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Modeling of drinking and driving behaviors among adolescents and young adults in the United States: Complexities and Intervention outcomes

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ABSTRACT

Alcohol-impaired driving is a formidable public health problem in the United States, claiming the lives of 37 individuals daily in alcohol-related crashes. Alcohol-impaired driving is affected by a multitude of interconnected factors, coupled with long delays between stakeholders' actions and their impacts, which not only complicate policy-making but also increase the likelihood of unintended consequences. We developed a system dynamics simulation model of drinking and driving behaviors among adolescents and young adults. This was achieved through group model building sessions with a team of multidisciplinary subject matter experts, and a focused literature review. The model was calibrated with data series from multiple sources and replicated the historical trends for male and female individuals aged 15 to 24 from 1982 to 2020. We simulated the model under different scenarios to examine the impact of a wide range of interventions on alcohol-related crash fatalities. We found that interventions vary in terms of their effectiveness in reducing alcohol-related crash fatalities. In addition, although some interventions reduce alcohol-related crash fatalities, some may increase the number of drinkers who drive after drinking. Based on insights from simulation experiments, we combined three interventions and found that the combined strategy may reduce alcohol-related crash fatalities significantly without increasing the number of alcohol-impaired drivers on US roads. Nevertheless, related fatalities plateau over time despite the combined interventions, underscoring the need for new interventions for a sustained decline in alcohol-related crash deaths beyond a few decades. Finally, through model calibration we estimated time delays between actions and their consequences in the system which provide insights for policymakers and activists when designing strategies to reduce alcohol-related crash fatalities.

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1. Background

In 2021, 13,384 people lost their lives in alcohol-impaired driving motor vehicle crashes in the United States; one such crash fatality every 39 min of every day (National Center for Statistics and Analysis, 2023). The highest percentage of alcohol-impaired drivers in fatal crashes was for the 21- to 24-year-old age group (27%) in 2021. Prevalence of driving while impaired (DWI) varies by age, ranging between 13% and 23% for the 17- and 22-year-old population, respectively (Li et al., 2013; Vaca et al., 2020).

Extensive research has examined the risk factors associated with youth's DWI. Binge drinking is associated with a higher likelihood of DWI (Terry-McElrath, O'Malley and Johnston, 2014; Vaca et al., 2020). Alcohol marketing significantly impacts alcohol consumption and drinking initiation among adolescents and young adults (Boggs, 2017; Gupta et al., 2016; Jernigan et al., 2017; Smith and Foxcroft, 2009; Stautz et al., 2016). The perception of peer alcohol use is also a strong predictor of initiation and consumption of alcohol. This perception is shaped through several mechanisms, including exposure to alcohol-related content on social media (Curtis et al., 2018) and drinking with peers (Brooks-Russell et al., 2014).

Various protective factors that deter adolescents and young adults from engaging in alcohol use and DWI have been extensively studied. The adoption of several laws by states over the past 4 decades was significantly associated with a reduction in alcohol-related crash fatalities (Fell et al., 2009; Fell and Scherer, 2017a, 2017b; Fell et al., 2016; Fell et al., 2015a). Highly publicized and visible law enforcement has deterred drinking and driving, as evidenced by the reduced probability of DWI when the rate of police traffic stops in the population increases (Fell et al., 2015b). States with more restrictive DWI laws and effective enforcement are more likely to experience a significant reduction in alcohol-related crash fatalities (Hosseinichimeh et al., 2022b). A high level of parental knowledge about their adolescents' lives, including with whom and how they spend their time, is a significant protective factor against DWI (Li et al., 2014aa; Li et al., 2015; Vaca et al., 2021; Vaca et al., 2020).

Youth DWI is a complex behavior because it is affected by multiple, interdependent and interacting factors (Hosseinichimeh et al., 2022a; Vaca et al., 2021; Vaca et al., 2022). Previous research mainly focused on determining the various factors influencing DWI (Li et al., 2014a,b ; Smailović et al., 2023; Vaca et al., 2021; Vaca et al., 2022). Notably, existing literature lacks a systems science approach that can examine multiple levels of key factors and synthesize their interconnected relationships. Such an approach is suited to estimate the potential impact of simulated interventions on related fatalities and, importantly, identify possible unintended consequences before implementing them in the real world.

To address these knowledge gaps, we conducted group model building (GMB) sessions with a team of multidisciplinary subject matter experts, mapped the main factors influencing DWI and the reciprocal relationships between them (Hosseinichimeh et al., 2022a), and developed the first system dynamics simulation model of drinking and driving behaviors among US adolescents and young adults. This article reports the quantification of the map, compares the simulated outcomes with the historical trends from 1982 to 2020, and demonstrates the likely impact of diverse interventions on alcohol-related crash fatalities among US adolescents and young adults.

2. Method

System dynamics (SD) modeling is an approach for understanding the structure and analyzing the dynamics of complex systems (Forrester, 1961; Richardson, 1999; Sterman, 2000). It is an iterative process of scope selection, hypothesis generation, causal loop diagraming, quantification and parameter estimation, testing, and policy analysis.

To model drinking and driving behaviors of youth, we first conducted a group model building (GMB) session with multidisciplinary subject-matter experts, reviewed the literature, and developed a causal loop diagram (CLD) of drinking and driving among adolescents and young adults. The CLD, presented in (Hosseinichimeh et al., 2022a), depicted the reciprocal relationships among factors affecting drinking and driving behaviors of youth in the U.S.

In the next phase of the project, we developed an SD simulation model of drinking and driving behaviors of adolescents and young adults in the U.S. based on the relationships captured in the qualitative model (i.e., CLD). We obtained multiple time series data from different sources (explained in section 2.2) to estimate the parameters of the model. After building confidence in the SD model by conducting various tests, including testing the model with the same subject-matter experts in the second and third GMB sessions, we simulated the SD model under different scenarios to examine the impact of interventions and identify unintended consequences. Potential interventions were elicited from the GMB participants using the Policy Levers script (Andersen and Richardson, 1997; Luna-Reyes et al., 2006) in the first GMB session. Supplementary document, A5, presents the list of policy levers and the variables in the model capturing these interventions.

The GMB participants, also coauthors of this article, comprised high-level content experts in the public health, policy, traffic safety, epidemiology, medical, adolescent development, youth behavior, and health statistics fields. The same experts participated in the three GMB sessions. The first GMB session was a two-day in-person meeting conducted in October 2019. The second and third GMB session were online, held in October 2020 and November 2022, respectively. The product of the first GMB session was a qualitative model (CLD) of factors influencing drinking and driving of youth, and their reciprocal relationships (Hosseinichimeh et al., 2022a). The product of the second and third GMB sessions is a quantitative SD simulation model of drinking and driving behaviors of youth, calibrated with multiple time series data, which can be used to test a wider range of interventions. The difference between the simulation models tested in the second and third sessions primarily relates to the level of aggregation. The simulation model in the second session captured a single group of individuals aged 15 to 24, whereas the model tested in the third session followed 20 groups—female and male individuals aged 15 to 24. Our goal for the second GMB session was to capture and test feedback processes for an aggregate population, then develop a disaggregated model by gender and age. The drinking and driving behaviors of youth vary by age and sex, thus it is crucial for the model to capture these differences. Between the second and third GMB sessions, the modelers consulted with experts to improve different sectors of the model. For example, the mechanisms of peer influence and enforcement were revised after the second session based on expert feedback and follow-up meetings. The focus of this article is to show the structure of the SD simulation model (i.e., the quantitative model), present the fit statistics (i.e., how well the simulation model can replicate the historical trends), illustrate the impact of interventions, and identify potential unintended consequences.

