Estimated Urban Runoff Copper Reductions Resulting from Brake Pad Copper Restrictions

California Stormwater Quality Association

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Preface

This report was prepared for the California Stormwater Quality Association (CASQA) under the supervision of CASQA's Watershed Management & Impaired Waters Subcommittee. The report is an update and expansion of a 2013 memorandum prepared for Richard Watson & Associates with funding from the Los Cerritos Channel Watershed Group (Moran 2013). This report is a component of CASQA's Source Control Initiative, which seeks to address stormwater and urban runoff pollutants at their sources. This report was commissioned to develop scientific estimates of copper load reductions due to vehicle brake pad copper content reduction mandates to inform decision-making by CASQA, stormwater permittees, and water quality regulators related to management of copper as a water pollutant.

This report documents scientific research. It relies on information from the scientific literature, vehicle industry, and government agencies. Because of the uncertainties inherent in research work and the reliance on scientific studies conducted by and information provided by other organizations, neither CASQA, its Board of Directors, the Watershed Subcommittee, any contributors, nor the authors make any warranty, expressed or implied, nor assume any legal liability or responsibility for any third party's use of this report or the consequences of use of any information, product, or process described in this report. Mention of trade names or commercial products, organizations, or suppliers does not constitute an actual or implied endorsement or recommendation for or against use, or warranty.

Note to Readers

While this report has been prepared primarily for CASQA members and others in California, it takes a generic approach to estimating urban runoff copper reductions due to North America-wide changes triggered by California and Washington State laws. Although the estimates use a few California-specific data sets (e.g., vehicle fleet mix data), most of the input information is generic, with the intent of providing information useful in any highly urbanized, highly impervious North American watershed (with consideration of local characteristics). The report relies heavily on data from two sources: (1) the California-founded Brake Pad Partnership, an international partnership that used San Francisco Bay as its case study example, and (2) the Washington Department of Ecology , which is the only organization that currently collects publicly available data characterizing brake pads sold in North America. Washington data, collected under requirements in its state law that are not part of California law, are particularly important because they are the first to cover all vehicle brake pads and they are updated quarterly, providing the ability track market changes . Organizations using these estimates should evaluate applicability to their specific watersheds carefully, considering watershed-specific characteristics and any special local copper sources, and should recognize the uncertainties inherent in these estimates as well as their generic nature.

Report Preparer and Acknowledgements

TDC Environmental, LLC prepared this report. Kelly D. Moran, Ph.D. was the lead author. The author appreciates the incredible dedication of the Brake Pad Partnership Steering Committee members and the Partnership's many funders, whose joint efforts made virtually all of information in this report available to the public and were the foundation for the brake pad copper reductions that are currently underway. The author thanks the following reviewers for their assistance with completing this report:

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Summary

In response to California and Washington state laws mandating the near phase-out of copper in vehicle brake pads, the transition to <0.5% copper brake pads (often called "copper free" or "no intentionally added copper") is well underway. Qualitatively, all signs point to significant upcoming reductions in brake pad copper. This report provides quantitative estimates of the anticipated upcoming copper reductions in the brake pad market, on-road vehicles, and urban runoff. These estimates are designed for urban runoff management planning purposes.

The estimates rely on available information, which was largely developed through the lengthy collaboration among brake pad manufacturers, government agencies, and environmental groups in the Brake Pad Partnership (BPP). Since certain elements of the brake pad copper reduction schedule are unknown at this time due to the proprietary nature of product formulation and sales data, the estimates are based on a series of reasonable assumptions developed on the basis of available data.

The estimates evaluated three scenarios (see Table 1) developed to span the reasonable range of industry product modification schedules. Scenario 3, which examines the effect of a replacement brake pad exemption for older vehicles, has two variants to encompass possible industry responses. For each scenario, the report provides quantitative estimates of brake pad copper content reductions and subsequent urban runoff copper reductions.

Based on compliance certification data, in mid-2015 44% of brake pad formulations contained <0.5% copper. Brake pads containing >5% copper (which average 13% copper by weight), cause the overall average copper content of all certified brake pads to be 5.6%, a 32% reduction from the BPP's 2006 rough estimate of new vehicle brake pad copper content and a 22% reduction from values reported in 2011.

The average brake pad *manufactured* in 2021 are expected to contain 81-99% less copper than they did in the early 2010s (See Figure 1). This estimate matches the Washington Department of Ecology's estimate, which used a different computational method. These brake pad copper content reduction estimates are consistent with brake pad copper data

Today, 44% of available brake pad formulations contain <0.5% copper.

Brake pads in mid-2015 contained an average of 5.6% copper – a 22% reduction from 2011 (reported data) and as much as 32% less than 2006 (rough estimate).

Brake pads manufactured in 2021 are expected to contain 81-99% less copper than they did in the early 2010s.

Urban runoff copper levels will begin responding measurably in the 2020s. Urban runoff copper loads are expected to be 46% to 57% lower by 2024.

collected to date by the Washington Department of Ecology (see black line in Figure 1). The current reduction trend appears to be midway between the most optimistic Scenario 1 and the moderate Scenario 2.

In any given year, urban runoff copper reductions lag behind copper content reductions in manufactured brake pads because brake pads are only changed on average every three to five years, wholesaler and retailer inventories take an average of two years to turn over, and urban watersheds do not immediately clear pollutants when discharges cease. Accounting for these factors, urban runoff reduction was estimated through 2032. The resulting estimates, summarized in Table 2 and graphed in Figure 2, are expressed as a percentage reduction in copper in urban runoff, with a maximum 61% reduction reflecting <0.5% copper in essentially all on-road vehicle brake pads. (Other copper sources compose the remaining 39% of urban runoff copper load.)

Urban runoff copper levels are expected to begin responding measurably to brake pad copper reductions in the 2020s. Urban runoff copper loads are expected to be 46% to 57% lower by 2024. The timeframe for reaching maximum reductions could be as soon as the early 2030s, but would be substantially delayed if Washington State (which has regulations that heavily influence the California brake pad market) were to modify its regulatory approach for replacement brake pads for older vehicles.

