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Article

Identifying Toxic Consumer Products: A Novel Data Set Reveals Air Emissions of Potent Carcinogens, Reproductive Toxicants, and Developmental Toxicants

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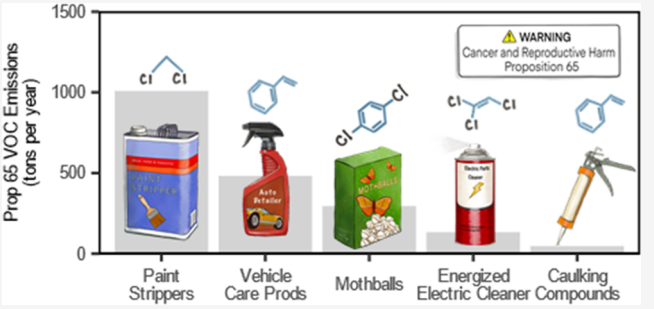
ABSTRACT: Consumer products are important sources of exposure to harmful chemicals. Product composition is often a mystery to users, however, due to gaps in the laws governing ingredient disclosure. A unique data set that the California Air Resources Board (CARB) uses to determine how volatile organic chemicals (VOCs) from consumer products affect smog formation holds a partial solution. By analyzing CARB data on VOCs in consumer products, we identified and quantified emissions of volatile chemicals regulated under the California Safe Drinking Water and Toxic Enforcement Act ("Prop 65"). We here highlight individual chemicals as well as consumer product categories that people are likely to be exposed to as individual consumers, in the workplace, and at the population level. Of the 33 Prop 65-listed chemicals that appear in the CARB emissions inventory, we classified 18 as "top tier priorities for elimination". Among these, methylene chloride and *N*-methyl-2-pyrrolidone were most prevalent in products across all three population groups. Of 172 consumer product categories, 105 contained Prop 65-listed chemicals. Although these chemicals are known carcinogens and reproductive/developmental toxicants, they remain in widespread use. Manufacturers and regulators should prioritize product categories containing Prop 65-listed chemicals for reformulation or redesign to reduce human exposures and associated health risks.



KEYWORDS: *consumer product exposures, VOCs, Prop 65, emissions, ingredients, carcinogens, reproductive/developmental toxicants, regulation*

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INTRODUCTION

Chemicals with known hazards are present in consumer products used regularly in the home and workplace. These products are an important source of chemical exposures.[1−5] Indeed, chemical exposures from use of consumer products are often higher than environmentally mediated, far-field exposures.[2,6] Identifying product ingredients is the first step in assessing associated health risks and prioritizing products for reformulation based on hazard. However, the data gap created by nonexistent or incomplete regulatory requirements for ingredient disclosure complicates even this initial identification step.

The California Air Resources Board (CARB) Consumer Product Regulatory Program fills an important part of this data gap with respect to volatile organic compounds (VOCs) and the slightly less volatile compounds defined in CARB regulations as low vapor pressure VOCs (LVP-VOCs). CARB conducts periodic surveys of product manufacturers who sell goods into California, collecting information about volatile chemicals in their products as part of the agency's work to understand and reduce air emissions that contribute to ground-level ozone (aka "smog").[7] Reporting is mandatory; companies certify that the information they provide is accurate to the best of their knowledge; and CARB conducts extensive quality assurance and quality control of the data, working with companies to correct any errors or deficiencies.[8] CARB also makes this industry-supplied data publicly available, albeit in aggregated form, *i.e.*, by consumer product category rather than by individual product. Although ripe with interpretive possibility, these data have not previously been analyzed to identify sources of exposure to chemical ingredients that may pose significant hazards to consumers or workers. Like CARB, we use the phrase "consumer products" to encompass both products used by individual consumers (such as dishwashing soap) and those used in commercial operations (such as pipe cement and floor

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maintenance products), with workers more likely to be highly exposed in the latter scenario.

Many chemicals, including ingredients commonly found in consumer products, are associated with a range of human health effects, including asthma, endocrine disruption, reproductive and developmental harm, and cancer.[9−15] Several authoritative lists link data on chemical hazards to specific adverse health outcomes. One such authoritative list is maintained under California's Safe Drinking Water and Toxic Enforcement Act (commonly known as Prop 65), which identifies chemicals known to the state of California as carcinogens, reproductive toxicants, and/or developmental toxicants.[16]

A unique right-to-know law, Prop 65 was passed by voters in 1986 to reduce consumer exposure to toxic chemicals through the power of information. The law's primary purpose was to incentivize manufacturers to introduce safer product formulations into the marketplace by empowering consumers to deselect products with known-hazardous ingredients. The secondary purpose of Prop 65 was to enable consumers to mitigate their risk of exposure to hazardous product ingredients, such as by using personal protective equipment, ensuring adequate ventilation during use, or reducing frequency of use.[17]

The Prop 65 list draws from multiple other authoritative lists of carcinogens and reproductive/developmental toxicants and from two Prop 65-specific expert scientific committees that are convened to evaluate additions to the list, including many chemicals that are not listed elsewhere. The list includes fifty-six carcinogens and fifty-five reproductive toxicants that were either not listed by another authoritative body at the time of Prop 65 listing (*e.g.*, bisphenol A) or not identified on other lists as reproductive or developmental toxicants (*e.g.*, benzene and *n*-hexane).[18] The Prop 65 list currently includes 624 carcinogens and 323 reproductive/developmental toxicants, with some chemicals listed for more than one of these endpoints. Prop 65 does not include other hazard endpoints, such as neurotoxicity, asthmagenicity, or endocrine disruption.

Using the Prop 65 list to identify hazardous volatile chemicals in consumer products reported in CARB inventories, we sought to understand how people may be exposed to those chemicals via products used at home and in the workplace. While the CARB data reflect products sold in California, the findings are relevant to the U.S. overall, given the size of the California market and evidence that products are not specially formulated for that state.[18] This analysis could inform consequential risk-reduction actions, the most obvious of which is reformulation of products in product categories posing a high likelihood of harm.

METHODS

Chemical List. We used California's Prop 65 list of chemicals, which is regularly updated, to identify known hazards among the CARB-surveyed volatile ingredients. The Prop 65 list includes chemical name, Chemical Abstract Service (CAS) number, date of listing, and whether a chemical is classified as a carcinogen, a reproductive toxicant, and/or a developmental toxicant. We analyzed the Prop 65 list as of December 31, 2021.