2.1. Structure of the system dynamics model

The model tracks male and female individuals aged 15 to 24 (i.e., 20 groups) in the United States from 1982 to 2020. As shown in Fig. 1 in purple boxes, individuals can be in one of these states: *abstainers*, *drinkers who do not drive after drinking*, *drinkers who drive after drinking*, and *never DWI again* (drinkers who ceased engaging in driving after drinking up to age 24). The number of youths in each state changes by the inflow and outflows of these states (e.g., *abstainers becoming drinkers*). These flows are regulated by five main reinforcing feedback loops (R1 to R5) and four balancing loops (B1 to B4) illustrated in Fig. 1.

A feedback loop is a series of variables and causal links that create a closed loop of causal influences. Reinforcing feedback loops (labeled with Rs in Fig. 1) tend to reinforce the direction of original change of any variable in the loop. For example, in the R1: Marketing Influence on

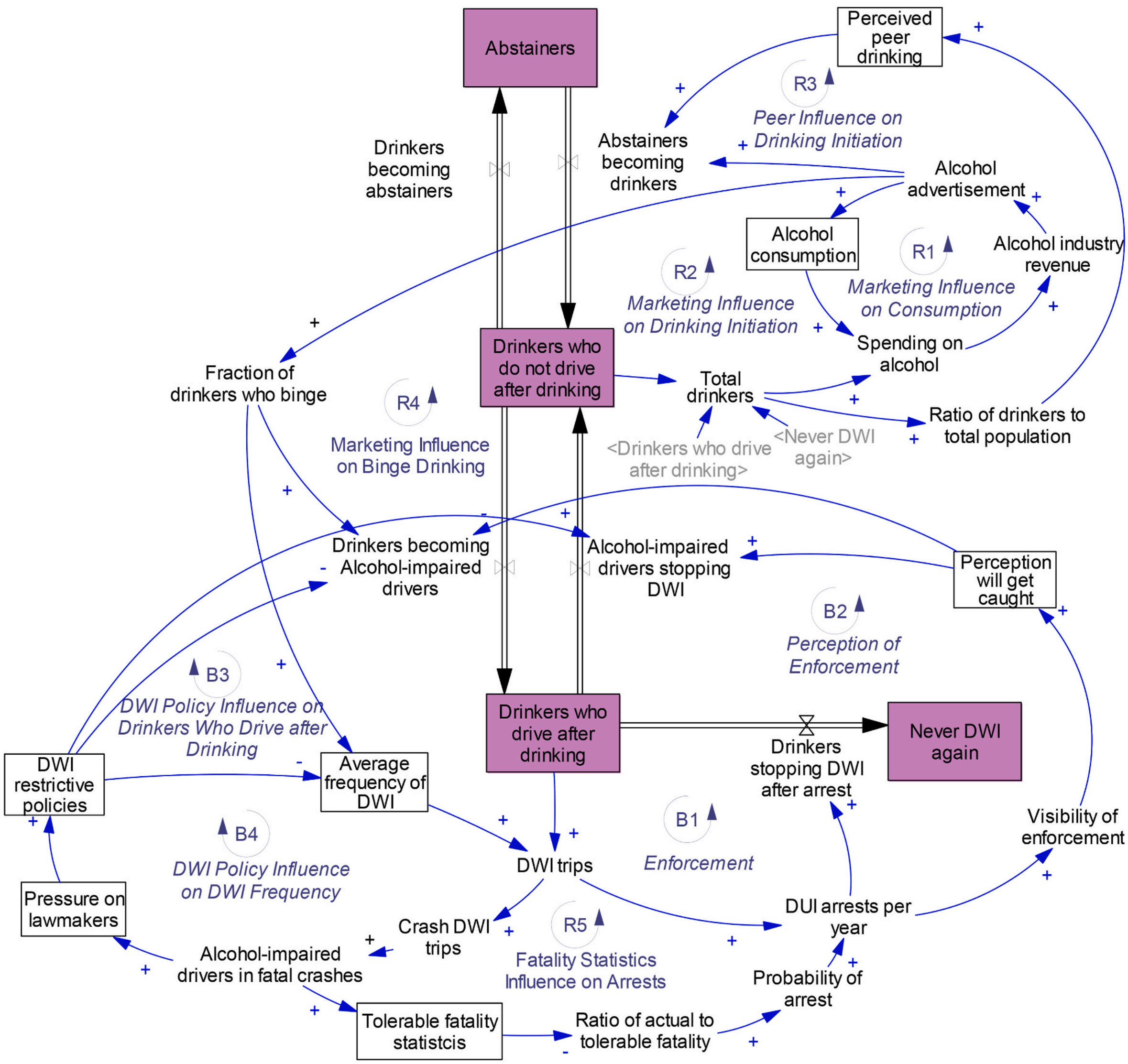

Fig. 1. A causal loop diagram of drinking and driving behaviors among adolescents and young adults.

Consumption loop (Fig. 1), more *alcohol advertisement* increases *alcohol consumption,* which increases *spending on alcohol,* which increases *alcohol industry revenue,* which, in turn, increases *alcohol advertisement*. As seen in the R2: Marketing Influence on Drinking Initiation loop, more *alcohol advertisement* increases the number of *abstainers becoming drinkers* which increases the number of *total drinkers,* which increases spending *on alcohol*. As *total drinkers* increase, *perceived peer drinking* increases which leads to more *abstainers becoming drinkers* (see R3: Peer Influence on Drinking Initiation). The R4: Marketing Influence on Binge Drinking loop illustrates that more *alcohol advertisement* increases *binge drinking* and consequently leads to more *drinkers becoming alcohol-impaired drivers* and a higher *average frequency of DWI*. We assumed that the alcohol industry increases alcohol marketing when the revenue goes below the desired level.

Balancing feedback loops (labeled with Bs in Fig. 1) push back in the opposite direction of the original change in a variable. For example, the B1: Enforcement loop illustrates that as the number of *drinkers who drive after drinking* increases, the number of *DWI trips* rises, which leads to more arrests due to driving under the influence (DUI).[1] More *DUI arrests* increases the number of *drinkers stopping DWI after arrest* which lowers the number of *drinkers who drive after drinking*. Thus the initial increase in impaired drivers works through the balancing feedback loop to reduce the number of impaired drivers. In addition, as seen in the B2: Perception of Enforcement loop, higher *DUI arrests* increase the visibility of enforcement which increases the perception of getting caught, which in turn, leads to a higher number of *alcohol-impaired drivers stopping DWI* and a lower number of *drinkers becoming alcohol-impaired drivers*. The B3: DWI Policy Influence on Drinkers Who Drive after Drinking loop illustrates that as the number of DWI trips increase, related fatalities rise, which in turn, increase pressure on lawmakers which leads to more restrictive DWI laws. More *restrictive DWI laws* lead to fewer *drinkers becoming alcohol-impaired drivers* and more *alcohol-impaired drivers stopping DWI*. As shown in B4: DWI Policy Influence on DWI Frequency loop, more *restrictive DWI laws* results in a reduction in the *average frequency of*

[1] We use driving under the influence (DUI) where referring to arrests due to impaired driving because this term is used for reporting the related arrests in the FBI website: https://cde.ucr.cjis.gov/LATEST/webapp/#/pages/explorer/crime/arrest.

DWI, which in turn, leads to lower *DWI trips*.

The role of fatality statistics is seen in the R5: Fatality Statistics Influence on Arrests loop at the lowest section of Fig. 1. As the number of *alcohol-impaired drivers in fatal crashes* goes down, the *tolerable fatality statistics* decline over time. A reduced threshold for acceptable *fatality statistics* and a higher *ratio of actual to tolerable fatalities* result in a higher *probability of arrest*, leading to more *DUI arrests*. Higher *DUI arrests* reduce *drinkers who drive after drinking* and subsequent fatalities are reduced, which leads to even lower *tolerable fatality statistics*.