The most significant uncertainties in these estimates are uncertainties in brake pad copper content (market volumes are unavailable), future changes in vehicle miles traveled, and watershed response times, which are affected by watershed-specific characteristics and variation in annual rainfall volumes.

In summary:

- Newly manufactured vehicle brake pads contain, on average, significantly less copper than they did in the early 2010s.
- In mid-2015, 44% of brake pad formulations contained <0.5% copper.
- Brake pads manufactured in 2021 are expected to contain 81-99% less copper than they did in the early 2010s.
- On-road brake pad copper content is dropping, but more slowly than manufactured brake pad copper content. A 35% to 43% reduction in on-road brake copper content should occur by 2019.
- Due to the slower change in on-road brakes and watershed lag times, urban runoff copper levels are slower. They are anticipated to drop by 21-27% by 2020 and by 46-57% by 2024.
- Washington State's upcoming decision about implementing requirements that all brake pads contain <0.5% copper has important water quality implications in California and the rest of the nation.

Recommendations for the California Stormwater Quality Association and its members:

(1) Share these projections with Washington State and with the vehicle industry.

(2) Update these copper reduction estimates in 2018 using data from implementation of California SB 346 and Washington State law.
(3) Use the California State Water Board Surface Water Ambient Monitoring Program Sediment Pollution Trends Program sediment monitoring to track brake pad copper reductions.
(4) Use the urban runoff copper reduction estimates in this report, in combination with local data, for urban runoff management planning purposes, doing so in a manner that recognizes that uncertainties in the estimates and unique local watershed characteristics.

Table 1. Copper Reduction Scenario Summary

Year	Scenario 1 – One-Step Reduction	Scenario 2 – Two-Step Reduction	Scenario 3a - Aftermarket Exemption from 0.5% Copper (Like-for-Like Replacement)	Scenario 3b - Aftermarket Exemption from 0.5% Copper (Unconstrained Replacement)
2014	0.5% copper brake pads begin to phase in to new vehicles	5% copper brake pads begin to phase into new vehicles	5% copper brake pads begin to phase into new vehicles	5% copper brake pads begin to phase into new vehicles
2015				
2016				
2017				
2018		0.5% copper brake pads begin to phase into new vehicles	0.5% copper brake pads begin to phase into new vehicles	0.5% copper brake pads begin to phase into new vehicles
2019				
2020				
2021	All OE Pads <0.5% copper	All OE Pads <5% copper	All OE Pads <5% copper	All OE Pads <5% copper
2022				
2023	All replacement Pads <0.5% copper	All replacement pads <5% copper	All replacement pads <5% copper	All replacement pads <5% copper
2024				
2025		All OE Pads <0.5% copper	All OE Pads <0.5% copper	All OE Pads <0.5% copper
2026				
2027		All replacement pads <0.5% copper		
2028				
2029				
2030				
2031				
2032			All replacement pads eventually <0.5% copper	

Figure 1. Average Brake Pad Copper Content by Year Manufactured: Reported Data Compared to Estimates