CARB Data. We used data from CARB's most recent Emissions Inventory (2020) to identify products associated with higher exposure potential. The 2020 Emissions inventory is based on product ingredient surveys conducted in 2013, 2014, and 2015.[19] Using comprehensive ingredient concentration data collected in these surveys, CARB estimates average weight fractions of chemicals in each product type, generating a speciation profile for each product category. Weight fractions are then combined with estimated total organic gas (TOG) emissions for each product category, with adjustments for fate and transport assumptions, to model emissions according to an emissions inventory code (EIC). CARB's fate and transport models account for the portion of product ingredients that are not ultimately emitted to air because they go down the drain or are combusted.

The current CARB emissions inventory, which was finalized in 2020, includes 173 consumer product categories designated by EIC codes (510-506-6###-0000).[20] In this analysis, we used an appendix to this report, "New OG Speciation Profiles for Consumer Products (2020 Update)", that we obtained from CARB by request. This file contains organic gas speciation profiles for 172 of the EICs (the last EIC, Washing Soda, consists of only inorganic ingredients and thus has no speciation profile). We also accessed CARB TOG emissions estimates for 2020.[21]

Chemical Classification by Priority for Elimination. Although all Prop 65-listed chemicals are by definition hazardous, we further subdivided them as to priority for elimination. Our categorization used a combination of scientific and policy judgments about where urgency is greatest, specifically EPA risk-based screening levels (RSLs) for residential indoor air (10^{-6} for cancer risk and 0.1 hazard quotient for noncancer hazard); EPA priorities under the Toxic Substances Control Act (TSCA); and the National Toxicology Program's (NTP) 15th Report on Carcinogens (ROC).[22] Where both cancer and noncancer RSLs exist, we used the lower value. (Although OEHHA-established "safe harbor" levels of exposure under Prop 65 are an additional useful measure of chemical hazard, we did not use these to determine comparative priority because too many chemicals of interest lacked safe harbor values.)

We classified chemicals as being "top tier priorities for elimination" if either (i) the RSL was below 1 ug/m^3, (ii) the chemical was one of the first 10 priority chemicals EPA is evaluating under the 2016 revised TSCA, or (iii) the NTP has listed the chemical in the 15th Report on Carcinogens, which "identifies substances that pose a cancer hazard for people in the United States".[22] The remaining chemicals were classified as "second tier priorities" (Table S1). Our rationale was to synthesize relevant information from authoritative risk assessments to identify the Prop 65-listed agents that pose the greatest hazard based on existing evidence. This sorting is necessarily imperfect insofar as some chemicals we designated as second tier may simply be less studied than those we designated top tier and may lack data indicating greater hazard. We nonetheless believe consideration of scientific and policy judgments about relative hazard is important—in addition to exposure—in considering how to prioritize among actions that reduce exposure to Prop 65 chemicals.

Prioritizing Chemicals and Product Categories Using CARB Ingredient Data. We merged the list of Prop 65 chemicals (n = 868 chemicals or chemical groups) with the CARB speciation profiles (n = 429 ingredients) using CAS numbers. We identified and analyzed product categories containing at least one Prop 65 chemical and, in these categories, investigated and analyzed only Prop 65-listed ingredients. We also noted which product categories did not contain any Prop 65 chemicals and eliminated them from further consideration (Table S2).

To select product categories for further study, we considered three population groups. We ranked product categories according to their potential exposures for (1) consumers, (2)

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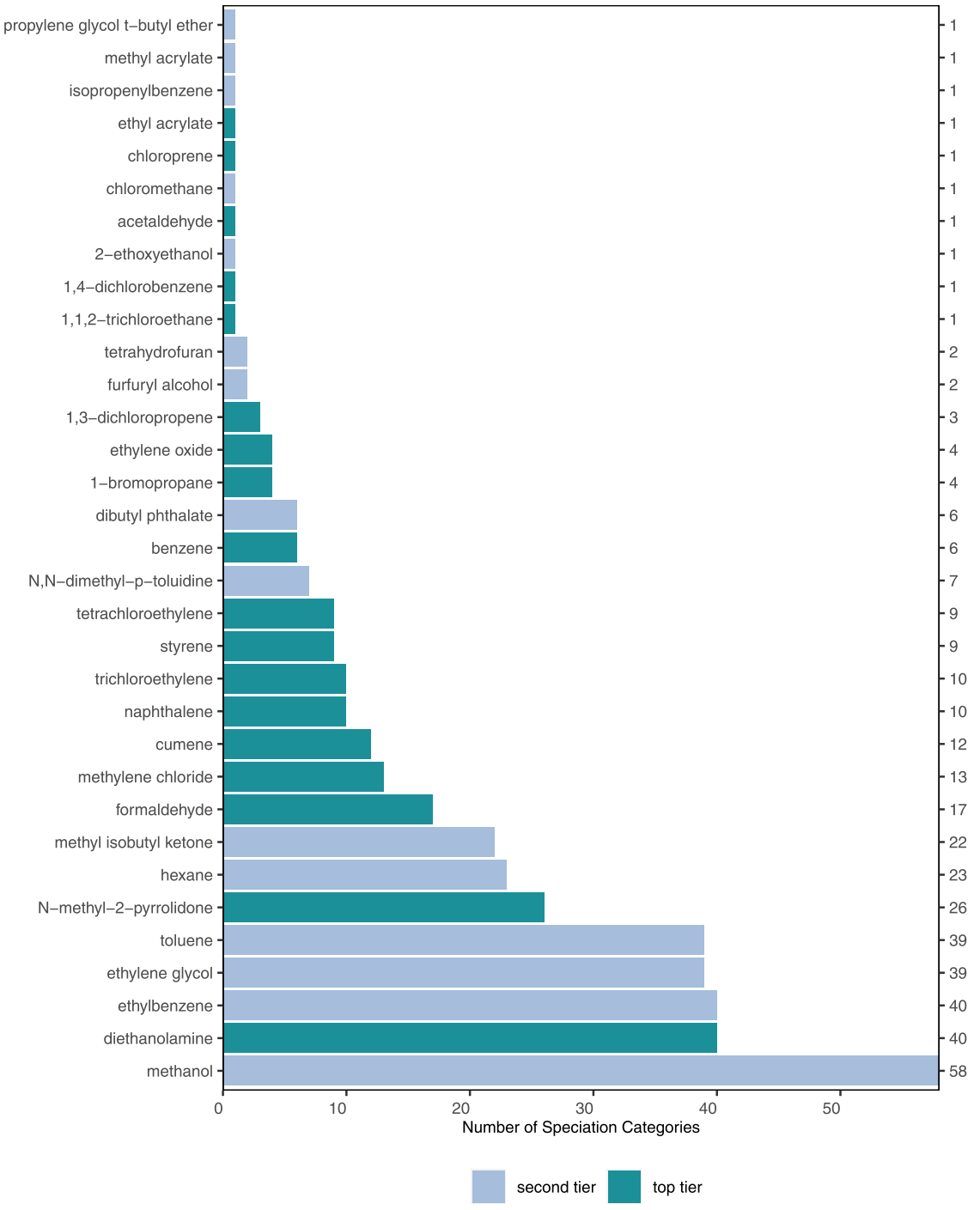