Model structure and formula are presented in supplementary document A1.

2.2. Data

Traffic fatalities: The number of drivers involved in fatal crashes by their blood alcohol concentration (BAC) level for each age group by sex from 1982 to 2020 were obtained from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS). FARS is a census of fatal traffic crashes in 50 states, the District of Columbia, and Puerto Rico. Only crashes that occurred on public trafficways and resulted in the death of a motorist or a non-motorist within 30 days of the crash are recorded in FARS. A driver is counted as a drinking driver if their blood was tested, and the BAC was positive (BAC $\geq$0.01 g/dl). When the BAC of the driver is missing or the driver was not tested, the BAC level is imputed based upon the police assessment, time of the crash, gender, age, and other factors (Subramanian, 2002).

Number of arrests due to driving under the influence: The number of arrests due to driving under the influence (DUI) for each age group by sex between 1985 and 2020 was obtained from the Federal Bureau of Investigation's Crime Data Explorer.

Alcohol-impaired driving Laws: Five laws are included in this study, 0.10 BAC per se, 0.08 BAC per se, administrative license revocation, minimum legal drinking age 21, and zero tolerance laws enacted in 50 states and the District of Columbia. The BAC per se laws indicate the BAC level at which a driver is considered intoxicated by law. The 0.10 BAC per se law reduced the BAC limit from 0.15 to 0.10 and the 0.08 BAC per se law lowered the BAC limit to 0.08. The administrative license revocation law allows the enforcement system and the state department of motor vehicles to suspend a driver's license if arrested for DWI. The minimum legal drinking age 21 law prohibits individuals younger than 21 from possessing, purchasing, and using alcohol. The zero-tolerance law makes it illegal to have any level of blood alcohol for those drivers under 21. Variables related to these laws are operationalized as dummy variables in which the variable is 1 after effective date in each state and zero otherwise. To estimate the number of laws in the US over time, we added these dummy variables each year. The effective dates of 0.08 BAC per se law for each state were obtained from the NHTSA website (National Highway Traffic Safety Administration, 2021). The effective dates of the administrative license revocation, minimum legal drinking age 21, and zero tolerance laws were the same used by Fell and colleagues' research on laws enacted between 1982 and 2012 (Fell and Scherer, 2017a). We updated their dataset by reviewing the NHTSA's Digest of Impaired Driving's documents (National Highway Traffic Safety Administration, 2007, 2011, 2012, 2013, 2015, 2016, 2017).

Fraction who drink alcohol: We used the estimates reported in tables 93, 94, and 95 in Monitoring the Future, occasional paper series 94 (Johnston et al., 2020). Tables 93, 94, and 95 reported trends in 30-day prevalence of alcohol use by gender in grades 8 and 10 between 1991 and 2019, and for grade 12 between 1976 and 2019, respectively. The prevalence of alcohol use for individuals aged 19 to 20, 21 to 22, and 22 to 23 was obtained from table 8 in Patrick et al. (2022).

Prevalence of binge drinking: Fractions of the population who binge among 10th and12th grades from 1982 to 2020 were obtained from Monitoring the Future (Miech et al., 2023). Prevalence of binge drinking for those aged 19 to 24 from 1982 to 2020 were from Monitoring the Future (Patrick et al., 2022).

Population aged 15 to 24: The population of the US by age and sex were obtained from the U.S. Census Bureau, Current Population Survey, School Enrollment Supplement. Three years were missing: 1984, 1987, and 2006. The data in 1994 comes from another source (Intercensal Estimates of the United States Resident Population by Age and Sex: 1990). For estimating the population in 1984,1987, and 2006, we used the average of a year before and a year after.

Other data: We used the NEXT Generation Health Study (NEXT) dataset (Simons-Morton et al., 2017), which was not used in the calibration process to test the model. The longitudinal NEXT study started in 2009–2010 U.S. school year and surveyed 10th graders and ended in 2016. We observe the prevalence of drinkers, drivers who drive after drinking, frequency of DWI, and prevalence of binge drinkers in this survey. The comparison of the model generated variables and the NEXT Generation estimates were limited to those years.

2.3. Model estimation

The parameters of the model were specified based on past research and formal model estimation. The parameters obtained from the literature include the fraction of revenue spent on alcohol advertisement (0.09) (Federal Trade Commission, 2014), price elasticity of demand for alcohol (−0.7) (Elder et al., 2010), average tax on alcohol ($1/gallon) (Alcohol Policy Information System, 2023), alcohol consumption per capita (2.93–3.95 gallon/person/year) (Slater and Alpert, 2023), movie alcohol exposure (8 h/year) (Sargent et al., 2006), fraction male and female abstainers aged 15 to 24 in 1982 (0.17–0.41) (Miech et al., 2023; Patrick et al., 2022), and fraction of male and female alcohol-impaired drivers aged 15 to 24 in 1982 (0.05–0.32) (Balmforth, 1998)Federal Trade Commission, 2014; National Center for Statistics and Analysis, 2023.

We estimated other model parameters using historical data on drivers in fatal crashes with BAC$\geq$0.01 g/dL, DUI arrests, the fraction who binge, the fraction of those who drink alcohol, and alcohol-impaired driving laws. The model is complex and nonlinear. Therefore, it is not possible to directly identify closed-form estimates of the value of parameters (Rahmandad et al., 2015). As a result, we estimated the model parameters by maximum likelihood to fit simulated time series to historical data (Struben et al., 2015). To do so, we used a Gaussian log-likelihood function and calibration weights for each time series to account for differences in their magnitude and variability. The standard deviation of time series data was used as calibration weights. To determine the uncertainties in estimated model parameters, we employed a Markov Chain Monte Carlo (MCMC) method designed to explore high dimensional parameter space (Vrugt et al., 2009). MCMC method explores the feasible parameter ranges and accepts combinations that align with the observed data. We sampled 10,000 model parameters from the credible region of parameter space to generate the plausible intervals on model projection (section 3.2. Interventions). The estimated parameters are reported in the supplementary document A2.

3. Results

3.1. Baseline simulation

The simulation model closely replicates 53 time series data, including male (Fig. 2) and female (Fig. 3) drivers in fatal crashes aged 15 to 24 with BAC$\geq$0.01 g/dL in the United States from 1982 to 2020. The average R^2 of the time series presented in Figs. 2 and 3 is 0.84, with the mean absolute percent error of 0.18 (see fit statistics for each time series in Supplementary document A4). The historical trajectories of DUI arrests, by age and sex, ratios of drinkers and binge drinkers in the