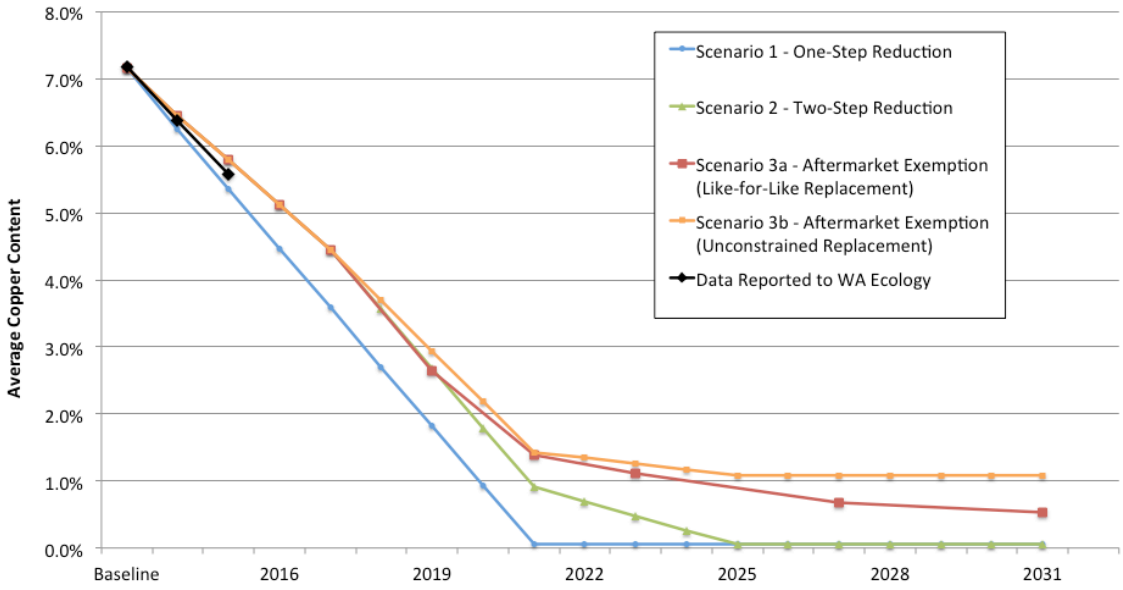

Figure 2. Urban Runoff Copper Reduction Projections

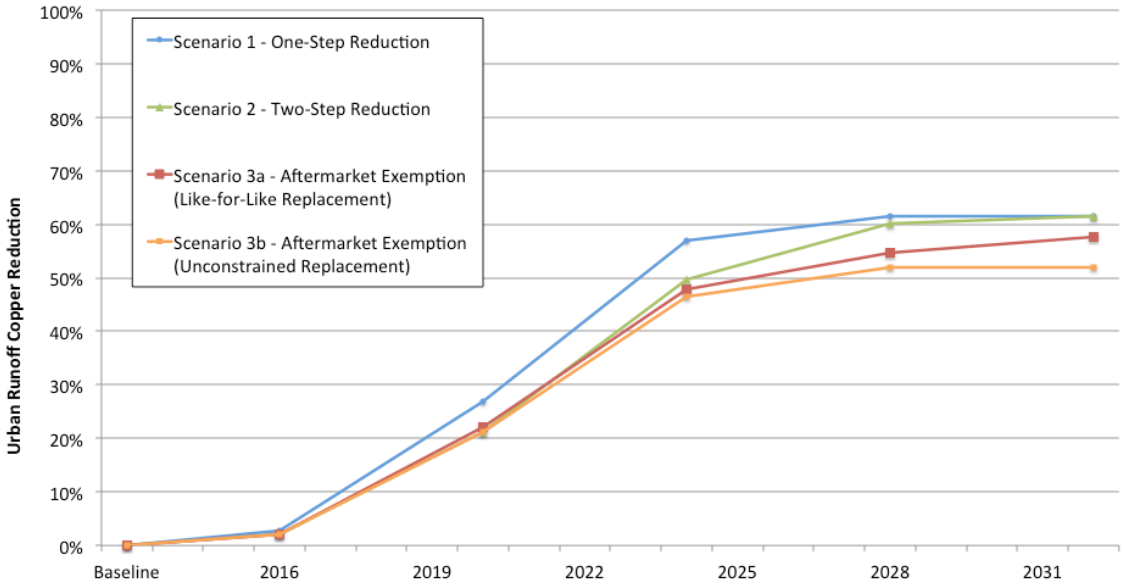

Table 2. Estimated Urban Runoff Copper Reduction from Brake Pads Alone

Year	Scenario 1 - One Step Reduction	Scenario 2 - Two Step Reduction	Scenario 3a - Aftermarket Exemption from 0.5% Copper with Like-for-Like Replacements	Scenario 3b - Aftermarket Exemption from 0.5% Copper with No Reduction in Copper Pad Market Fraction
2016	2.8%	2.2%	2.2%	2.2%
2020	27.0%	21.3%	22.1%	21.2%
2024	57.0%	49.8%	47.9%	46.4%
2028	61.6%	60.3%	54.6%	51.9%
2032	61.6%	61.6%	57.7%	52.0%

Section 1: Background

A simple action—vehicle drivers hitting the brakes—released about 600,000 kilograms (1.3 million pounds) of copper into California's environment in 2010. Each time vehicle brakes engage, a tiny amount of fine dust wears off of the vehicle's brake pads. When it rains, some of this dust washes into urban runoff. Scientific studies indicate that dust generated by vehicle brakes is by far the most significant source of copper in urban watersheds. In California's most urbanized watersheds, brake pad copper is estimated to compose more than 60% of all copper in urban runoff (Donigian 2009).[1]

1.1 Brake Pad Copper Reduction Requirements

A California law enacted in 2010, California SB 346 (Kehoe) set in place a program that will nearly eliminate copper use in brake pads. California SB 346 requires that brake pads sold in California contain no more than 5% copper by weight by 2021, and no more than 0.5% by 2025. According to a representative industry analysis, as of 2006, new vehicle brake pads contained an average of about 8% copper by weight (BPP 2008). The law also limits dangerous—but fortunately less common—brake pad pollutants, by prohibiting sale of brake pads containing more than trace amounts of lead, mercury, asbestos, cadmium, and hexavalent chromium in 2014. To avoid replacing one environmental problem with another, California SB 346 requires manufacturers to examine new formulations carefully and to select alternatives that pose less potential hazard to public health and the environment. Consumer safety will be ensured through a limited deadline extension process for the 2025 0.5% copper requirement (available starting only when a manufacturer demonstrates that no alternative brake friction materials will be safe and available) and by provisions allowing continued sales of replacement brake pads for older vehicles. The brake pad copper content certification and labeling system established by California SB 346 will provide for ready identification of brake pads with the lowest copper content.

Following California's model, the State of Washington also enacted restrictions on brake pad copper content in 2010 (Washington State 2010). Washington's law provides slightly different exemptions than California's law—notably a much narrower exemption for "aftermarket" brake pads that replace the "original equipment" brake pads sold with new vehicles. Washington law also has another important difference from California law—it requires manufacturers to provide Washington State Department of Ecology with periodic reports of brake pad copper, antimony, nickel, and zinc content, starting in 2013.

[1] See reference list at the end of this report.

1.2 Implementing Brake Pad Copper Reduction

Due to the importance of California's vehicle market and the interconnection of vehicle parts distribution systems throughout North America, brake pad manufacturers expect that it is unlikely that any manufacturer will produce California-specific or Washington-specific products (MEMA 2012a). Instead, copper reduction will be integrated throughout the entire North American brake pad market (MEMA 2012a).

Reflecting its nationwide commitment to brake pad copper reduction, vehicle industry associations signed a 2015 Memorandum of Understanding (MOU) with the U.S. Environmental Protection Agency (U.S. EPA) committing to taking the California/Washington copper reduction program nationwide (U.S. EPA 2015).

Table 3 provides a timeline of key implementation actions since the brake pad copper reduction laws were adopted.

Table 3. Brake Pad Copper Reduction Implementation Timeline

Year	Action	References
2010	California and Washington brake pad copper laws adopted	California SB 346 2010; Washington State SB 6557 2010
2011-2012	Automotive industry developed and adopted compliance certification markings, box markings, and certified chemical analysis methods.	SAE 2011; SAE 2012; MEMA 2012b
2012	Washington State adopted regulations specifying testing, marking, and reporting requirements	Washington Department of Ecology 2012
2013	NSF International, the sole brake friction material certification organization (also known as the "registrar") began issuing brake friction material certifications.	NSF International 2015
2014	Brake pads bearing compliance certification markings began appearing on California retail shelves. California Department of Toxic Substances Control (DTSC) initiated development of regulations to make California SB 346 fully enforceable in California. Adoption has been delayed due to California DTSC resource constraints, but is anticipated in 2016.	
2015	As of October 2015, NSF International had certified more than 5,000 brake friction material formulations, 44% of which contain <0.5% copper. See Section 2.2 for more information on brake pad copper content). Most brake pads available for sale in California bear compliance markings, both on pads and boxes. Washington Department of Ecology issues finding that copper free brake pads "may" be available, triggering the next steps in Washington's regulatory process to determine whether (or when) to implement requirements that all brake pads contain <0.5% copper (similar to California's 2025 requirements).	NSF International 2015 Washington Department of Ecology 2015b

Based on the frameworks in the state laws and systems adopted by the industry, brake pads are certified in three groups—A, B, and N—summarized in Table 4. The matching box compliance marking logo, called the "LeafMark" is a 3-leaf symbol that accompanies the certification letter. The number of dark leaves in the logo indicates the certification level, with the darkest shading for the lowest copper brake pads.