Figure 1. Prop 65-listed chemicals reported as ingredients in CARB's 2020 emissions inventory. Chemicals are distinguished by priority tier. Right margin shows the number of product categories with each chemical.

workers, and (3) the general population, classified as follows (Figure S1). For consumers, we identified product categories as "used on the body", "routinely used in the home", "specialty use in the home", or "other". Each product category was assigned to only one of these use categories (Table S2). Three of the authors independently classified product categories and subsequently arrived at a consensus through discussion. We then designated the first two categories as potential sources of high consumer exposures. We ranked product categories so designated by the number of top tier Prop 65 chemicals they contained. We ranked top tier Prop 65 chemicals by the number of product categories they appeared in.

To identify product categories likely to cause high occupational exposures, we classified product categories by their use in the workplace (Table S2), using the same method to classify and achieve consensus. We again ranked product categories so designated by the number of top tier Prop 65 chemicals they contained. We ranked top tier Prop 65 chemicals by the number of product categories they appeared in.

For product categories likely to cause widespread population-level exposures, we focused on those product categories with the

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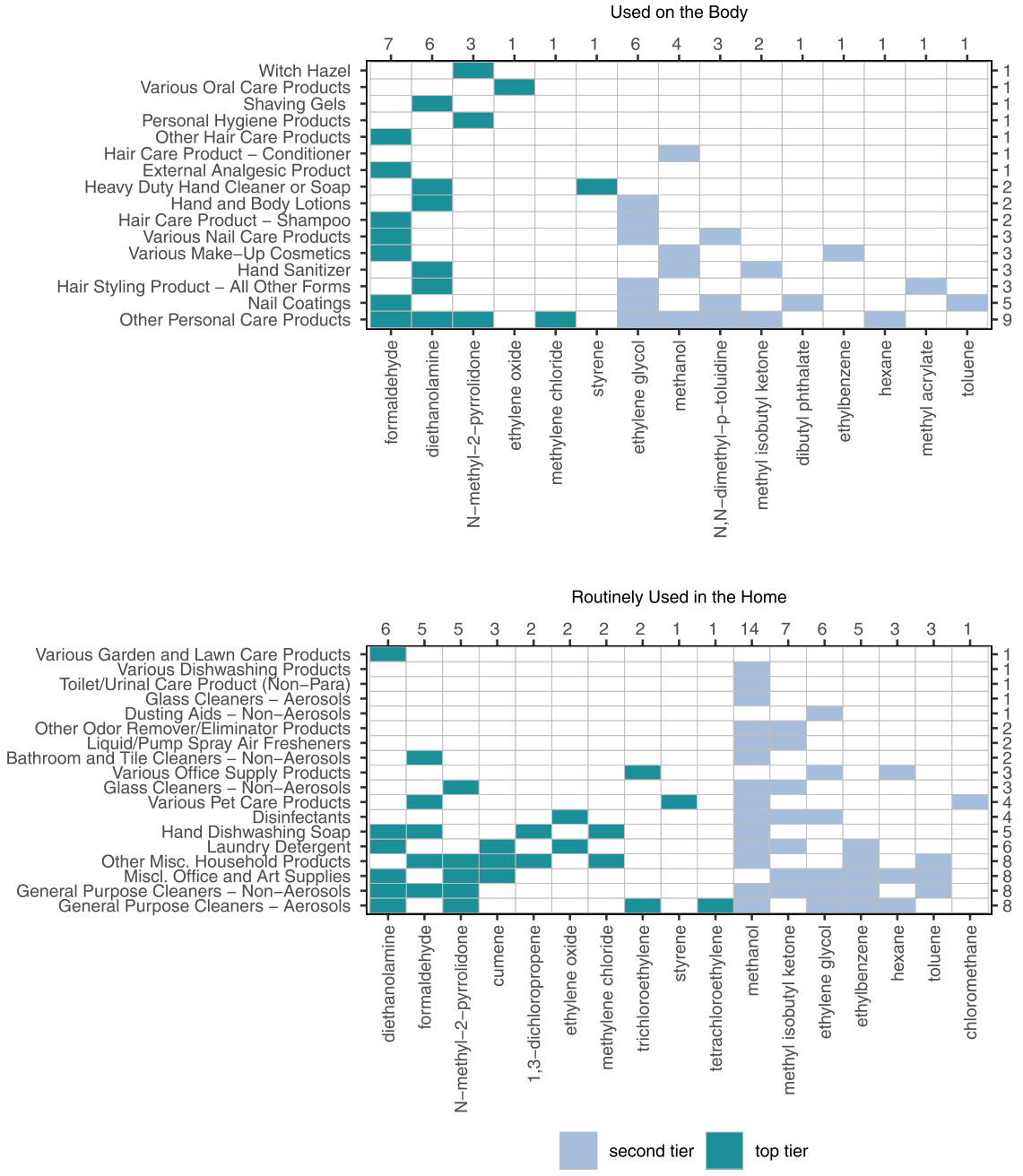

Figure 2. Product categories prioritized based on consumer exposures had to contain at least one Prop 65-listed chemical and be classified as "used on the body" or "routinely used in the home". Top margin shows the number of product categories with each chemical; right margin shows the number of Prop 65-listed chemicals in each product category.

highest emissions of volatile Prop 65 chemicals. By linking EICs to speciation profiles containing information on weight fractions of each chemical ingredient, we calculated the total emissions in tons per day associated with each volatile Prop 65 chemical in each EIC, then summed across EICs to obtain total emissions for each Prop 65 chemical and ranked them by total estimated emissions (Figure S2).

