading preventable cause of premature death worldwide (Boyle, 1997; Thun et al., 1997; Centers for Disease Control and Prevention, 2008). It increases the risk for many adverse health outcomes including cancer, heart disease, stroke, and chronic obstructive pulmonary disease (COPD; Ambrose and Barua, 2004; Sasco et al., 2004; Forey et al., 2011). While the overall smoking prevalence has decreased over the past two decades in the United States (US), disparities among racial/ethnic minorities and low-income populations have persisted (Leventhal et al., 2019).

Approximately 90% of cigarette users began smoking during their adolescent years (U.S. Department of Health and Human Services, 2012). In addition to vulnerability to social influences, the adolescent brain is highly susceptible to rapid nicotine addiction (DiFranza et al., 2011). This initial onset of tobacco use leads to addictive behaviors to the point where the individual is unable to quit and most likely leads to heavy tobacco use as an adult (U.S. Department of Health and Human Services, 2012). The US Surgeon General has expressed concern about the potential long-term cognitive effects of exposure to nicotine during brain development (i.e., adolescence) based on the high rate of premature deaths (U.S. Department of Health and Human Services, 2014).

Research shows that underage youth who use tobacco most often access tobacco products from their social networks (friends and family; Ahmad and Billimek, 2007). The use of social networks to access tobacco products has doubled since 1995, when the national minimum legal purchase age (MLPA) for tobacco was set to 18 years (Centers for Disease Control and Prevention, 2003). Currently, underage tobacco users

* Corresponding author at: MPH, Department of Health and Kinesiology, Texas A&M University, 4243 TAMU, College Station, TX 77843, USA.
E-mail addresses: wrgarney@tamu.edu (W. Garney), sonya.panjwani@tamu.edu (S. Panjwani), laura.king@heart.org (L. King), joan.enderle@heart.org (J. Enderle), dara.oneil@heart.org (D. O'Neil), yan.li1@mountsinai.org (Y. Li).

https://doi.org/10.1016/j.pmedr.2022.101896
Received 2 October 2021; Received in revised form 13 May 2022; Accepted 2 July 2022
Available online 6 July 2022

typically go to individuals in their peer networks who are over the MLPA (18–19 year olds) to access tobacco products. Due to the social aspects of youth access to tobacco, policies that reduce youth's opportunities to access tobacco through legal buyers are essential (Institute of Medicine (IOM), 2015; Ahmad, 2005).

In December 2019, the US Congress enacted the Tobacco 21 (T21) law, which raised the MLPA for tobacco products from 18 to 21 years, and authorized the US Food and Drug Administration (FDA) to enforce the law (Colston et al., 2020). Current rates show that there is a minimal chance of ever becoming a smoker for an individual that reaches 21 years of age as a never smoker (Winickoff et al., 2014). Therefore, raising the MLPA to 21 could significantly decrease current youth tobacco use rates, thereby decreasing the chances of youth becoming tobacco dependent (Winickoff et al., 2014). Although growing evidence has shown that the T21 law is effective in reducing smoking among young adults, many states have not enacted the law (Friedman and Wu, 2020). While the federal law affects all states, policymakers are encouraging states to pass the law at the state-level for stronger enforcement. By adopting more stringent T21 laws locally, state authorities can bolster compliance and strengthen local and state level enforcement measures to supplement national efforts, thereby improving the effectiveness of the T21 law. Currently, the US FDA does not have the capacity to conduct compliance checks with every tobacco retailer; therefore, it is up to state authorities to verify all tobacco product retailers are in compliance with the T21 law. Consequently, state-level policymakers need evidence on the impact of the T21 law at the local level to encourage buy-in and adequate enforcement. Moreover, it is unclear how the T21 law would affect the prevalence of smoking in the long-term and how it would affect downstream disease burdens and health care costs.

Texas, which passed its T21 law in June 2019, is one of nineteen states that had enacted the T21 law by the time of the passing of the law at the federal level. Under the Texas T21 law, similar to the federal law, individuals under the age of 21 are not permitted to purchase tobacco products if they are born after August 31, 2001. Violation of purchasing, attempting to purchase, or knowingly providing cigarettes, e-cigarettes, or tobacco products is punishable by state law and results in a fine not to exceed $100, a court ordered tobacco awareness class, and/or community service hours. Retailer penalty for noncompliance is a fine up to $500 and enforcement of the law is primarily focused on retailers rather than users. State and local law enforcement officers have the authority to enforce the state law, including retailer compliance checks and penalizing retailers for sale to those under 21 (Paso del Norte Foundation, 2019).