Table 4. Brake Pad Copper Content Categories

Certification Level	Definition	Box Marking Symbol*
A	Meets legal standards for asbestos, cadmium, chromium, lead, and mercury	Single shaded leaf
B	Same as A and < 5% and ≥ 0.5% copper ("low copper")	Two shaded leaves
N	Same as A and <0.5% copper ("copper free")	All three leaves shaded

*Logo graphics not included due to industry restrictions on logo use.

In the years since California SB 346 was enacted, the vehicle industry has actively engaged in implementing the law (e.g., Moran 2011). There has been strong industry attention to formulating, testing, and marketing low-copper and copper-free brake pads (Honeywell undated; FDP Brake 2010-2012; Venetis 2012; Performance Friction 2012; Williams undated; Fastmagna.com 2010; Bendix 2012; Phoenix 2010; ALCO 2012; Wilson 2012; Crowe 2012; Aftermarket News 2012; Murphy 2012; Bosch Auto Parts 2014). Prominent manufacturers have issued a steady stream of product announcements, such as:

- Early leaders, like FDP Brake, Honeywell, and Williams, announced copper-free product lines as soon as 2010 (Honeywell undated; FDP Brake 2010-2012; Williams undated).
- Starting in 2010, manufacturers like Bendix and TRW Lucas with existing copper-free products included the lack of copper as a product benefit in promotions (Fastmagna.com 2010; Bendix 2012).
- By 2012, copper-free products were being tested by vehicle manufacturers for use in new and updated vehicles. Major European manufacturer Brembo's 2012 Annual Report described vehicle manufacturer acceptance of the company's copper-free formulations (Brembo 2013). Federal Mogul's products were accepted by multiple vehicle manufacturers (Federal Mogul 2013).
- In 2012, both Honeywell and Federal Mogul announced lines of low copper and copper-free brake pads, both seeking to be among the first major manufacturers to market full lines of copper-free products (Federal Mogul 2013, Honeywell 2013). In October 2014, Federal-Mogul announced a related brake pad line for trucks (Green Car Congress 2014).

- In late 2014, one of the world's largest brake friction manufacturers, Bosch Auto Parts,[2] announced the availability of copper-free brake pads in its major product lines. It also announced plans for transition to copper-free formulations for products serving all U.S. domestic, Asian, and European vehicles years ahead of regulatory deadlines (Bosch Auto Parts 2014; Auto Service Professional 2015).

Reflecting these developments, one of the major themes of the Society of Automotive Engineers 2014 Brake Colloquium & Exhibition (Burlingame California September 2014) was the transition to copper-free brake pads. Manufacturers advertised new lines of copper free brake friction materials, suppliers offered formulation ingredients to support the transition to copper-free formulations, and presentations told the stories of brake friction material manufacturer (e.g. Akebono) and automobile manufacturer (e.g., Ford, Chrysler) programs underway to transition away from high copper brake pads. The emphasis was on copper-free, rather than <5% copper brake pads, and a worldwide scope for industry brake pad copper elimination programs, which simplifies product management and regulatory compliance for the diverse international supply chains in the vehicle industry.

[2] According to Bosch, one of every three vehicles on the road contains a Bosch braking component (Auto Service Professional 2015).

Section 2: Summary of Available Information

This section summarizes the available information that forms the basis for the brake copper reduction estimates.

2.1 Brake Pad Copper Reduction Schedule

In 1999, the Brake Manufacturer's Council committed to offer new low-copper brake pad materials to customers within 5 years of any BPP decision that brake pads are a major copper source (Lawrence 1999). This commitment was triggered by the BPP in late 2008. As discussed in Section 1, many manufacturers are currently offering low copper and copper-free brake pads to customers. The timelines in California SB 346 and Washington state law provided eight years after the 2013 reformulation commitment for vehicle manufacturers to re-engineer all vehicle platforms to incorporate the new brake pad formulations (BPP 1996-2012). This timeframe was specifically selected to allow vehicle manufacturers to complete the required brake system re-engineering in conjunction with their regular re-engineering of vehicle platforms. Both laws provide for a second overlapping vehicle re-engineering cycle to reach the 2025 0.5% copper standard, which required technology that was not in sight when the laws were adopted in 2010 (but that is now commercially available as documented above).

Information summarized in Section 1 shows that the transition to the lowest copper brake pads is proceeding in accordance with the process anticipated by the BPP – and perhaps even more quickly than the was anticipated.

2.2 Brake Pad Copper Content

Through the BPP, brake pad manufacturers reported brake pad copper content annually from 1998-2006 for the highest sales volume new vehicles (BPP 2008). In 2006, original equipment brake pads contained an estimated overall average of 8.2% copper by weight. This average represents a mixture of high-copper brake pads (10-20% copper) and brake pads with no intentionally added copper. In 2008, manufacturers collected formulation type data to estimate the fraction of the market composed of no-copper brake pads (Phipps 2008). Because the BPP reporting covered only original equipment brake pads (those sold on new vehicles), the BPP developed a separate estimate of the copper content in aftermarket (replacement) brake pads (Rosselot 2009).

To meet certification requirements under Washington State law, which are slightly different than those in California, brake pad manufacturers must provide laboratory reports documenting testing of each certified brake pad formulation to the state. These data are currently the best available information about brake pad copper content. Washington Department of Ecology compiles these copper content data quarterly and posts the average brake pad copper content on the Internet (Washington Department of Ecology 2015a). Because sales volumes are not reported, Washington Department of Ecology assumes that each formula has an equal chance of being used (Washington Department of Ecology 2015a).

The Washington data reveal that significant copper reductions have already occurred as compared to the BPP estimate and Washington's own baseline data (see Table 5).