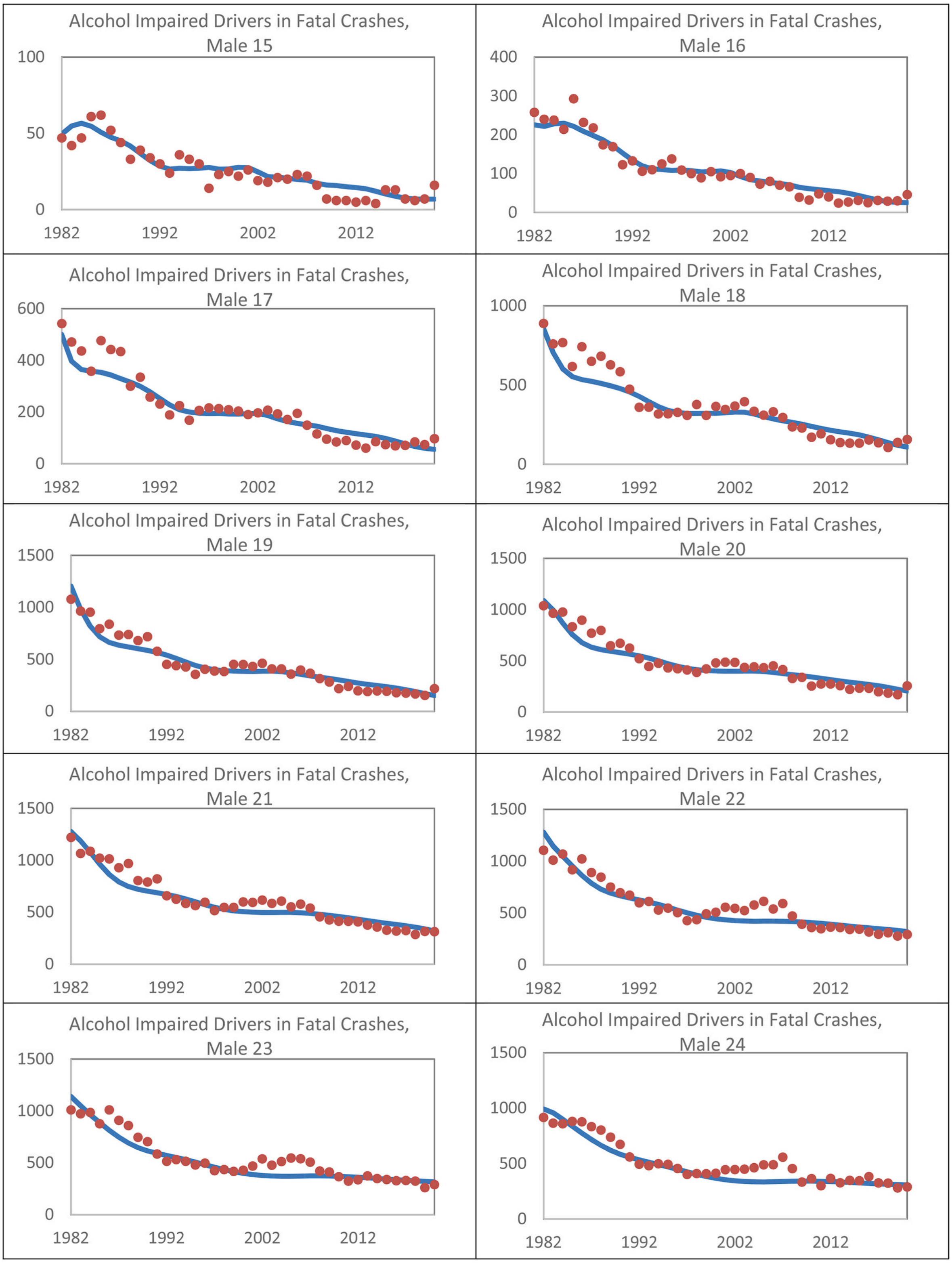

Fig. 2. Male drivers in fatal crashes with BAC≥0.01 g/dL; Historical trends are shown by red dots and the simulation results are shown by blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

population for multiple age groups by sex, and the total number of laws related to alcohol-impaired driving are presented in the supplementary document A3. Please note that the magnitude of Y-axis in Figs. 2 and 3 changes by age and sex (increases as age increases and it is higher for male individuals).

3.2. Interventions

We investigate the impact of a wide range of interventions suggested by the experts in the GMB sessions including higher enforcement, alternative transportation, alcohol truth campaign, ignition interlock, legislating a new restrictive policy in 50 states, and higher tax on

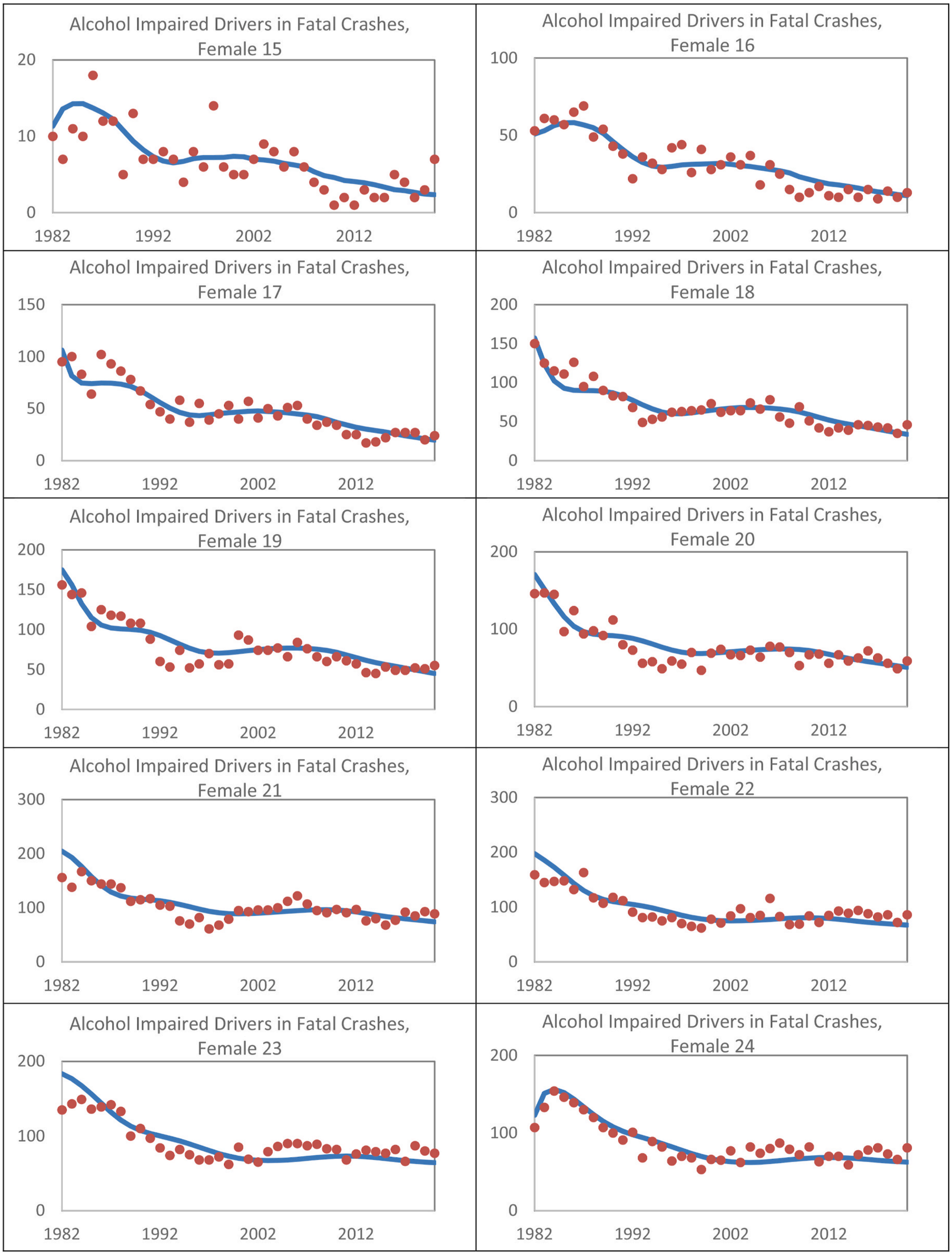

Fig. 3. Female drivers in fatal crashes with BAC≥0.01 g/dL; Historical trends are shown by red dots and the simulation results are shown by blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

alcohol. Interventions implemented in 2025 take two years to be fully implemented and last until 2050.