All analyses were conducted in R Version 4.0.3.

RESULTS

Thirty-three Prop 65-listed chemicals were reported as ingredients in the 2020 CARB emissions inventory (Figure 1). Methanol was the most prevalent, i.e., present in most product categories, followed by diethanolamine, ethylbenzene, ethylene glycol, and toluene. Among the top tier Prop 65-listed chemicals, diethanolamine, *N*-methyl-2-pyrrolidone, and formaldehyde were most prevalent.

Of the 172 speciation profiles in the 2020 CARB inventory, 67 lacked Prop 65-listed chemicals. The remaining 105 categories contained between 1 and 17 Prop 65-listed chemicals. There were 78 product categories that contained at least one top tier Prop 65-listed chemical. The category "Other Adhesives" contained the most Prop 65-listed chemicals overall and also the most top tier chemicals (9) (Table S2).

Consumer Exposures. The CARB survey included 16 "used on the body" product categories containing at least one

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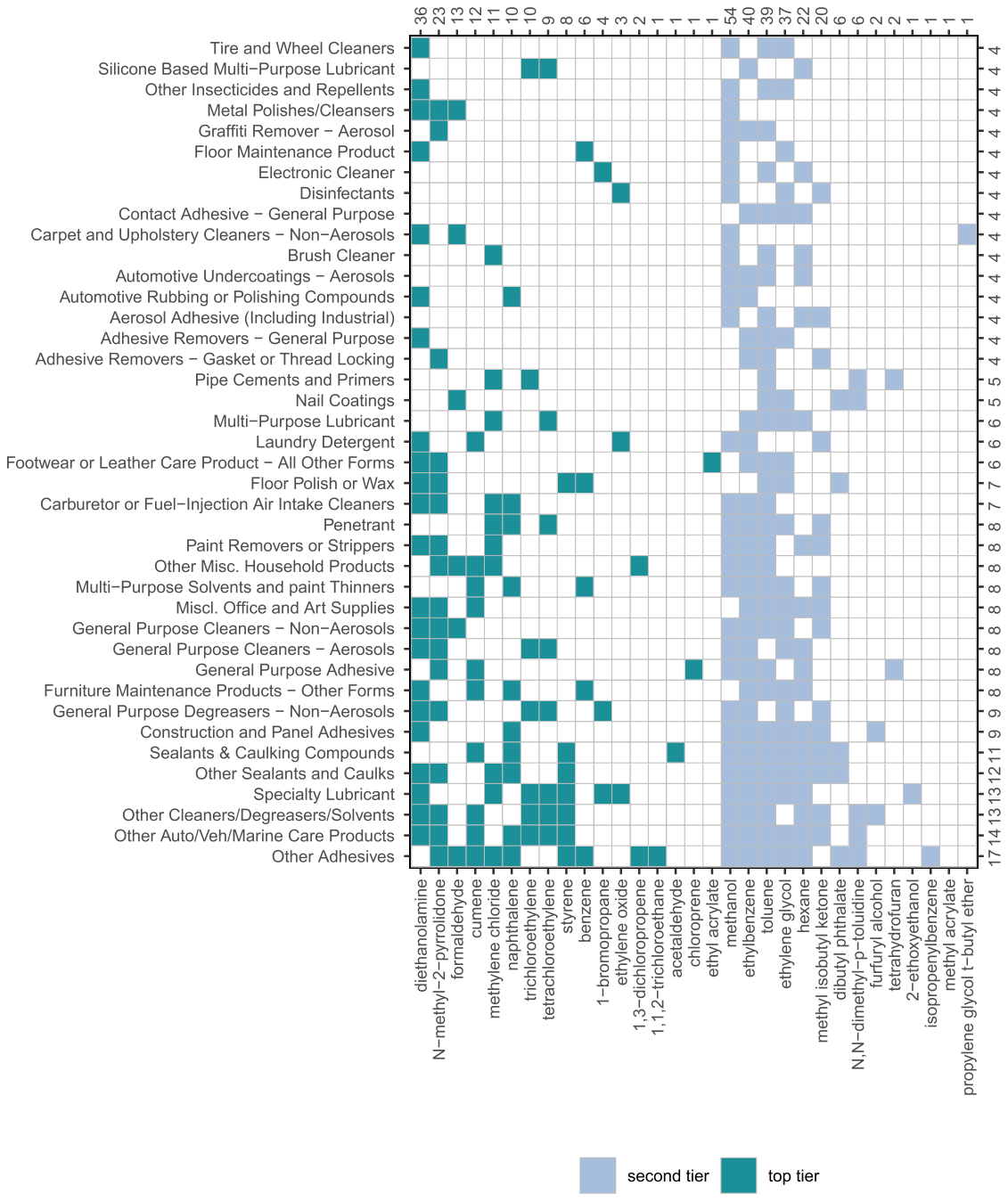

Figure 3. Product categories prioritized for worker exposures had to contain at least one Prop 65-listed chemical and be classified as "likely used in the workplace". This is an abridged figure showing only product categories with at least four Prop 65-listed chemicals; the unabridged version is in Figure S3. The top margin shows the number of product categories with each chemical (from the unabridged figure); the right margin shows the number of Prop 65 chemicals in each product category.

Prop 65 chemical (Figure 2). "Other Personal Care Products" contained the greatest number of Prop 65 chemicals as well as the greatest number of top tier Prop 65-listed chemicals. Formaldehyde, found in 7 categories, was the most commonly reported top tier Prop 65-listed chemical among categories used on the body, followed by diethanolamine, *N*-methyl-2-pyrrolidone, ethylene oxide, methylene chloride, and styrene. Among the second tier Prop 65 chemicals, ethylene glycol was reported most often, followed by methanol and *N*,*N*-dimethyl-p-toluidine.