Table 5. Average Manufactured Brake Pad Copper Content, 2006-2015

Date	Average Copper Content	Reduction Compared to BPP 2006 Estimate	Reduction Compared to Washington 2011 Baseline	Source
2006	8.2%*	--	--	BPP 2008
2011 (Washington Baseline)	7.2%	16%	--	Washington Department of Ecology 2013
July 1, 2014	6.4%	22%	11%	Washington Department of Ecology 2015a
July 1, 2015	5.6%	32%	22%	Washington Department of Ecology 2015a

*Original Equipment brake pads only

Based on the data for the 4,862 brake pad formulations certified as of July 1, 2015,[3] average copper content for each certification level was calculated. The results are in Table 6 and Figure 3.[4]

Washington also required a "baseline" report providing estimated copper content of brake pads sold in 2011 (Washington Department of Ecology 2013). For the baseline report, Washington did not require chemical measurements—just estimates based on manufacturer formulations. The baseline report covered far fewer formulations (1,720) than 2015 reporting. These data are summarized in Table 7.

For the baseline reporting only, Washington required manufacturers to identify brake pads used for "heavy duty" vehicles (i.e., large trucks). These data, when separately analyzed and corrected based on information from the Society of Automotive Engineers, showed a relatively low 0.5% average copper content for truck brakes (Washington Department of Ecology 2013).[5]

The 2011 baseline estimates had almost the same average copper content as the 2015 measured data (Table 6) for brake pads that would have fallen in the A and B certification levels, but a lower average for formulations that would have fallen in the N certification level. This latter value may reflect the presence of then unknown trace copper in non-copper ingredients.

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[3] An anonymized version of these data were provided by Washington Ecology.

[4] These values are similar to prior assumptions—A (10%), B (4%), N (0.1%)—that were based on informal estimates from the Brake Pad Partnership (Moran 2013).

[5] This excludes formulations for rarely used truck disc brakes (Washington Department of Ecology 2013).

Figure 3. Average Brake Pad Copper Content by Certification Level

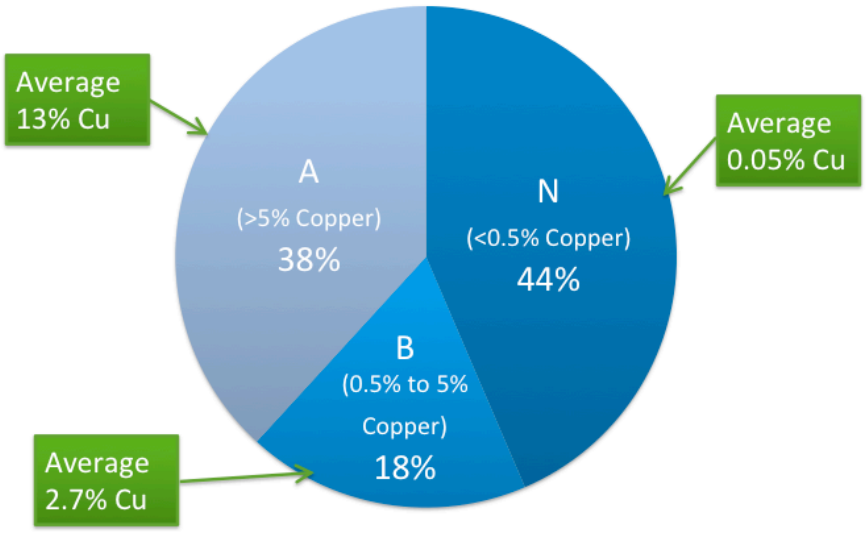

Table 6. Average Brake Pad Copper Content by Certification Level, July 2015

Certification Level	Average Copper Content	Fraction of Certified Formulations
A	13%	39%
B	2.7%	18%
N	0.05%	43%
ALL	**5.6%**	**100%**

Source: Washington Ecology data for brake pad formulations certified as of July 1, 2015.

Table 7. Average Estimated Brake Pad Copper Content 2011

Copper Content Category	Average Estimated Copper Content (All Formulations)	Average Estimated Copper Content (Excluding Heavy Duty)	Fraction of Reported Formulations (Excluding Heavy Duty)
>5% (A Level)	13%	13%	52%
< 5% and ≥ 0.5% (B level)	2.9%	3%	13%
<0.5% (N level)	0.02%	0.003%	35%
ALL	**6%**	**7.2%**	**100%**

Source: Washington Ecology baseline brake pad copper content reporting.

The Washington data set represents all vehicle brake pads that may legally be sold in Washington State. Because manufacturers do not report (and treat as confidential) sales data for each certified brake pad formulation, the Washington data cannot account for each formulation's market share. Consequently, the data represent an average of all available formulations, not the average content of brake pads sold.

2.3 Brake Pad Replacement Frequency

Brake pad material wears off gradually over the lifetime of the pad. To support the work of the BPP, manufacturers shared proprietary market survey data characterizing the replacement frequencies of original equipment and aftermarket brake pads (BPP 1996-2012; AAIA 2008). These data showed that on average, original equipment brake pads are replaced when a vehicle is 3-4 years old. Because older vehicles are driven fewer miles per year (FHWA 2009; Santos 2011), their aftermarket brake pads are only replaced at a rate of about 21% per year (AAIA 2008).

2.4 Vehicle Fleet Characterization

The California Department of Finance periodically publishes summaries of vehicle registration data. The most recent data were published in 2009 (DOF 2009). These summaries provide vehicle age distributions and the fraction of vehicle registrations by type (light-duty, heavy-duty, motorcycle, trailer). In addition to these data, information from the Southern California Association of Governments' transportation monitoring and information system (SCAG 2012), Washington State (Washington Department of Ecology 2013), and the BPP (BPP 1996-2012 and Rosselot 2010) provide the basis for assuming that neglecting contributions from heavy duty vehicles (i.e. large trucks), motorcycles, and trailers will not introduce significant error in the copper reduction estimate.

2.5 Brake Pad Copper in Urban Runoff

The BPP completed peer-reviewed scientific studies to characterize brake pad emissions (BMC PEC 2006; Haselden 2004; Schlautman 2006), examine all environmental copper sources (Rosselot 2006a; Rosselot 2006b), and develop quantitative estimates of the brake pad copper contribution to total stormwater copper loads using linked air and watershed models (Pun 2006a; Pun 2006b; Donigian 2007; Donigian 2009).