3.2.1. Higher enforcement

Under this scenario, the probability of arrest increases by 50% from 2025 to 2027 and then remains at the increased level from that point on. The vertical dash-dotted line in Fig. 4 shows the start time of the intervention. The black line and gray dashed lines depict the baseline and confidence interval, respectively. The red line and the red dotted lines capture the intervention and related confidence interval. Higher enforcement increases the number of DUI arrests and reduces both alcohol-impaired drivers aged 15 to 24 in fatal crashes (Fig. 4, left

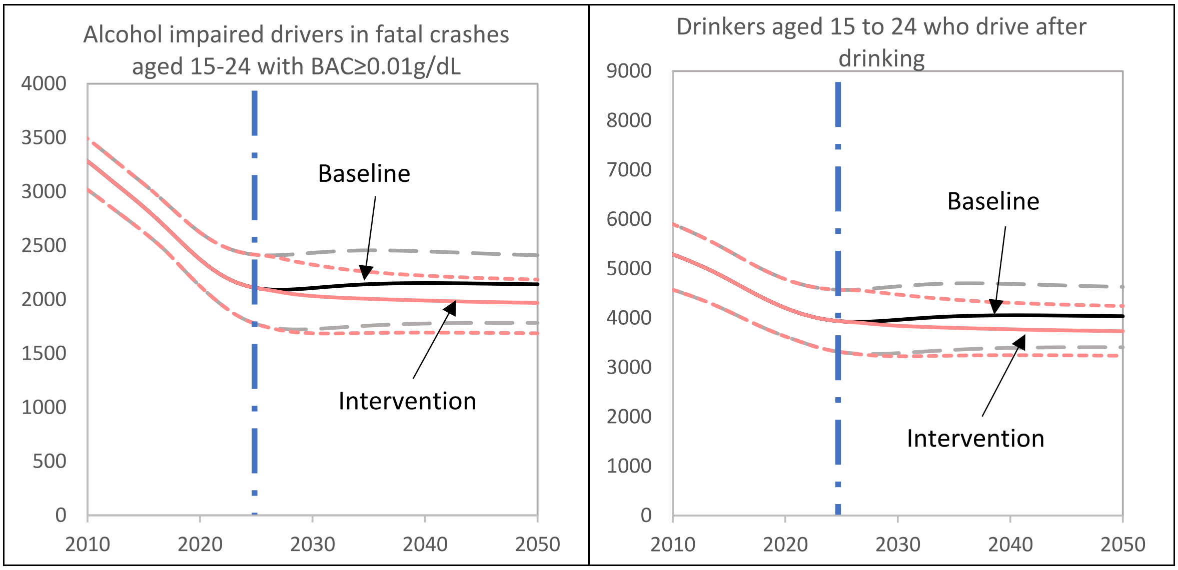

Fig. 4. Impact of higher enforcement on alcohol-impaired drivers in fatal crashes and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

panel), and the number of drinkers aged 15 to 24 who drive after drinking (Fig. 4, right panel).

3.2.2. *Alternative transportation*

This intervention reduces frequency of DWI by 50% from 2025 to 2027 and then remains at the reduced level from that point on. As expected, the number of alcohol-impaired drivers in fatal crashes decreases (Fig. 5, left panel), but the number of drinkers who drive after drinking increases (Fig. 5, right panel). The balancing feedback loop B2 (perception of enforcement) explains this unexpected outcome. Providing alternative transportation, reduces *average frequency of DWI* and leads to lower number *of DWI trips* and subsequently lower *DUI arrests*. As the number of *DUI arrests* decline, *visibility of enforcement* and the *perception will get caught* decreases. As a result, more drinkers drive after drinking and fewer drinkers who drive after drinking stop DWI. Thus, the number of *drinkers who drive after drinking* rises (Fig. 5, right panel).

3.2.3. *Alcohol truth campaign*

This intervention reduces the “fraction of individuals who initiate drinking” and “per capita alcohol consumption” by 20% after 2025. Initially, the number of alcohol-impaired drivers in fatal crashes goes down (Fig. 6, top-left panel) because the number of abstainers (Fig. 6, lower-right panel) increases and the frequency of DWI goes down. However, after a few years, both the number of alcohol-impaired drivers in fatal crashes and drinkers who drive after drinking increases (Fig. 6, top panels). The rebound is caused by the reaction of the alcohol industry. As per capita alcohol consumption and the number of drinkers decline, the revenue of the alcohol industry decreases, and the industry reacts by increasing the alcohol marketing expernidture(Fig. 6, lower left panel). Higher alcohol advertisement reduces the number of abstainers (Fig. 6, lower right panel), and increases binge drinking, which leads to a higher average frequency of DWI and higher driving after drinking and related fatalities (Fig. 6, top left panel).

3.2.4. *Ignition interlock*

This intervention increases the fraction of people who stop driving

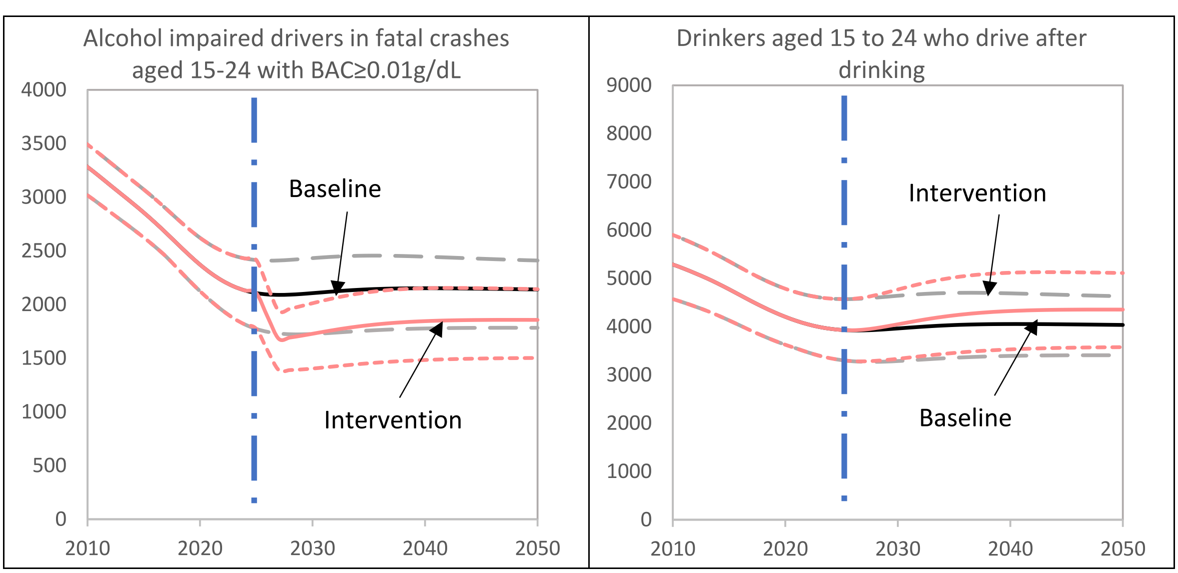

Fig. 5. Impact of alternative transportation on alcohol-impaired drivers in fatal crashes, and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