Among product categories routinely used in the home, "General Purpose Cleaners—Aerosols", "General Purpose Cleaners—Non-aerosols", "Miscl. Office and Art Supplies", and "Other Miscl. Household Products" each contained 8 Prop 65 chemicals; "Other Miscl. Household Products" contained the greatest number of top tier Prop 65-listed chemicals (Figure 2). The top tier Prop 65 chemicals found most often in products routinely used in the home were diethanolamine, formaldehyde, *N*-methyl-2-pyrrolidone, cumene, 1,3-dichloropropene, ethylene oxide, methylene chloride, and trichloroethylene. Among the second tier Prop 65-listed chemicals, methanol was found

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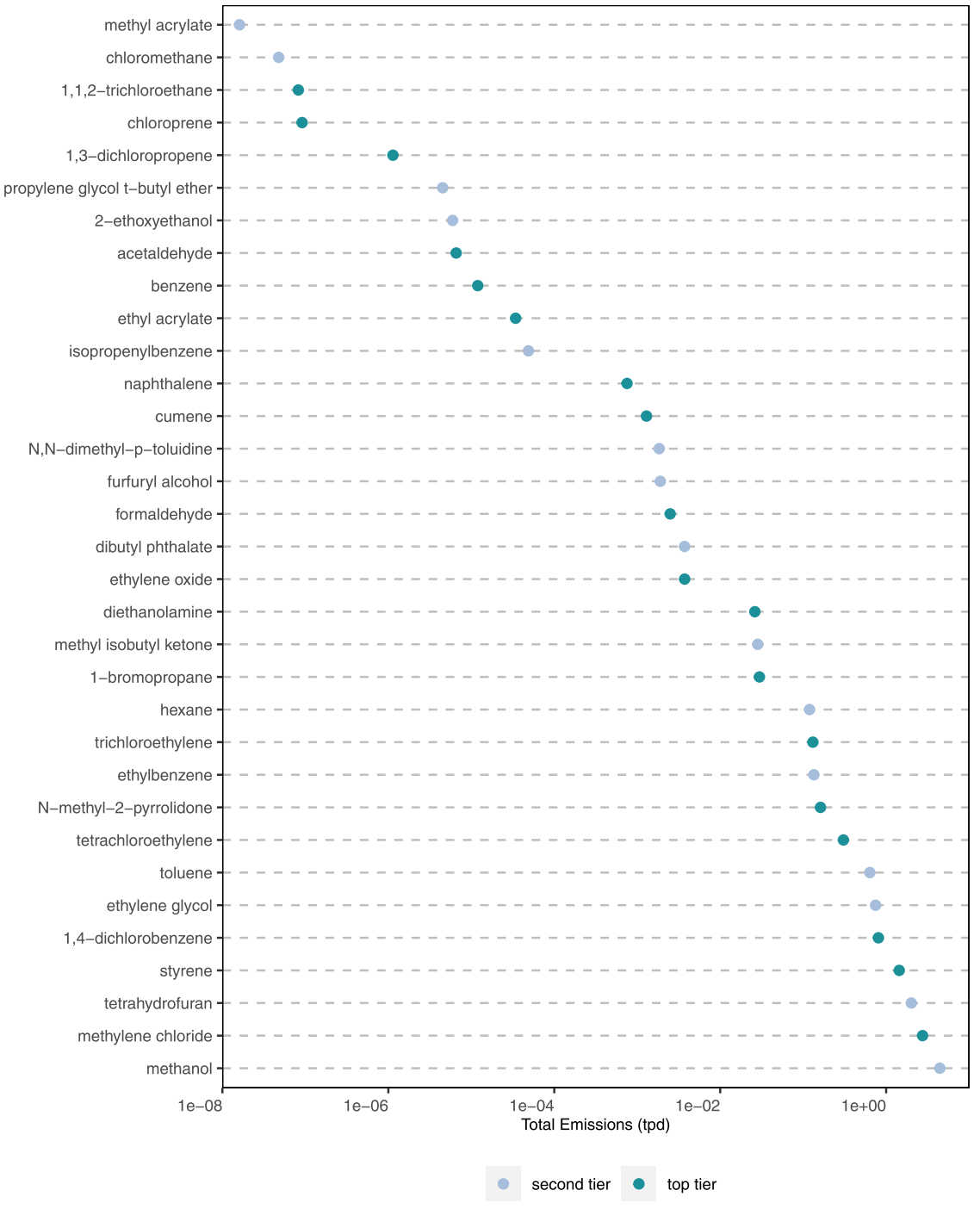

Figure 4. Total estimated 2020 emissions in tons per day of Prop 65-listed chemicals in consumer products. Emissions summed across all emissions inventory categories.

most often, followed by methyl isobutyl ketone and ethylene glycol.

Workplace Exposures. The CARB survey included 94 workplace-related product categories containing at least one Prop 65-listed chemical (Figure S3). Within these categories, "Other Adhesives" contained the greatest number of Prop 65-listed chemicals, as well as the most top tier Prop 65-listed chemicals (Figure 3). The top tier Prop 65 chemicals that appeared in the most product categories were diethanolamine, *N*-methyl-2-pyrrolidone, formaldehyde, cumene, and methylene chloride. The second tier Prop 65-listed chemicals that appeared in the most categories were methanol, ethylbenzene, and toluene. These categories and chemicals likely cause significant exposures to workers.

Population-Level Exposures. CARB's estimated 2020 emissions enabled prioritization by the volume of Prop 65-listed chemicals released from a product category. Among the top tier Prop 65-listed chemicals, methylene chloride was emitted in the greatest total volume (across all product categories), followed by styrene, 1,4-dichlorobenzene, tetrachloroethylene, and *N*-methyl-2-pyrrolidone (Figure 4). Among the second tier Prop 65-listed chemicals, the highest emissions were associated with

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methanol, followed by tetrahydrofuran and ethylene glycol. Methylene chloride appeared in 13 EICs, and 96% of these emissions were from the EIC "Paint Removers or Strippers". Styrene appeared in 9 EICS, and 91% of these emissions were from the EIC "Other Auto/Veh/Marine Care Products". 1,4-dichlorobenzene appeared in one EIC: "Mothballs". These three EICs emitted the most top tier Prop 65-listed chemicals (Figure S4). Looking at total emissions of all Prop 65-listed chemicals rather than just the top tier chemicals, "Paint Removers or Strippers" was still the highest-emitting category, followed by "Automotive Windshield Washer Fluid—Type A Areas", where Type A Areas are colder areas of California, where anti-freeze is permitted to be added to windshield washer fluid.