Most recent data (2020) from Texas shows that the average age of first tobacco product use is 13.2 years of age (Marchbanks et al., 2020). Additionally, 15% of adolescents in grades 7–12 indicate that it is very easy to access tobacco products (Marchbanks et al., 2020). Within Texas Region 9/10, which includes the El Paso metropolitan area, we observe a younger age of first use of tobacco products (12.9 years of age), but a slightly lower ease of access to tobacco products (13.2%; Marchbanks et al., 2020). El Paso County, Texas is unique given its geographic location and racial/ethnic make-up. It constitutes a primarily Hispanic population (82.9%) and is located along the Texas-New Mexico-Mexico border (United States Census Bureau, 2019). Furthermore, the MLPA for tobacco products in Mexico is 18; previous studies have shown that border-crossing has frequently been used as a way to avoid policies aimed at discouraging consumption of specific goods, such as tax policies on tobacco products (DeCicca et al., 2013). Understanding how the T21 policy could reduce tobacco use at the local level in the long-term, and thereby reduce disease burdens, warrants further study.

Systems science methodologies, such as agent-based modeling, have frequently been used as a method for visualizing, analyzing, and informing complex public health interventions and policies with the goal of estimating population-level outcomes (Auchincloss and Diez Roux, 2008; El-Sayed et al., 2012; Luke and Stamatakis, 2012). This approach utilizes computational methods to consider how agents with a specified set of characteristics interact with one another and their environment (Tracy et al., 2018). These agents may adapt their behavior in response to experiences or their environment (e.g., policy implementation) and give rise to potential outcomes of interest, such as health or economic outcomes. The benefit of this methodology is that it allows for the prediction of population-level phenomena in the long-term through the aggregation of individual behaviors (Bonabeau, 2002). Thus, agent-based models take on a bottom-up approach, in which micro-level behaviors give rise to dynamics at the macro-level (Epstein and Axtell, 1996). While not definitive, results from agent-based modeling analysis provide potential benefits of public health interventions and policies and can be a useful tool for advocacy efforts.

To inform policy-making, this study investigates the potential long-term health and economic impacts of the T21 law in El Paso County, Texas, using an agent-based simulation model of smoking behavior and cardiovascular disease (CVD). We use CVD as the outcome of interest as it is the leading cause of death in the US, and smoking is one of the most important risk factors for CVD. (Arnett et al., 2019) In addition, there are stark sex and racial and ethnic disparities in CVD risk factors in El Paso County and across the country (Kanchi et al., 2018; Centers for Disease Control and Prevention, 2019). As such, we also aim to examine how the T21 law may differentially affect individuals across sex and race and ethnicity, including whether or not the policy would reduce disparities in health outcomes and health care costs.

2. Material and methods

We developed an agent-based model of smoking behavior and CVD to project the long-term impact of a tobacco control policy or intervention on CVD health outcomes and health care costs. In the agent-based model, simulated individuals are generated with predefined characteristics (e.g., age, sex, race, ethnicity). Their smoking behaviors can be modified to understand how they would impact health outcomes, including coronary heart disease (CHD) and stroke, as the simulation runs. (Rutter et al., 2011; Krijkamp et al., 2018). By simulating the same group of individuals under different policy scenarios, researchers can compare the impact of different policies and identify the most effective or cost-efficient policy in a low-cost, low-risk environment.

2.1. Model structure

The agent-based model used for this study projects CVD outcomes (CHD and stroke) and health care costs among adults in El Paso County, Texas. Fig. 1 shows the model schematic design. Specifically, the model can generate a group of individuals with a variety of demographic characteristics. Each simulated individual is assigned to be a current cigarette smoker, past smoker (quit $\leq$ 12 months ago), or non-smoker (never or quit $>$ 12 months ago) based on a probability that is calculated taking into account his/her sex and race/ethnicity (Supplemental Table S2). As the simulation runs, individuals will age and potentially develop CVD (see Supplemental Table S1 for model parameters on disease progression). Finally, the model will calculate the total numbers of CHD and stroke and cumulative health care costs due to CVD.

2.2. Parameter estimation

We estimated and calibrated model parameters from multiple sources. Briefly, population demographics and disease transition probabilities were estimated based on data from the National Health Interview Survey, US Life Tables, and the National Health and Nutrition Examination Survey. Annual smoking prevalence was derived from the Texas Behavioral Risk Factor Surveillance System and County Health Rankings. Detailed model parameters and their data sources are shown in Supplemental Table S1. Since this study was based on publicly available anonymized databases, it is exempt from human subject approval.