The BPP's "Upper Colma" modeling watershed is the most urbanized among the watersheds considered in BPP modeling. It best represents urban runoff, which was not separately modeled. It is also most like other highly urbanized watersheds across the state because of its combination of high urbanization, high traffic levels, and location surrounded by other urban areas. In this watershed, brake pad copper was estimated to compose 58-66% of total anthropogenic copper.

BPP modeling estimated watershed response time to brake pad copper reductions (Donigian 2009). For urban runoff, response time can reasonably assumed to be

similar to the BPP's estimates for response times in highly urbanized watersheds with concrete lined channels. In the most highly impervious watersheds, the BPP estimated watershed response times are relatively quick, with >70% copper reductions estimated the first year after a change in brake pad reformulation and nearly 90% reduction in 5 years. Concrete channels were found to further reduce watershed response times. Response times in surface waters receiving urban runoff depend on site-specific factors like channel length, shape, channel bottom material, and sediment loads (Donigian 2009).

Section 3: Computational Assumptions

The copper reduction estimates rely on a series of reasonable assumptions that were developed on the basis of available information, including the brake pad-specific information summarized in Section 2. These assumptions are detailed in Tables 8-14.

Table 8. Original Equipment Brake Pad Copper Reduction Schedule Assumptions

Assumption	Basis	References
By January 1, 2021, all original equipment brake pads will contain less than 5% copper. **By January 1, 2025, all original equipment brake pads will contain less than 0.5% copper**	Requirements of California SB 346	California SB 346
Extension requests for 0.5% copper requirement will be relatively limited.	Difficulty of extension process and short time frame for each extension, long time frame for development of alternatives, industry press and informal communications indicating that alternatives are becoming available.	California SB 346; BPP 1996-2012; sources in Section 1
Lower copper brake pads will be phased in on new vehicles at a constant rate over an 8-year period prior to each compliance deadline.	Estimates from brake pad and vehicle manufacturers, who have consistently explained that they plan to introduce new brake pads when completing the cyclical re-engineering of vehicle platforms. Industry press and brake pad manufacturer announcements have been consistent with the statements made during development of legislation.	MEMA 2010; BPP 1996-2012; sources in Section 1
Washington State will require new vehicle brake pads to contain less than 0.5% copper by January 1, 2025 (same schedule as California).	Washington State law establishes the same compliance date as California law for brake pads < 5% copper, but does not establish a firm date for requiring brake pads < 0.5% copper. Washington must conduct a review and must find that <0.5% copper pads are "available" (as defined under Washington law) to set the compliance date. Washington's review will occur in 2016 based on a preliminary determination issued in late 2015. Washington's review process and decision will take 1-2 years, after which manufacturers will have 8 years to comply, setting up timing for implementation on 1/1/25, concurrent with California implementation. The industry and the two states have worked to harmonize the implementation of the California and Washington laws.	Washington State 2010; Washington Department of Ecology 2015b; sources in Section 1

Table 9. Aftermarket* Brake Pad Copper Reduction Schedule Assumptions

Assumption	Basis	References
Non-compliant replacement brake pads for pre-2021 and pre-2025 vehicles may be sold indefinitely.	Provision of California SB 346	California SB 346
Under Washington state law, starting on January 1, 2021, all newly manufactured replacement brake pads must contain less than 5% copper. Non-compliant replacement brake pads manufactured prior to January 1, 2021 may be sold until December 31, 2030. Non-compliant replacement brake pads may be sold indefinitely, but only if they are identical to original equipment brake pads.	Washington State law	Washington State 2010; Washington Department of Ecology 2012
Washington State's exemption for original equipment brake pads that are identical to the ones sold with the new vehicle will have only a small effect.	Original equipment service (replacement) pads that are identical to the ones sold with the vehicle compose a very small fraction of the market because for cost reasons, even vehicle dealers switch from these pads to lower cost vehicle manufacturer approved service pads a few years later. Vehicle manufacturers protested the narrow nature of this exemption during development of Washington's legislation and its regulations, but the Automotive Aftermarket Industry Association supported it.	BPP 1996-2012
Recognizing that brake pad sales lag behind shipments of new products due to the inventory "turn time" in the brake pad supply chain, only 45% of brake pads sold in a given year are shipped in that year. The remaining sales are composed of brake pads shipped in the previous year (30%) and brake pads shipped two years prior (25%).	A typical replacement brake pad inventory "turn time" is <2 years. Some low volume pads may be held in inventories for as long as ten years. Inventory carrying costs hold down inventory volumes. Brake pad inventory turn time is longer than other retail inventory turn times because of the plethora of vehicle models and some manufacturers' historic lack of standardization of parts across vehicle models.	BPP 1996-2012
Replacement brake pads for vehicles manufactured with low copper brake pads will also be low in copper, even if the vehicle is manufactured prior to compliance deadlines.	Braking performance will be most easily matched with lower copper formulations.	BPP 1996-2012

*Replacement

Table 9. Aftermarket Brake Pad Copper Reduction Schedule Assumptions (Continued)

Assumption	Basis	References
Replacement brake pads containing lower levels copper that are designed for vehicles manufactured with high copper brake pads are phasing in at a constant rate starting in 2014. The end of the phase in period will be determined by Washington's compliance deadlines.	Since safety standard apply to new vehicles—and not to brake pads—there is no specific regulatory constraint on aftermarket brake pad formulations. Drivers for the aftermarket include cost, safety, and customer acceptance. Since copper is an expensive ingredient, cost considerations point toward early reformulation. Aftermarket manufacturers have a history of making products available to fit new vehicles within a few months of the vehicle's initial manufacture, suggesting that they will make products available on a schedule that phases in over the same general time period as the phase in for original equipment brake pads. Press releases and industry websites indicate that brake pads containing <5% copper and brake pads containing less than 0.5% are both already available. Manufacturers may be less motivated to introduce new products for old vehicles, which present the need to design pads with characteristics similar to those provided by high copper brake pads.	BPP 1996-2012; sources in Section 1