Summary of Prioritization. Table 1 shows the top five top tier Prop 65-listed chemicals from each prioritization scheme,

Table 1. Summary of Prioritized Chemicals by Prioritization Scheme

	population group		
	consumers	workers	general population
1,3-dichloropropene	√		
1,4-dichlorobenzene			√
cumene	√	√	
diethanolamine	√	√	
ethylene oxide	√		
formaldehyde	√	√	
methylene chloride	√	√	√
N-methyl-2-pyrrolidone	√	√	√
styrene	√		√
tetrachloroethylene			√
trichloroethylene	√		

with more chemicals shown in cases of ties. Notably, methylene chloride and *N*-methyl-2-pyrrolidone (also known as *N*-methylpyrrolidone (NMP)) were each prioritized for all three population groups (consumers, workers, and the general population). Cumene, diethanolamine, and formaldehyde were each prioritized for both consumers and workers. Styrene was prioritized for both consumers and the general population.

NMP is a solvent used for cleaning and degreasing and in the manufacture of electronics, petrochemicals, and polymers. It is listed on Prop 65 as a developmental toxicant. NMP appeared as an ingredient in 26 CARB product categories and was prioritized based on its use in a variety of cleaning-related product categories, in paint strippers, and in personal hygiene products and other personal care products. Total estimated emissions of NMP across all product categories are 0.16 tons per day.

Another solvent, methylene chloride, appeared in 13 CARB product categories, including paint removers, lubricants, adhesives, cleaners, and hand dishwashing soap. CARB estimated that 2.75 tons per day of methylene chloride were emitted in 2020 from consumer products, mostly from paint removers. We would expect methylene chloride emissions from this use to decline over time, following an EPA rule banning the use of the chemical in consumer paint strippers nationwide after November 2019.[23] Other sources of methylene chloride emissions included pipe cements, carburetor or fuel-injection air intake cleaners, sealants and caulks, and penetrants. Methylene chloride has been listed on Prop 65 as a carcinogen since 1988. IARC classifies it as a possible human carcinogen (Group 2A).[24] At least 85 methylene chloride-related fatalities occurred in the US between 1980 and 2018, with most attributable to use of paint strippers.[25]

We prioritized the chemicals cumene, diethanolamine (DEA), and formaldehyde because of their ability to cause both consumer and occupational exposures. Cumene (also known as isopropylbenzene) is used as a solvent in home maintenance products and in chemical production and is also found in petroleum products.[26] Cumene appeared as an ingredient in 12 product categories, including "Laundry Detergent", "Crawling Bug Insecticide", "Multi-Purpose Solvents", "Sealants & Caulking Compounds", "Miscellaneous Office and Art Supplies", and "Other Miscellaneous Household Products".

DEA, used in the production of soaps and surfactants and found in both cleaning products and personal care products,[13,27,28] appears in 40 product categories. DEA has the potential to cause high consumer exposures because of its inclusion in lotions, hair products, shaving gel, hand sanitizer, cleaners, and garden and lawn care products. In workplaces, DEA may cause exposures because of its presence in products such as cleaners and degreasers. DEA was listed as a carcinogen under Prop 65 after it was identified by IARC as possibly carcinogenic to humans (2B).[27] DEA is also considered an occupational asthmagen[29] and is prohibited for use in cosmetics in the EU.[30]

Formaldehyde appeared in 17 product categories reported to CARB, including nail care products, hair products, and cleaners. Formaldehyde has long been identified as a chemical of concern in nail products: it has been the subject of several indoor air quality assessments in salons[31−33] and has (along with toluene and dibutyl phthalate) been part of the "three-free" branding of less toxic nail care products. Formaldehyde is listed as a Prop 65 carcinogen and is classified by IARC as carcinogenic to humans (Group 1).[34]

We prioritized styrene for both consumer and general population exposures based on its reporting to CARB as an ingredient in nine product categories. Among products with potentially high consumer exposures, styrene appears in "Heavy-Duty Hand Cleaner" and "Various Pet Care Products". Styrene, which was added to the Prop 65 list for cancer in 2016, was also found in vehicle care products, adhesives, cleaners, and sealants, with estimated total emissions of 1.44 tons per day.

We prioritized the remaining five chemicals based on a single scenario. We prioritized 1,3-dichloropropene, ethylene oxide, and trichloroethylene for consumers, and 1,4-dichlorobenzene and tetrachloroethylene (or perchloroethylene) for population-level exposures. 1,3-dichloropropene, listed on Prop 65 for cancer, appeared in three CARB product categories. We prioritized it for consumer exposures due to its presence in "Hand Dishwashing Soap" and "Other Miscellaneous Household Products". Ethylene oxide, listed on Prop 65 for cancer, developmental toxicity, and male and female reproductive toxicity, appeared in four CARB product categories. We prioritized it for consumer exposures due to its presence in "Various Oral Care Products", "Laundry Detergent", and "Disinfectants". Trichloroethylene, listed on Prop 65 for cancer, developmental toxicity, and male reproductive toxicity, was present in 10 CARB product categories. It was prioritized for consumer exposures due to its presence in "General Purpose Cleaners—Aerosols" and "Various Office Supply Products".

CARB emissions estimates indicated 1,4-dichlorobenzene (or *p*-dichlorobenzene) was likely to cause widespread population-level exposures, with 0.81 tons per day released in 2020, all from

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use in mothballs. We also expect this use to be associated with high consumer exposures because of volatilization into indoor air and the breathing zone of users. 1,4-dichlorobenzene is listed as a carcinogen on the Prop 65 list.

Finally, emissions data indicated tetrachloroethylene could cause high exposure for the general population, with 0.31 tons per day of tetrachloroethylene released in 2020 from product use, largely from "Energized Electrical Cleaner". Tetrachloroethylene was also found in various cleaners, degreasers, and lubricants. Tetrachloroethylene is listed by Prop 65 as a carcinogen and is classified by IARC as a probable human carcinogen (Group 2A).[35] Although tetrachloroethylene is also used in high volumes in dry cleaning, garment cleaning products are not reportable to CARB in the consumer product surveys and are instead regulated separately through the Airborne Toxic Control Measure for Emissions of Perchloroethylene from Dry Cleaning Operations.[36]

Both hazard and exposure potential are relevant to risk-based prioritization and factor into our designation of priorities for elimination. Of the 15 chemicals with the highest emissions (>0.01 tons per day), eight are top tier priorities for elimination, while seven are second tier priorities. These highest emission second tier chemicals include methanol, tetrahydrofuran, ethylene glycol, and toluene.