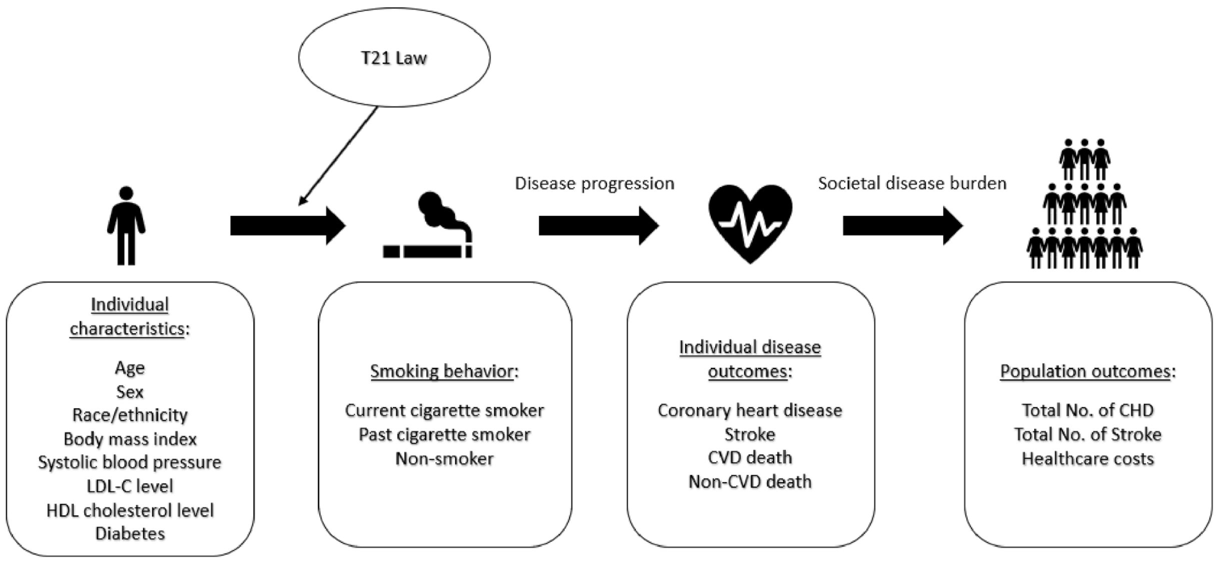

Fig. 1. Model Schematic. Notes: In the agent-based model, people of age 18 years or older with different demographic characteristics and health profiles will be generated first. Then each simulated individual will become either a smoker, non-smoker, or past smoker (if the person quitted smoking in the past) based on a probability that is calculated based on his/her demographic characteristics. As the simulation runs, individuals will grow older and develop either coronary heart disease, stroke, or decease due to CVD or non-CVD reasons. Finally, the model will calculate the total numbers of coronary heart diseases.

The CVD risk factors included in the model are: age, sex, race, ethnicity, body mass index, systolic blood pressure, LDL-C level, HDL cholesterol level, diabetes, and smoking status. Annual CVD event and CVD-related mortality probabilities were estimated using Cox proportional hazards regression functions (Equation 1) based on data from a National Heart, Lung, and Blood Institute Pooled Cohort (Zhang et al., 2019).

$$P(incidentCVDevent) = \frac{expexp\left(\alpha + \beta_{BMI}BMI + \beta_{LDL-c}X_{LDL-c} + \cdots + \beta_{sbp}X_{sbp}\right)}{1 + expexp\left(\alpha + \beta_{BMI}BMI + \beta_{LDL-c}X_{LDL-c} + \cdots + \beta_{sbp}X_{sbp}\right)} \quad (1)$$

We estimated health care cost parameters based on the Medical Expenditure Panel Survey (MEPS) data (Jasani et al., 2020). Specifically, every simulated individual accrues annual age-specific "background" cost when he/she has not developed CVD yet. When the simulated individual develops CHD or stroke, the specific cost associated with that disease will be added to the total health care costs (Supplemental Table S3). All health care costs were discounted at 3% and converted to 2018 US dollars.

After the initial model was developed, we conducted model calibration and validation by comparing the simulated CVD mortality rates with the reported CVD mortality rates based on the CDC Wonder data (Centers for Disease Control and Prevention, 2015). This ensured that our model can predict long-term CVD outcomes with reasonable validity.

2.3. Simulation experimental design

Our study includes two simulation scenarios—enacting the T21 law and not enacting the law (baseline). We assume that retailers are 100% compliance with the law since state and local law enforcement officers have the authority to enforce the law and penalize retailers for any violation (Paso del Norte Foundation, 2019). Also, we do not consider potential increase in border crossing for people under 21 years old to purchase cigarettes due to limited data on this behavior. In each of the simulation scenarios, we simulated 10,000 people based on population demographics in El Paso County, Texas. For each of the simulation scenarios, we projected the changes in smoking prevalence among adults in El Paso County from 2020 to 2080, overall and by sex. We also projected the cumulative lifetime cases of CHD and stroke as well as health care costs associated with CVD. We calculated the averted cases of CHD and stroke and health care cost saving among adults in El Paso County after the T21 law was enacted. We further calculated the reductions in the incidence of CHD and stroke and associated health care costs across sex and racial and ethnic groups to examine the impact of the policy on health disparities in the long-term.