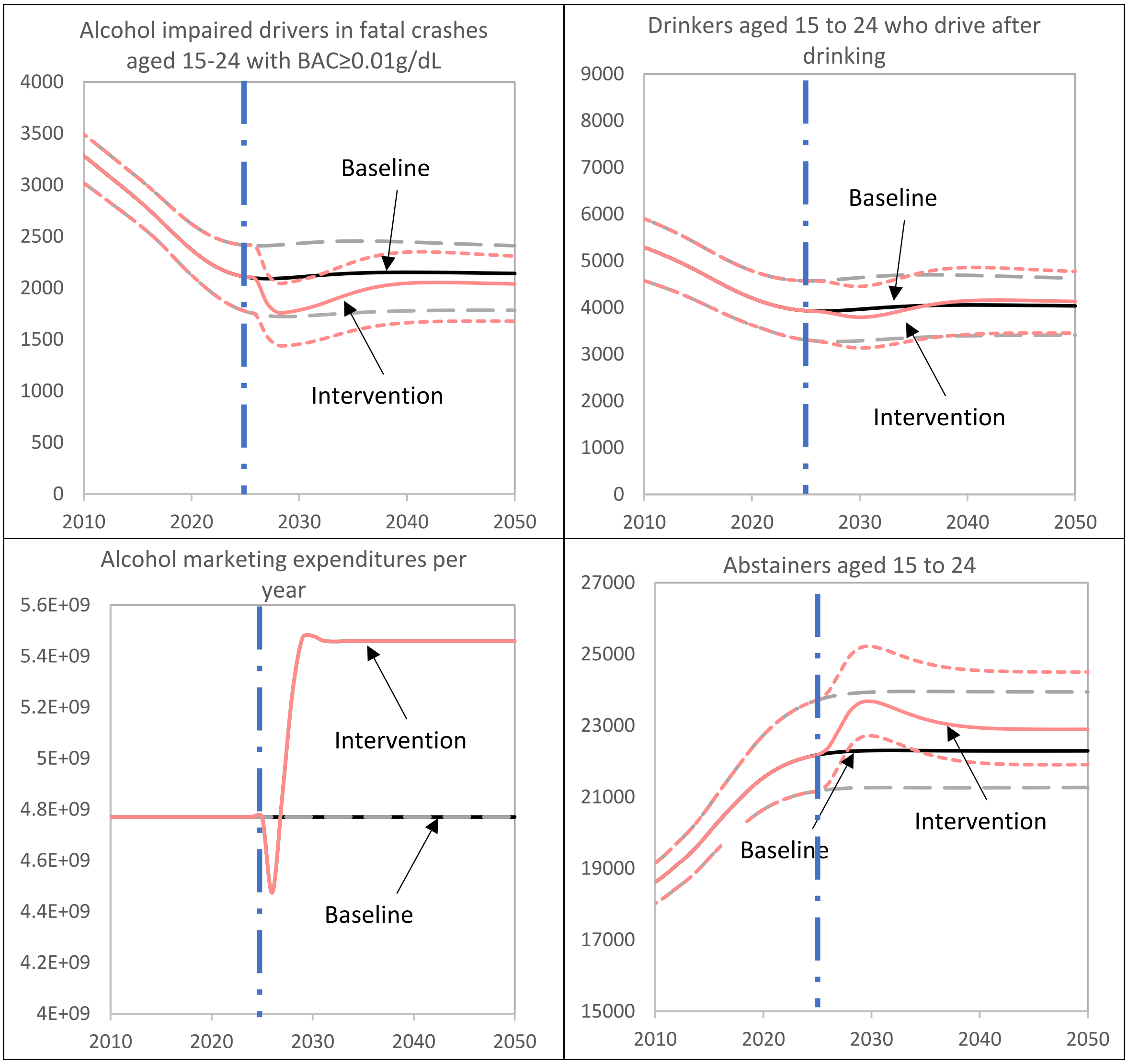

Fig. 6. Impact of an alcohol truth campaign on alcohol-impaired drivers in fatal crashes, the number of drinkers aged 15 to 24 who drive after drinking in 1,000, alcohol marketing, and total abstainers.

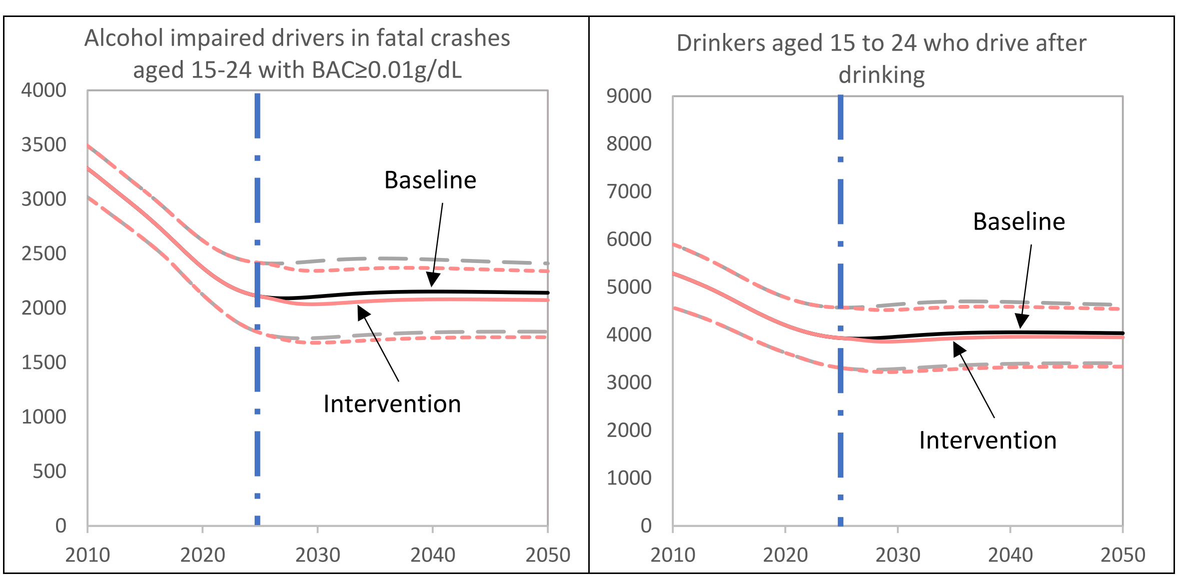

Fig. 7. Impact of ignition interlock on alcohol-impaired drivers in fatal crashes, and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

after drinking following a DUI arrest from 40% to 80%. Under this scenario, the number of alcohol-impaired drivers in fatal crashes and drinkers who drive after drinking declines slightly (Fig. 7).

3.2.5. DWI restrictive law

If a new law is enacted in 50 states, alcohol-impaired drivers in fatal crashes decline significantly (Fig. 8, left panel). This is achieved through a reduction in the frequency of DWI and the number of drinkers who initiate alcohol-impaired driving, as well as increase in the number of drinkers who stop driving after drinking. In the current model, the DWI restrictive laws are aggregated and include administrative license revocation (ALR), minimum legal drinking age 21 (MLDA), zero tolerance laws, and BAC per se laws (e.g., 0.05 g/dL). The model calibration provided the aggregate impact of such laws on frequency of DWI and the number of individuals who DWI. As a result, this scenario investigates the impact of a law representing an average DWI restrictive law, encompassing aforementioned laws (i.e., ALR, MLDA, zero tolerance laws, and BAC per se), on related fatalities and number of drinkers who drive after drinking.

3.2.6. Alcohol tax

This scenario involves increasing the average tax on alcohol from $1 to $5. Under this scenario, both the number of alcohol-impaired drivers in fatal crashes and the number of drinkers who drive after drinking decline slightly (Fig. 9). The model behavior is sensitive to the amount of tax increase. For example, increasing the alcohol tax to $12 increases both alcohol-impaired fatalities and the number of drinkers who drive after drinking slightly (not shown) because it triggers a response by alcohol industry.

3.2.7. Combined interventions

Based on insights from single interventions, a scenario that combines three interventions, including enactment of a new restrictive law in 50 states, providing alternative transportation, and higher enforcement is tested (Fig. 10). The number of alcohol-impaired drivers in fatal crashes drop the most under this scenario. However, the number of alcohol-impaired drivers dropped initially and then rebounded.

Table 1 reports the cumulative lives saved after implementing each intervention from 2025 to 2050. The cumulative lives saved were obtained by subtracting drivers in fatal crashes with BAC≥0.01 g/dL related to each intervention from the related fatalities in the baseline simulation.