Table 2 shows the top five product categories from each prioritization scheme, with more categories shown in cases of ties. We identified 30 product categories as targets for reformulation based on (1) the presence of multiple top tier Prop 65-listed chemicals reported as product ingredients, and (2) high exposure potential for at least one population group.

We prioritized several product categories under multiple scenarios. For example, we prioritized "Other Auto/Veh/Marine Care Products" and "Other Sealants and Caulks" for potential occupational and population-level exposures, and we prioritized "Other Miscl. Household Products" for both consumer and worker exposures.

Table 2. Summary of Prioritized Product Categories by Prioritization Scheme

	population group		
	consumers	workers	general population
energized electrical cleaner			√
external analgesic product	√		
general purpose cleaners—aerosols	√		
general purpose cleaners—non-aerosols	√		
general purpose degreasers—non-aerosols		√	
hair care product—shampoo	√		
hair styling product—all other forms	√		
hand and body lotions	√		
hand dishwashing soap	√		
hand sanitizer	√		
heavy-duty hand cleaner or soap	√		
laundry detergent	√		
misc. office and art supplies	√		
mothballs			√
nail coatings	√		
other adhesives		√	
other auto/veh/marine care products		√	√
other cleaners/degreasers/solvents		√	
other hair care products	√		
other miscl. household products	√	√	
other personal care products	√		
other sealants and caulks		√	√
paint removers or strippers			√
personal hygiene products	√		
shaving gels	√		
specialty lubricant		√	
various make-up cosmetics	√		
various nail care products	√		
various oral care products	√		
witch hazel	√		

DISCUSSION

Chemicals associated with cancer, reproductive harm, and developmental harm are used in many consumer products sold in California. Because Prop 65 is primarily a right-to-know law, a listed chemical may still be used as long as, when exposure potential exceeds particular risk thresholds, consumers are notified about the chemical's presence. Although Prop 65 has reduced a number of chemical exposures in California and beyond by spurring voluntary reformulation, litigation-induced reformulation, and direct regulation,[18] many exposures to Prop 65 chemicals persist. For example, trichloroethylene's health risks have been well documented for decades; however, it is still used in 10 categories of consumer products, including lubricants, cleaners, and degreasers, and it is among the dozen chemicals with highest total emissions.

Using a unique data set of consumer products sold in California, we identified volatile chemical ingredients listed by Prop 65 as carcinogens and reproductive/developmental toxicants. We then used speciation profiles to identify 33 Prop 65-listed chemicals in products and 105 product categories containing Prop 65-listed chemicals. Translating this information into priorities for toxics-reduction action requires identifying high-risk chemicals and associated product categories. By using information on chemical priority and assessing different exposure scenarios, we identified 11 priority chemicals and 30 priority product categories as immediate targets for regulatory restriction or manufacturer redesign.

Many of the product categories we identified as targets for reformulation rose to the top because of their particular use in workplaces, and some occupations may further expose workers to products containing Prop 65-listed VOCs that were prioritized based on the potential for consumer or population-level exposures. For example, professional janitors may use products within five prioritized categories, including general-purpose cleaners, degreasers, detergents, and other household products. People working in nail and hair salons could be exposed to Prop 65-listed VOCs emitted from 10 different prioritized product categories, including shampoos, styling, and other hair products; lotions; nail products; cosmetics; and sanitizer. Automobile maintenance and repair workers also likely experience significant cumulative exposures from a dozen product categories, including electrical cleaners, cleaners and degreasers, adhesives, vehicle care products, lubricants, and heavy-duty hand cleaners, while construction workers might use some of those products, as well as sealants and caulks, and paint removers or strippers (Table 2). This analysis confirms that workplaces can expose people to a range of Prop 65-listed VOCs, and many of these exposures are unlikely to be fully

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addressed by workplace protection laws or hazard communication programs.

Risks from these exposures are not equally distributed in the general population, and there are other vulnerable groups to consider as well. For example, developmental and reproductive toxicants and carcinogens pose more significant risks to people during development, such as early life, puberty, and pregnancy. Sociocultural forces cause women generally to use more cosmetic, personal care, and cleaning products than do men,[37] so they are likely to be more highly exposed to harmful chemicals in these categories. Further, products with more toxic ingredients are often marketed to marginalized communities, including racial minorities (as in the case of hair relaxers and skin lighteners) and low-income populations (as in the case of "dollar store" merchandise).[38,39] Thus, our recommendations for top tier priorities for intervention to reduce harmful chemical exposures at the population level should be considered as but one important policy input, alongside strategies to achieve risk-reduction goals with respect to preferentially vulnerable or exposed subpopulations.

CARB's Consumer Products Program: A Unique Resource for Exposure Research. The emissions inventory undertaken by CARB's consumer product program, although developed to mitigate smog formation, provides invaluable information about toxic volatile chemicals in consumer products sold in California. The emissions estimates that CARB uniquely generates, which are based on sales volume, average weight fractions of chemicals in products, and fate and transport assumptions, enabled us to identify specific chemicals and product categories that may cause widespread, population-level exposures to toxic chemicals. Furthermore, the chemical information that manufacturers report directly to CARB under law is likely more comprehensive and reliable for the chemicals at issue than are product labels, which lack consistent requirements for ingredient disclosure across product types. Data reported to CARB are also likely to be more accurate than safety data sheets, which often fail to identify all hazardous ingredients.[40−42]

As a form of cross-check on our analysis, we compared the outcomes of our prioritization scheme with information in US EPA's Consumer Product Database (CPDat).[43,44] This database compiles manufacturers' voluntary reports of chemical ingredients in consumer products. We identified Prop 65-listed chemicals that appeared in the highest number of CPDat product use categories as methanol, toluene, ethylene glycol, and formaldehyde. These chemicals likewise emerged as high-priority chemicals for interventions based on our analysis of CARB ingredient data. Despite this comparability, there are several advantages to using the CARB data: they are collected from manufacturers in a standardized format at a single point in time, and reporting is mandatory. By contrast, CPDat information is generated voluntarily (and therefore inconsistently) and over a long time period. Furthermore, CARB's modeled emissions estimates provide a clearer picture of population-level exposures.