Table 10. Brake Pad Replacement Assumptions

Assumption	Basis	References
Original equipment brake pads are replaced when vehicle is 3.5 years old.	Brake pads are typically replaced after 3-4 years of service, after about 35,000-40,000 miles of driving.	BPP 1996-2012
Vehicles more than 3.5 years old have their brake pads replaced once every 5 years.	Automotive Aftermarket Industry Association survey data of the aftermarket indicate that 20-22% of vehicles more than 3 years old have their brake pads replaced each year. Older vehicles likely have a lower brake pad replacement rate than new vehicles because vehicle miles traveled falls with vehicle age.	AAIA 2008; BPP 1996-2012; FHWA 2009; Santos 2011

Table 11. Brake Pad Copper Content Assumptions

Assumption	Basis	References
In 2013, vehicle brake pads—including both original equipment and aftermarket—contained an average of 7.2% copper by weight.	Washington Ecology brake certification baseline data set (2011 brake pads) for light-duty vehicles.	Washington Department of Ecology 2013
In 2013, vehicle brake pads—including both original and aftermarket—contained copper as follows: • **52% contained >5% copper, averaging 13% copper by weight** • **13% contained between 5% and 0.5% copper, averaging 3% copper by weight** • **35% contained <0.5% copper, averaging 0.05% copper by weight**	Washington Ecology brake certification baseline data set (2011 brake pads) for light-duty vehicles (Table 6). Measured values from the 2015 data set are used for the <0.05% copper brake pads because the 2011 estimated values did not appear to account for trace copper in non-copper ingredients.	Washington Department of Ecology 2013; Washington Ecology data for brake pad formulations certified as of July 1, 2015
Brake pads meeting the <5% copper requirement will contain an average of 2.7% copper by weight. Brake pads meeting the <0.5% copper requirement will contain an average of 0.05% copper by weight.	Washington Ecology brake certification 2015 data (See Table 5). Future formulations are assumed to continue to have similar concentrations. Due to variation in materials input and manufacturing processes for brake pads (which are heterogeneous materials), to ensure compliance, products are being designed with copper content well below compliance levels. Since copper reportedly does not serve a useful design purpose below 1% concentrations, brake pads containing less than 0.5% copper likely only contain trace copper introduced via impurities in other ingredients (e.g., recycled metals).	Washington Ecology data for brake pad formulations certified as of July 1, 2015
Brake Pad copper content reported to Washington State is the same as California brake pad copper content.	The brake pad marketplace covers all of north America. Distribution channels do not differentiate brake pads by state. Washington Ecology advised manufacturers that did not know which states their products were sold in to report on all products sold in North America. Ecology believes most manufacturers reported for all products sold in North America.	BPP 1996-2012, U.S. EPA and co-signers 2015; Washington Department of Ecology 2013

Table 12. Vehicle Fleet Assumptions

Assumption	Basis	References
The age distribution of California's vehicle fleet will remain essentially the same as the distribution in 2007	No available information suggests that future distributions will change dramatically. The gyrations in vehicle sales volumes during the economic downturn appear to have ended. California has ceased preparation of vehicle registration reports; no alternative public data source was identified.	DOF 2009. Table J3: "Distribution Of Fee-Paid Registrations By Type And Year First Registered California, 2007."
Heavy-duty (truck) brake copper contributions are small.	Trucks have larger brake pads, but since consumer acceptance issues (noise, braking comfort) that have driven copper in use in vehicles are not present in this market and disc brakes (which typically have higher copper content) are uncommon in the U.S. heavy-duty vehicle market, copper use is relatively low, on average about 0.5%, which is <10% of average copper concentrations in light-duty vehicles. Heavy-duty trucks compose a relatively small fraction of total California urban VMT, e.g., SCAG vehicle miles traveled (VMT) data show trucks represent less than 3.5% of total vehicle miles traveled in Los Angeles County. Washington Ecology estimated that truck brakes composed <10% of copper releases.	SCAG 2012; Gilroy 2011; BPP 1996-2012; Washington Department of Ecology 2013
Motorcycle contributions are small	Motorcycles were estimated to be <1% of statewide brake pad copper emissions by the BPP. Washington Ecology estimated motorcycle emissions represent <0.1% of total statewide brake pad copper emissions .	Rosselot 2010; Washington Department of Ecology 2013
Trailer contributions are small	Trailers comprise less than 10% of total California vehicle registrations. Trailers probably represent a relatively small portion of the vehicle miles traveled and are primarily used on heavy-duty trucks (see above) and for recreational purposes.	DOF 2009. Table J5: "Registration of Motor Vehicles and Trailers which Paid Fees by Type of Vehicle California, 1971 to 2007"
Other vehicle types exempted from California SB 346 release negligible quantities of copper	Brake Pad Partnership informal analysis	BPP 1996-2012

Table 13. Vehicle Miles Traveled (VMT) Assumptions

Assumption	Basis	References
Brake pad wear is proportional to VMT	Information provided by brake pad manufacturers to the Brake Pad Partnership.	Phipps 2006
VMT will not change significantly in coming years.	Future VMT trends over the next two decades are uncertain, depending on factors—including public policy actions—that cannot be predicted today. VMT peaked in the mid-2000s, signaling an apparent major shift in mobility behavior. While VMT rebounded in 2014-15, it remains below the prior peak. Long-term projections are highly uncertain. Increasing gasoline prices and legislation, regulation, and planning activities to reduce VMT because of climate change could stabilize—and may actually reduce—future VMT.	Hymel 2014; SCAG 2012; Caltrans 2015
The relative fraction of vehicle miles traveled on highways (as compared to city streets) will not change significantly in coming years.	Brake Pad manufacturer data show that brake pad wear rates on city streets are 5-10 times greater than emissions on highways, due to lower use of brake pads per mile traveled on highways. As long as the relative proportion of vehicle miles traveled on theses two types of road does not change, this does not affect load estimates.	Phipps 2006