3. Results

Fig. 2 shows the projected trend of the prevalence of smoking after the T21 law was enacted in El Paso County in 2020, overall and by sex. Overall, the prevalence of smoking could decrease from 13.7% in 2020

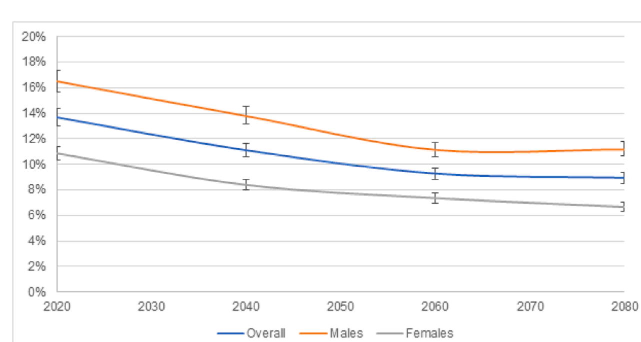

Fig. 2. Projected smoking prevalence among adults in El Paso County, TX, under the T21 law.

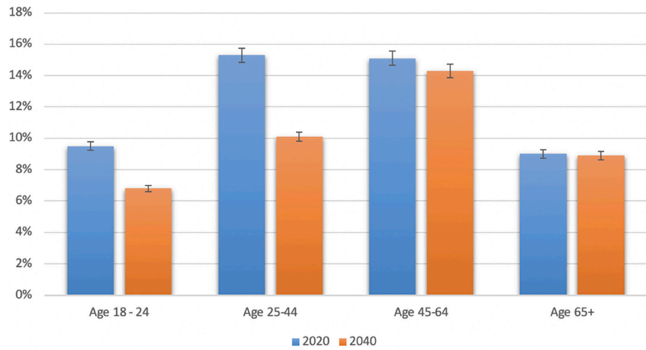

Fig. 3. Projected 20-year changes in smoking prevalence among different age groups in El Paso County, TX, under the T21 law.

to 8.9% in 2080 ($p < .001$) with policy enactment. By gender, the prevalence could decrease from 16.5% to 11.2% ($p < .001$) among males and from 10.9% to 6.7% ($p < .001$) among females. Note that this projection only took into account the impact of the T21 law; other future tobacco policies that may affect the prevalence of smoking were not captured in the model.

The T21 law would have varying effects across different age groups. As Fig. 3 shows, the law could have the largest effect among young adults. Our model projected that, in 20 years, the prevalence of smoking could decrease from 9.5% to 6.8% among people aged 18–44 and from 15.3% to 10.1% among people aged 25–44. The effect of the law could be small among older adults as the prevalence of smoking among this group was projected to reduce by only 0.1% in 20 years.

Table 1 reports the projected cumulative numbers of CHD and stroke as well as lifetime health care costs among simulated adults in El Paso County with and without the T21 law. Without the T21 law, the model estimated that there would be 305.2 (95% CI: 294.5–316.7) cases of CHD and 168.2 (95% CI: 158.1–177.7) cases of stroke per 1,000 adults. The enactment of the T21 law could avert 5.4 cases of CHD and 6.1 cases of stroke per 1,000 adults. Without the T21 law, an average adult in El Paso County was projected to incur $42,929 in health care costs over his/her lifetime. The enactment of the law could save an average of $1,034 per person due to the reduced smoking rate and subsequently reduced burden of CVD.

Table 1 also presents the projected lifetime CVD outcomes and health care costs with and without T21 law by sex and race/ethnicity. The results show that males had a higher risk of developing CHD compared to females, while the risks of developing stroke were similar between both sexes. The T21 law would be more effective in averting CHD by reducing the cases from 346.3 to 338.2 per 1,000 adult males, compared to a moderate reduction from 231.1 to 228.3 per 1,000 adult females. This implies that the law could reduce sex disparity in CHD. However, the law may not be able to reduce racial/ethnic disparities in CVD outcomes as it was estimated to have similar effect across different racial/ethnic groups. More specifically, the law could reduce the number of strokes from 159.1 to 153.0 among Whites, from 178.1 to 170.1 among African Americans, and from 165.7 to 158.8 among Hispanics, respectively, per 1,000 adults simulated. The results also show that females, Hispanics, and Whites could have a higher lifetime health care costs compared to males and African Americans, implying that lifetime health care costs were mainly driven by life expectancy rather than disease burden, as females and Whites had a longer life expectancy compared to other population groups.