Limitations. Precise estimates of the quantity of high-hazard chemicals in a specific consumer product are not possible from CARB data because the CARB emissions inventory aggregates data from specific products at the level of product categories. Were we able to access data on the chemical ingredient concentration for individual products, we might have prioritized a different set of chemicals and product categories. This suggests a useful line of future research that integrates CARB emissions estimates with product-specific CPDat data.

Further, while CARB data provide a uniquely comprehensive picture of volatile chemicals in consumer products, they exclude the many other hazardous chemicals in consumer products that are not reportable because they do not contribute to smog formation (the reason for which CARB gathers data). Of the 868 Prop 65-listed chemicals, just over 200 are VOCs;[45] we were therefore unable to assess exposure hazards in consumer products of the remaining 500-plus Prop 65 chemicals. Additionally, some important sources of VOC emissions, such as architectural coatings/paints, dry cleaning, industrial emissions, and mobile sources, are excluded from CARB's consumer product surveys because they are regulated through other mechanisms, limiting the comprehensiveness of our exposure estimates.

Our analysis is also limited by the nature of the Prop 65 list. While the list contains known carcinogens and reproductive and developmental toxicants, consumer products also include chemical ingredients associated with health endpoints that are not covered by Prop 65, such as asthma, neurotoxicity, and endocrine disruption.[46] Although many non-Prop 65 endpoints remain incompletely assessed, and thus chemicals that may cause these endpoints appear on few authoritative lists, it is important to remember that as expansive as the Prop 65 list may be, it is underinclusive of chemicals posing toxicity concern.

For all of these reasons, our analysis does not capture the full extent of chemicals of health concern in California products, and a different data set and hazard list might produce a different set of prioritized chemicals and product categories.

Thresholds used in our prioritization schemes also affect our findings. We classified chemicals as top tier or second tier priorities for elimination and did not prioritize any second tier chemicals, although some chemicals that do not meet our criteria for top tier may simply be less well studied.

Finally, we used emissions estimates for 2020, which were based on product ingredient surveys conducted by CARB from 2013 to 2015. We are unable to evaluate any changes in product composition that might have occurred since this data was collected.

Translation and Implications. Our analysis highlights 11 top tier Prop 65-listed chemicals that are widespread in the material economy and may pose a health risk to consumers, workers, or the general population. We also identified 30 product categories likely to cause significant exposure to these especially toxic VOCs. Manufacturers, retailers, regulators, and health advocates can use these findings to prioritize chemicals and product categories for reformulation or restriction in order to reduce hazardous chemical exposures.

EPA has targeted five of the Prop 65-listed chemicals in our analysis for risk assessment pursuant to the 2016 amendments to TSCA, which required EPA to identify 10 chemicals for scrutiny within 6 months as a precursor to evaluation (and likely regulation).[47] These include four of our prioritized chemicals (NMP, methylene chloride, tetrachloroethylene, and trichloroethylene), and one other top tier Prop 65 chemical reported to CARB (1-bromopropane), all of which EPA determined pose an unreasonable risk to workers and consumers.[48] In 2019, EPA additionally identified formaldehyde and 1,4-dichlorobenzene—both prioritized in our analysis—as high-priority chemicals under TSCA; they are currently undergoing risk evaluation.[49]

As EPA addresses more chemicals under TSCA, our analysis suggests the agency should consider five additional chemicals

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that we designated as top tier priorities but that are not currently being evaluated: 1,3-dichloropropene, cumene, diethanolamine, ethylene oxide, and styrene. Further, many chemicals we designated as second tier are used in substantial numbers of consumer products, whose uses deserve regulatory scrutiny. These chemicals include methanol, tetrahydrofuran, ethylene glycol, toluene, and ethylbenzene.

Some chemical−product combinations we identified have been regulated at the consumer level but continue to pose workplace risks. The use of methylene chloride in paint strippers is one such example. Other high-priority chemical−product combinations, such as 1,4-dichlorobenzene in mothballs, merit regulatory consideration based on emissions data, indicating widespread population-level exposures. This information could serve environmental health advocacy organizations and state consumer product regulatory programs. The latter include (but are not limited to) California's Safer Consumer Products program, which identifies chemical/product combinations meriting alternatives assessment and possible reformulation to reduce the potential for toxic exposures.

A final, sobering lesson from our analysis of CARB's data set is that the potential for coexposure to multiple hazardous chemicals from consumer products is both enormous and understudied. As but one example, the CARB category "Other Adhesives" included 17 different Prop 65-listed ingredients, 9 of which were top tier chemicals. This suggests that people using such adhesives are likely exposed to multiple chemicals simultaneously, which may be carcinogens, reproductive toxicants, developmental toxicants, or all three. In addition to mixed exposures to the combinations of chemicals in these types of chemically intensive products, some individual chemicals appeared in so many product categories that people are likely exposed to multiple sources. Methanol and diethanolamine are two such Prop 65 chemicals: the former was reported in the greatest number of product categories (58), and the latter appeared in 40 product categories. Given that consumers and workers use multiple products daily, our analysis highlights the need to address risks from both exposure to common chemical mixtures and aggregate exposures to the same chemical across multiple sources.

Consumers often believe—wrongly—that the products they buy have been comprehensively assessed for safety before they are sold. As our analysis shows, however, more than 5000 tons of volatile Prop 65-listed chemicals were released from California consumer products in 2020. Gathering equivalent data for all hazardous chemicals in consumer products would facilitate a more comprehensive assessment of exposure potential and corresponding action to reduce exposure risk. Even such incomplete data as we have analyzed, however, point to numerous places for interventions to reduce human exposure to volatile chemicals in consumer products that contribute to reproductive harm, developmental harm, and cancer.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c07247.

Details of chemical priority classification and prioritization workflows (PDF)

Summary Information on CARB product categories (Table S2) (XLSX)

Prioritized worker exposures (Figure S3) (PDF)

Prioritized population exposures (Figure S4) (PDF)

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Notes

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