4. Discussion

This paper presents the first system dynamics simulation model of alcohol-impaired driving behavior of adolescents and young adults in the United States from 1982 to 2020. The model closely replicated historical data series from multiple data sources and was simulated to test interventions including higher enforcement, alternative transportation, alcohol truth campaign, ignition interlock, legislating a new restrictive policy, and higher alcohol tax.

We found that while some interventions initially lead to a reduction in alcohol-related crash fatalities, their impact diminishes over time due to the interactions with other feedback mechanisms. For example, an alcohol truth campaign that reduces abstainers who initiate drinking and alcohol consumption per capita lowers alcohol-impaired fatalities by reducing the average frequency of DWI and the number of alcohol-impaired drivers. However, this leads to lower revenue for the alcohol industry. If the industry reacts by increasing alcohol advertisements, over time, more abstainers initiate drinking and the prevalence of binge drinking increases, which may lead to an increase in alcohol-impaired crash fatalities.

Although ignition interlock intervention contributes to a reduction in alcohol-related crash fatalities, the effect size is relatively modest. This intervention increases the fraction of alcohol-impaired drivers who stop DWI after arrest from 40% to 80%, but the alcohol-related crash fatalities do not change significantly. The limited impact of this intervention can be primarily attributed to the infrequent occurrence of DUI arrests. As estimated, not only in this study but also in others, the likelihood of being arrested for driving while impaired is exceedingly low, approximately 0.001 (Beitel et al., 2000; Miller et al., 1998; Zaloshnja et al., 2013). Consequently, only a small number of alcohol-impaired drivers face arrest each year, thus the implementation of ignition interlock systems has a comparatively minor influence on reducing fatalities. This is consistent with some previous studies that showed the impact of ignition interlock is constrained by the low participation rate of offenders in the program (Elder et al., 2011). While laws mandating alcohol ignition interlocks, especially those covering all offenders, are an effective strategy to reduce alcohol-impaired drivers in fatal crashes (Teoh et al., 2021), a greater effect could be realized if states convert their interlock laws to being mandatory, especially as part of the combination of more restrictive laws. However, interlock penetration rates are low (25%–50%), even in mandatory states so unless that is resolved, interlocks will have small effects on reducing fatalities.

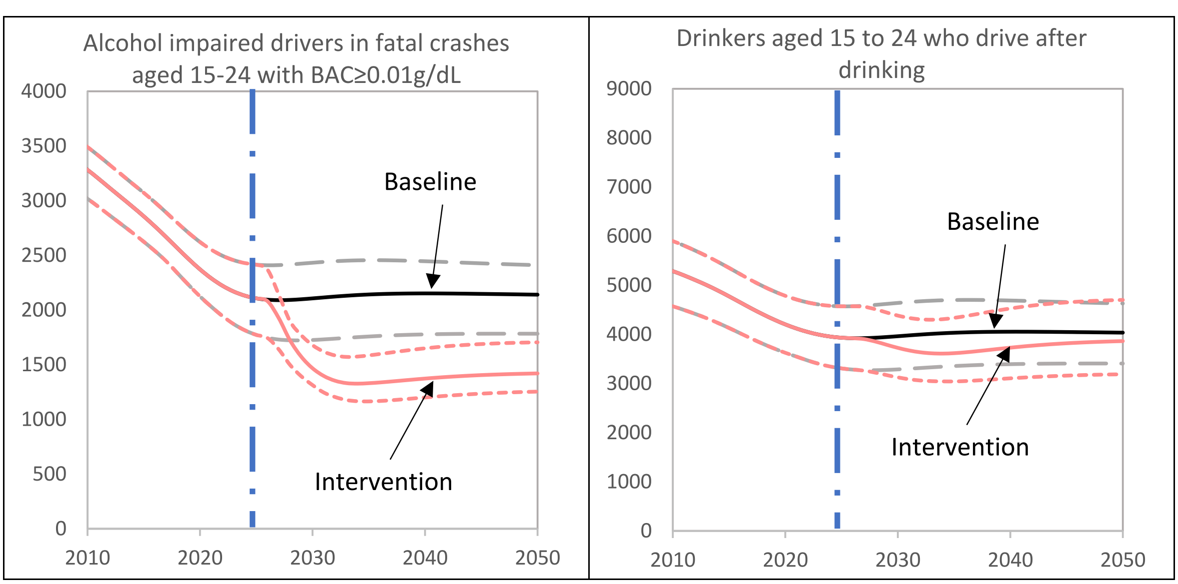

Fig. 8. Impact of DWI restrictive law on alcohol-impaired drivers in fatal crashes, and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

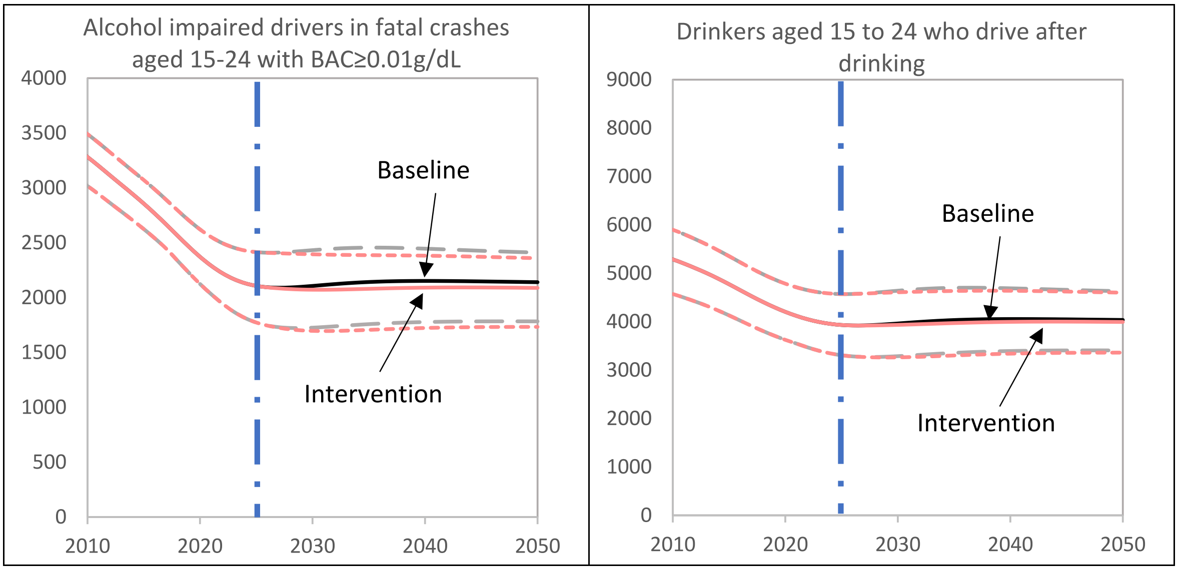

Fig. 9. Impact of increasing alcohol tax on alcohol-impaired drivers in fatal crashes, and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