Table 1
Projected lifetime CVD outcomes and health care costs among adults in El Paso County, TX.

	Without T21 Law		T21 Law	
	mean	95% CI	mean	95% CI
Number of CHD, per 1,000 adults	305.2	(294.5, 316.7)	299.8	(288.1, 312.2)
Male	346.3	(326.4, 366.1)	338.2	(319.1, 357.7)
Female	231.1	(217.9, 243.5)	228.3	(215.5, 240.9)
Whites	282.0	(255.3, 307.2)	276.1	(251.6, 302.4)
African Americans	276.1	(259.7, 292.7)	269.4	(254.0, 285.4)
Hispanics	251.5	(230.6, 273.8)	248.7	(226.8, 269.8)
Averted cases of CHD, per 1,000 adults	——	——	5.4	——
Number of stroke, per 1,000 adults	168.2	(158.1, 177.7)	162.1	(152.3, 171.3)
Male	164.5	(149.7, 179.9)	160.1	(145.5, 174.9)
Female	170.4	(157.9, 182.6)	163.3	(151.4, 175.7)
Whites	159.1	(138.0, 179.4)	153.0	(132.4, 174.8)
African Americans	178.2	(157.1, 200.1)	170.1	(144.2, 187.6)
Hispanics	165.7	(152.6, 178.8)	158.8	(145.0, 172.8)
Averted cases of stroke, per 1,000 adults	——	——	6.1	——
Health care costs ($), per person	42,929	(42,417, 43,485)	41,895	(41,405, 41,445)
Male	35,633	(34,904, 36,337)	35,603	(34,868, 36,322)
Female	47,229	(46,524, 47,956)	47,191	(46,501, 47,910)
Whites	42,587	(41,575, 43,610)	42,551	(41,550, 43,576)
African Americans	40,546	(39,561, 41,525)	40,523	(39,551, 41,537)
Hispanics	46,655	(45,841, 47,631)	46,617	(45,799, 47,599)
Health care cost saving, $ per person	——	——	1,034	——

4. Discussion

Using an agent-based model of smoking behaviors and CVD, we showed that the T21 law implemented in El Paso County, Texas, would reduce the prevalence of smoking significantly and result in decreases in CVD incidence and healthcare cost in the long term. It is worth noting that a 2015 Institute of Medicine (IOM) report used two different simulation models (the CISNET Model and SimSmoke Model) to project the effect of a national T21 law on adult smoking prevalence (IOM, 2015). Our projected reductions in adult smoking prevalence rate are similar to those projected by the CISNET Model but are greater than those reported by the SimSmoke Model (IOM, 2015). The difference in the projections is likely due to the differences in our baseline population demographics (national population vs. El Paso population) as well as in model assumptions. Our research reaffirms the T21 law's ability to decrease tobacco use among younger populations (Ahmad and Billimek, 2007; Ahmad, 2005; Winickoff et al., 2014; Friedman and Wu, 2020). The study also shows the potential benefits of the T21 law on CVD outcomes as well as its potential for reducing sex disparities. Although our results did not show a reduction in racial/ethnic disparities under the T21 law, we should not make such a conclusion because the population in El Paso are predominantly Hispanics and, thus, the racial/ethnic results may be biased. Further investigation towards the effect of the law on racial/ethnic disparities is needed. This study advances the field since it was undertaken in El Paso (which has a distinct population and borders Mexico) and provides data at a local level where earlier assessment initiatives have not occurred.

The T21 law's potential impact on adolescents is profound. At the surface level, T21 law appears to target young adults aged 18–21 by delaying their ability to purchase and use tobacco. However, the T21 law also decreases youth (age < 18) access to tobacco products by reducing the amount of people in their social networks who can legally purchase tobacco products, which in turn, decreases their opportunity to get tobacco products from social contacts (Ahmad, 2005). Diffusion of information and access to tangible resources is a common use of social networks. The ability of T21 to reduce the diffusion of tobacco products in youth networks provides an example for future policy and research that could impact network properties of harmful health behaviors. Furthermore, T21 has the ability to decrease tobacco use among a subpopulation where tobacco rates are rising due to the introduction of novel electronic nicotine delivery systems (ENDS; Vallone et al., 2019; Stanton et al., 2020).

In addition to providing valuable information for policymakers in the US, this study also has implications globally. Most countries, especially in Europe and South-East Asia, have yet to raise the MLPA of tobacco products, noting that the T21 policy is a low priority and has low public support in comparison to other tobacco control policies (Nuyts et al., 2020; Rani et al., 2017). A recent study noted that in order for these policies to gain momentum, more evidence is needed on the effectiveness of T21 laws on smoking prevalence (Nuyts et al., 2020). The findings from this study provide the evidence needed for such policies by demonstrating the statistically significant decreases in tobacco use over time and the policy's benefits through the potential positive health and economic outcomes following policy implementation. The latter data is particularly relevant for low- and middle-income countries with limited health resources, illustrating the practical implications of the results from this study.