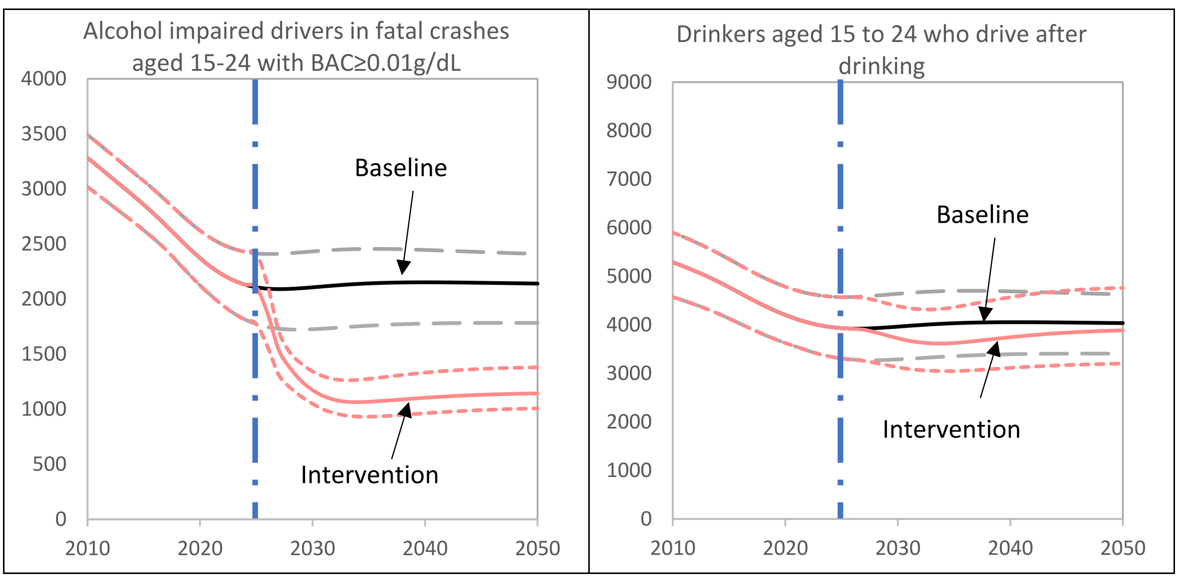

Fig. 10. Impact of combined interventions (enactment of a new restrictive law in 50 states, providing alternative transportation, and higher enforcement) on alcohol-impaired drivers in fatal crashes, and the number of drinkers aged 15 to 24 who drive after drinking in 1000.

Table 1
Potential cumulative lives saved from 2025 to 2050.

Interventions	Lives saved	Lower limit	Upper limit
Alcohol tax	1,192	1,047	1,251
Ignition interlock	1,620	1,221	1,856
Higher enforcement	3,135	2,354	4,341
Alcohol truth campaign	4,080	3,723	4,298
Alternative transportation	7,884	7,231	8,034
DWI restrictive law	16,643	11,839	21,574
3 Interventions Combined (Enforcement, Alternative transportation, and DWI law)	23,480	18,503	28,699

Certain interventions reduce both the number of individuals who drive after consuming alcohol and the associated fatalities. Conversely, other interventions reduce alcohol-related crash fatalities but may inadvertently lead to an increase in the number of individuals who drive while impaired. For instance, heightened enforcement efforts serve to decrease both the population of alcohol-impaired drivers and the related fatalities. However, alternative transportation intervention primarily reduced alcohol-impaired fatalities, while paradoxically contributing to an increase in the number of individuals who drive after drinking. This increase is attributed to the fact that alternative transportation intervention decreases the average frequency of DWI. Consequently, as the frequency of DWI and related arrests declines, the visibility of enforcement diminishes, and the perceived risk of getting caught decreases. As a result, fewer alcohol-impaired drivers are deterred from driving while impaired, and more individuals are inclined to initiate DWI behavior. Such unintended consequences can be avoided by combining several interventions.

Based on the insights from these simulation experiments, we combined alternative transportation, higher enforcement, and a new restrictive policy and found out that the combined intervention reduces alcohol-related crash fatalities without increasing the number of impaired drivers. In fact, the combined strategy saves the most lives in the next 25 years and reduces the number of drinkers who drive after drinking. However, the impact of interventions on the number of alcohol-impaired drivers diminishes in the long run (Fig. 10, right panel) because as the number of DWI trips and related arrests decline, more drinkers drive after drinking and fewer alcohol-impaired drivers stop DWI (balancing loop B2: perception of enforcement in Fig. 1). In addition, the number of associated fatalities stabilizes over time, signaling the necessity for new interventions if policymakers intend to sustain a continuous decline in alcohol-related crash fatalities beyond a few decades.

The model calibration provided interesting insights about time delays in the system. For example, we estimated that it takes around 23 years to build pressure to introduce a new law, around 13 years for fatality threshold to change, and approximately 9 years to change perception about enforcement. In other words, reducing alcohol-related crash fatalities is very complex, may lead to unintended consequences, and involve a long delay between actions and their impacts.

5. Limitations

This study has several limitations. First, the detailed extent to which the alcohol industry responds to a decline in revenue is unknown. We assume that the industry will increase their advertisement by 50% in response to a 20% decline in revenue. Moreover, industry may not rely solely on more advertisement but may have a targeted response. For example, if there is social pressure for responsible drinking, industry may respond to declining revenue by promoting higher-priced products that align with these social demands rather than increasing overall consumption. Future research could explore this potential strategy and its impact on alcohol-impaired crash fatalities. Another related limitation is that states vary in terms of their restrictive policies targeting the alcohol industry. A state-level SD model can capture such variations and better capture the impact of policies such as an alcohol truth campaign.

Second, the simulation model does not closely replicate the ratio of female individuals aged 19 to 22 and 23 to 24 who binge (see A3-5 in the supplementary document). Past studies showed that the gender gap in alcohol use and binge drinking have narrowed in adolescences and young adulthood because alcohol use declined faster for male than female adolescents and young adults (Grucza et al., 2018; Keyes et al., 2019; White, 2020). The mechanisms underlying different reductions in alcohol use among girls and boys are not known (Keyes et al., 2019) and not included in this SD model. This affects the projection of alcohol-impaired crash fatalities and DUI arrests. To check how this limitation affects the projections, we used the historical data on ratio of binge drinkers as an exogenous variable (instead of generating the ratio endogenously by the simulation model) and estimated R^2 and MAPE of alcohol-impaired crash fatalities and DUI arrests. The fit statistics of the alcohol-impaired crash fatalities did not change substantially (R^2 changed from 0.84 to 0.86 and MAPE changed from 18.1 to 16.2). However, the fit statistics of DUI arrests deteriorated when binge drinking is generated endogenously by the simulation model as opposed to using the historical data exogenously (R^2 declined from 0.83 to 0.55 and MAPE increased from 0.10 to 0.19). As the interventions are compared based on the projected alcohol-impaired crash fatalities, the insights generated by the model are not affected by this limitation. Nevertheless, future models as suggested by other studies (Pape et al., 2018; Törrönen et al., 2019) should investigate population level factors to identify why drinking and binge drinking of some groups declined but increased for other groups. For example, binge drinking among male individuals aged 19 to 22 declined while it increased among a female counterpart between 2000 and 2009.

Finally, the simulation does not include implementing vehicle technology that would prevent drivers from driving alcohol-impaired either via BAC detection systems or analyses of driver behaviors, or both. That is the subject of future analyses.

6. Conclusion

Drinking and driving among adolescents and young adults is a complex health and public safety problem that involves a multitude of factors interacting over time. We have developed the first system dynamics simulation model of youth alcohol-impaired driving, investigated the impact of diverse interventions on related fatalities, and identified a comprehensive strategy with the highest potential to reduce alcohol-related crash fatalities among adolescents and young adults. The interventions we tested used a variety of potential levers – economic, social, technological and regulatory. Findings suggest that such an approach is needed to compensate for responses to interventions in the system that result in paradoxical outcomes such as a reduction in abstainers or increases in the number of drivers who DWI. Future innovations might benefit from such a multi-pronged approach.

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CRediT authorship contribution statement

Niyousha Hosseinichimeh: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rod MacDonald:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Kaigang Li:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **James C. Fell:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Denise L. Haynie:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Bruce Simons-Morton:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Barbara C. Banz:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Deepa R. Camenga:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Ronald J. Iannotti:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Leslie A. Curry:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **James Dziura:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **David F. Andersen:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Federico E. Vaca:** Writing – review & editing, Validation, Supervision, Funding acquisition, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2024.117087.

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