Despite the fact that the T21 law was passed at the federal level, it is largely administered and enforced at the state and municipal levels. The FDA requires assistance in ensuring that the policy is implemented locally, therefore public support for the T21 law must continue to grow. These efforts can be supported by enacting the policy at the state-level that enables reinforcement of FDA compliance checks through state law enforcement, even though disparities may still exist in retailer compliance and youth access (Silver et al., 2016). Using the data in this study, advocates can focus grassroots efforts on quality implementation to ensure that the policy influences the maximum number of people. It is imperative to translate meaningful research, like this study, to the public to ensure public health interventions are supported by local policymakers and the general public.

Furthermore, this research is an innovative approach to assessing the potential benefits of a tobacco control policy through use of advanced systems science methods (agent-based modeling). While systems modeling was conducted by federal entities to assess the potential impact of the T21 law, it is not frequently used at a state or local level to assess potential long-term impacts of policy. Due to the nature of policy-level interventions, it is impossible to see immediate changes in health outcomes like CVD, as they take many years to develop. Limited funding and support for long-term evaluations necessitates policy research to be conducted retrospectively. As a result, translating research to the general public is typically delayed despite the need to use this information to build community support and buy-in. Systems science methods, like agent-based modeling, allow researchers to use existing data and evidence to build simulations that estimate the impact of policies on long-term health outcomes. Sensitivity analysis allows researchers to understand the degree of implementation, which is especially important in policy research because effectiveness relies heavily on the degree to which a policy is implemented and enforced.

Although this study provides useful information related to the potential effects of the T21 law for policymakers and practitioners, it is not without limitations. Namely, the developed agent-based model does not take into account social influences or other risk factors, such as depression, related to tobacco use for those 21 years or older. Understanding how these factors influence tobacco use could provide more detailed information on disease burden and health care costs and could assist in advocating for efforts that target these influences beyond implementation of the policy. Furthermore, the model does not take into account the health effect of secondhand smoking, which has been shown to have nearly as large an effect as chronic active smoking(Barnoya and Glantz, 2005). Lastly, we did not consider border crossing or the use of ENDS in the model when projecting the impact of the T21 law as there is limited data. Besides ENDS, research is needed to examine the impact of the T21 law on the use of other tobacco products such as cigars, water pipes, and smokeless tobacco products.

5. Conclusions

This study utilized agent-based modeling as a tool to understand the potential health and economic impacts of the T21 law in El Paso County, Texas. Our study suggests that in the long-term, there will be a reduction in smoking prevalence, with the largest reduction among 18–44 year olds. Furthermore, policy implementation could result in a reduction in the number of CHD and stroke occurrences, and economically, results suggest the policy is cost-effective. Most importantly, our results indicate that implementation of the T21 law may reduce sex-related disparities related to CVD. This study offers a platform for policymakers and practitioners focused on T21 law to advocate for the law at the local level.

CRediT authorship contribution statement

Whitney Garney: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Sonya Panjwani:** Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Laura King:** Writing – review & editing, Project administration, Funding acquisition. **Joan Enderle:** Writing – review & editing. **Dara O'Neil:** Writing – review & editing. **Yan Li:** Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is supported in part by a grant from the U.S. Centers for Disease Control and Prevention (CDC) (6 NU58DP006584-01-03) and a grant from the National Heart, Lung, and Blood Institute of the National Institutes of Health (NIH) (R01HL141427). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the U.S. CDC or NIH. No financial disclosures were reported by the authors of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pmedr.2022.101896.

References

Centers for Disease Control and Prevention (CDC). Smoking-attributable mortality, years of potential life lost, and productivity losses–United States, 2000-2004. *MMWR Morb Mortal Wkly Rep*. 2008;57(45):1226.

Centers for Disease Control and Prevention. *Underlying Cause of Death 1999–2014 on CDC Wonder Online Database.* Centers for Disease Control and Prevention; 2015.

Ahmad, S., 2005. Closing the youth access gap: The projected health benefit and cost savings of a national policy to raise the legal smoking age to 21 in the United States. Health Policy. 75, 74–84.

Ahmad, S., Billimek, J., 2007. Limiting youth access to tobacco: Comparing the long-term health impacts of increasing cigarette excise taxes and raising the legal smoking age to 21 in the United States. Health Policy 80, 378–391.
Ambrose, J.A., Barua, R.S., 2004. The pathophysiology of cigarette smoking and cardiovascular disease: an update. J Am Coll Cardiol. 43 (10), 1731–1737.
Arnett, D.K., Blumenthal, R.S., Albert, M.A., Buroker, A.B., Goldberger, Z.D., Hahn, E.J., Himmelfarb, C.D., Khera, A., Lloyd-Jones, D., McEvoy, J.W., et al., 2019. 2019 ACC/AHA guideline on the primary prevention of cardiovascular disease: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. J Am Coll Cardiol. 74 (10), e177–e232.
Auchincloss, A.H., Diez Roux, A.V., 2008. A new tool for epidemiology: the usefulness of dynamic-agent models in understanding place effects on health. Am J Epidemiol. 168 (1), 1–8.
Barnoya, J., Glantz, S.A., 2005. Cardiovascular effects of secondhand smoke. Circulation 111, 2684–2698.
Bonabeau, E., 2002. Agent-based modeling: methods and techniques for simulating human systems. PNAS. 99 (Suppl. 3), 7280–7287.
Boyle, P., 1997. Cancer, cigarette smoking and premature death in Europe: A review including the recommendations of European Cancer Experts Consensus Meeting, Helsinki, October 1996. Lung Cancer. 17 (1), 1–60.
Centers for Disease Control and Prevention. *Health United States Spotlight: Racial and Ethnic Disparities in Heart Disease*. https://www.cdc.gov/nchs/hus/spotlight/HeartDiseaseSpotlight_2019_0404.pdf. Published April 4, 2019. Accessed January 5, 2021.
Centers for Disease Control and Prevention. *Youth Risk Behavior Surveillance System (YRBSS), 1995-2003*. http://www.cdc.gov/HealthyYouth/yrbs/data/index.htm. Published 2003. Accessed on October 14, 2019.
Colston, D.C., Titus, A.R., Thrasher, J.F., Elliott, M.R., Fleischer, N.L., 2020. Area-Level Predictors of Tobacco 21 Coverage in the US Before the National Law: Exploring Potential Disparities. Am J Prev Med. 60 (1), 29–37.
DeCicca, P., Kenkel, D., Liu, F., 2013. Excise tax avoidance: The case of state cigarette taxes. J Health Econ. 32 (6), 1130–1141.
Paso del Norte Foundation. *Texas Tobacco 21: A New Law in Texas.* https://pdnhf.org/news/e-cigarette-use-particularly-by-youth-is-rapidly-increasing#:~:text=Texas%20Tobacco%2021%20is%20the%20new%20law%20that,August%2031%2C%202001%20are%20exempt%20from%20the%20law. Published July 16, 2019. Accessed May 12, 2021.
DiFranza, J.R., Wellman, R.J., Mermelstein, R., Pbert, L., Klein, J.D., Sargent, J.D., Ahluwalia, J.S., Lando, H.A., Ossip, D.J., Wilson, K.M., et al., 2011. The natural history and diagnosis of nicotine addiction. Curr Pediatr Rev. 7, 88–96.
El-Sayed, A.M., Scarborough, P., Seemann, L., Galea, S., 2012. Social network analysis and agent-based modeling in social epidemiology. Epidemiol. Perspect. Innov. 9 (1), 1.
Epstein, J.M., Axtell, R.L., 1996. Growing artificial societies: Social science from the bottom up. Brookings Inst. Press, Washington, DC.
Forey, B.A., Thornton, A.J., Lee, P.N., 2011. Systematic review with meta-analysis of the epidemiological evidence relating smoking to COPD, chronic bronchitis and emphysema. BMC Pulm Med. 11 (1), 36.
Friedman, A.S., Wu, R.J., 2020. Do local tobacco-21 laws reduce smoking among 18 to 20 year-olds? Nicotine Tob Res. 22 (7), 1195–1201.
Institute of Medicine (IOM). *Public health implications of raising the minimum age of legal access to tobacco products*. Washington, DC: The National Academies Press; 2015.
Jasani, F.S., Seixas, A.A., Madondo, K., Li, Y., Jean-Louis, G., Pagán, J.A., 2020. Sleep Duration and Health Care Expenditures in the United States. Med Care. 58 (9), 770–777.
Kanchi, R., Perlman, S.E., Chernov, C., Wu, W., Tabaei, B.P., Trinh-Shevrin, C., Islam, N., Seixas, A., Rodriguez-Lopez, J., Thorpe, L.E., 2018. Gender and race disparities in cardiovascular disease risk factors among New York City adults: New York City Health and Nutrition Examination Survey (NYC HANES) 2013–2014. J Urban Health. 95 (6), 801–812.
Krijkamp, E.M., Alarid-Escudero, F., Enns, E.A., Jalal, H.J., Hunink, M.M., Pechlivanoglou, P., 2018. Microsimulation modeling for health decision sciences using R: A tutorial. Med Decis Making. 38 (3), 400–422.
Leventhal, A.M., Bello, M.S., Galstyan, E., Higgins, S.T., Barrington-Trimis, J.L., 2019. Association of cumulative socioeconomic and health-related disadvantage with disparities in smoking prevalence in the United States, 2008 to 2017. JAMA Intern Med. 179 (6), 777–785.
Luke, D.A., Stamatakis, K.A., 2012. Systems science methods in public health: dynamics, networks, and agents. Annu Rev Public Health. 33, 357–376.
Marchbanks MP, Pearson S, Rhodes S, Williams A. *Texas School Survey of Drug and Alcohol Use 2020: State Report.*. https://texasschoolsurvey.org/Documents/Reports/State/20State712.pdf. Published 2020. Accessed May 12, 2021.
Marchbanks MP, Pearson S, Rhodes S, Williams A. *Texas School Survey of Drug and Alcohol Use 2020: HHSC Region 9 and 10 Report.*. https://texasschoolsurvey.org/Documents/Reports/Region/20Region9-10.pdf. Published 2020. Accessed May 12, 2021.
Nuyts, P.A.W., Kuipers, M.A.G., Willemsen, M.C., Kunst, A.E., 2020. An increase in the tobacco age-of-sale to 21: For debate in Europe. Nicotine Tob Res. 22 (7), 1247–1249.
Rani, M., Thamarangsi, T., Agarwal, N., 2017. Youth tobacco use in South-East Asia: Implications for tobacco epidemic and options for its control in the region. Indian J Public Health. 61 (5), 12–17.
Rutter, C.M., Zaslavsky, A.M., Feuer, E.J., 2011. Dynamic microsimulation models for health outcomes: a review. Med Decis Making. 31 (1), 10–18.
Sasco, A.J., Secretan, M.B., Straif, K., 2004. Tobacco smoking and cancer: A brief review of recent epidemiological evidence. Lung Cancer. 45, s3–s9.
Silver, D., Macinko, J., Giorgio, M., Bae, J.Y., Jimenez, G., 2016. Retailer compliance with tobacco control laws in New York City before and after raising the minimum legal purchase age to 21. Tobacco Control 25 (6), 624–627.
Stanton CA, Sharma E, Edwards KC, Halenar MJ, Taylor KA, Kasza KA, Day H, Anic G, Gardner LD, Hammad HT, et al. Longitudinal transitions of exclusive and polytobacco electronic nicotine delivery systems (ENDS) among youth, young adults and adults in the USA: Findings from the PATH Study Waves 1-3 (2013-2016). *Tob Control.* 2020;29:s147–s154.
Thun, M.J., Myers, D.G., Day-Lally, C., Namboodiri, M.M., Calle, E.E., Flanders, W.D., Adams, S.L., Health, C.W., 1997. Age and the exposure-response relationships between cigarette smoking and premature death in Cancer Prevention Study II. *Shopland Chang Cigar-Relat Dis Risks Their Implic Prev Control Natl Inst Health Bethesda Md.* Published online 383–413.
Tracy, M., Cerda, M., Keyes, K.M., 2018. Agent-based modeling in public health: Current applications and future directions. Annu Rev Public Health. 39, 77–94.
U.S. Department of Health and Human Services. *Preventing tobacco use among youth and young adults: A report of the surgeon general*. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, Office on Smoking and Health, 2012.
U.S. Department of Health and Human Services. *The health consequences of smoking—50 years of progress: A report of the surgeon general*. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, Office on Smoking and Health, 2014.
United States Census Bureau. *Quick Facts: El Paso County, TX.* https://www.census.gov/quickfacts/elpasocountytexas. Published 2019. Accessed May 21, 2021.
Vallone, D.M., Bennet, M., Xiao, H., Pitzer, L., Hair, E.C., 2019. Prevalence and correlates of JUUL use among a national sample of youth and young adults. Tob Control. 28, 603–609.
Winickoff, J.P., Hartman, L., Chen, M.L., Gottlieb, M., Nabi-Burza, E., DiFranza, J.R., 2014. Retail impact of raising tobacco sales age to 21 years. Am J Public Health. 104 (11), e18–e21.
Zhang, Y., Vittinghoff, E., Pletcher, M.J., Allen, N.B., Al Hazzouri, A.Z., Yaffe, K., Balte, P. P., Alonso, A., Newman, A.B., Ives, D.G., et al., 2019. Associations of blood pressure and cholesterol levels during young adulthood with later cardiovascular events. J Am Coll Cardiol. 74 (3), 330–341.