Table 14. Urban Runoff Assumptions

Assumption	Basis	References
Urban Runoff Copper Fraction = 62%	In the most highly urbanized watersheds, brake pad copper represents 58-66% of total anthropogenic copper.	Donigian 2009
Urban runoff watershed response time = 1 year	Urban runoff response times are assumed to be represented by the most highly impervious San Francisco Bay area (California) watersheds that were modeled by the BPP. In these watersheds, response time is estimated to be relatively quick, with >70% copper reductions estimated the first year after brake pad reformulation and nearly 90% reduction in 5 years. Modeling suggests that channelized watersheds, which could be considered akin to piped storm drains, experience a slightly quicker wash out period than the natural channels modeled in the San Francisco Bay area, California. Weather introduces uncertainty into predicted copper reduction schedules. Wet weather and large storms mobilize copper in watersheds, increasing the speed of copper reductions. Dry years reduce the washout, increasing the length of time that it takes for brake pad copper reductions to be fully reflected in waterways. Modelers found that dry water year scenarios slightly increased washout time, by at most a few years. These response times are only for urban runoff; response times in surface waters depend on multiple factors that cannot be estimated generically.	Donigian 2009

Section 4: Brake Pad Copper Reduction Scenarios

The following three scenarios were developed on the basis of available information to bracket the range of potential rates of brake pad copper reduction. Each scenario is based on a different potential pathway for the market transition to the brake pads containing less than 0.5% copper. The third scenario has two variants to examine the implications of potential manufacturer responses if Washington Department of Ecology abandons its precedent for handling exemptions when making its decision about implementation of requirements that all brake pads contain <0.5% copper.

Scenario 1 – One-Step Reduction

Virtually all original equipment (new vehicle) and aftermarket (replacement) brake pads are reformulated to <0.5% copper by January 1, 2021 (first California SB 346 copper compliance deadline). Virtually all aftermarket brake pads containing higher copper levels that remain in distributor and retailer inventories are sold within two years of this date.

Brake pad, brake systems, and new vehicle manufacturers would greatly reduce their engineering costs for the transition to low copper brake pads if they can move directly to brake pads with less than 0.5% copper. This scenario describes the copper reductions that would occur if brake pad manufacturers complete product reformulation in a single cycle, thus avoiding two rounds of re-engineering of their products and their manufacturing processes. The primary basis for this scenario is the assumption that all manufacturers can quickly develop products containing less than 0.5% copper that meet all manufacturing, cost, and customer requirements.

As Section 1 details, there is some evidence suggesting that this scenario may occur. Major vehicle manufacturers are requesting that suppliers provide brake pads with less than 0.5% copper for their new vehicle models. Brake pad manufacturers are currently bringing to market both original equipment and aftermarket brake pad lines with less than 0.5% copper. Some of these lines are specifically designed to replicate the braking performance properties of higher copper formulations.

For aftermarket brake pads, this scenario assumes that Washington State requirements will drive the market transition. Unlike California law, Washington law has very narrow exemptions for aftermarket brake pads (Washington State 2010). Due to the complexity of brake pad distribution chains, if higher copper brake pads enter national distribution systems after Washington's compliance deadlines, manufacturers and retailers will have trouble avoiding non-compliance with Washington requirements (BPP 2008-2010). Consequently, brake manufacturers have stated their intent to implement brake pad copper reductions nationally (U.S. EPA and co-signers 2015; MEMA 2012a).

The primary exemption for aftermarket brake pads under Washington law is an allowance for "inventory runoff" of brake pads manufactured prior to the compliance deadline (Washington State 2010). To ensure compliance, brake pad manufacture date must be marked on pads; this date marking is part of the

nationwide brake pad compliance marking system (SAE 2012). Typical replacement brake pad inventory turnover time is less than two years (BPP 1996-2012). Thus, after two years, most brake pads more than two years old have been sold.

Another consideration for the aftermarket is that copper is far more expensive than other brake pad ingredients (BPP 1996-2012). Since price is the primary customer interest in the aftermarket, manufacturers have a financial incentive to eliminate copper in aftermarket brake pads, particularly now that higher copper content is no longer perceived as a positive attribute.

This scenario also may avoid the need for purchase of special chemical analysis equipment for manufacturers to monitor products for compliance with the 5% copper standard. In brake pad materials (friction materials), copper concentration measurements around 5% copper pose unique chemical analysis challenges that do not occur at the 0.5% level (BPP 1996-2012). Developing manufacturing process controls for this copper concentration would cause manufacturers to incur one-time costs that have only short-term benefits.

The primary shortcomings of this scenario are:

(1) Some manufacturers may not successfully develop brake pads containing less than 0.5% copper that meet all manufacturing, cost, and customer requirements soon enough to transition all of their products by the above dates.

(2) Some manufacturers may delay transitions until legal deadlines.

(3) Washington State might provide broader exemptions when it implements its requirement for brake pads to contain less than 0.5% copper, delaying the aftermarket transition to the lowest copper brake pads.

This scenario is optimistic. It is included to show the earliest reasonable dates for achievement of brake copper reductions.

Scenario 2 – Two-Step Reduction

Virtually all original equipment (new vehicle) brake pads are reformulated to <5% copper by January 1, 2021 and <0.5% copper by 2025 (California SB 346 compliance deadlines), with minimal use of exemptions and extensions. Virtually all higher copper aftermarket (replacement) brake pads remaining in inventories are sold within two years of each compliance date.

This scenario assumes that brake pad manufacturers will implement a two-step transition to the lowest copper brake pads, based on legal deadlines. Under this scenario, in the first step manufacturers would replace current high copper products with products containing less than 5% copper. The majority of manufacturers would delay introduction of products with less than 0.5% copper for several years, which would provide additional time for development of formulations containing less than 0.5% copper.

The 5% standard is included in California and Washington laws because when the laws were adopted, brake pad manufacturers indicated that most companies were capable of producing brake pads meeting the 5% standard (BPP 2008-2010). The long transition time provided in the laws before all new vehicles are required to meet the 5% standard was to provide adequate time for re-engineering of the braking systems of every new vehicle that currently uses higher copper brake pads (MEMA 2010).

When the laws were passed, manufacturers indicated that companies would need to develop new formulation approaches to formulate brake pads with less than 0.5% copper while meeting all manufacturing, cost, and customer requirements. California SB 346 provided an additional four years after the 5% standard takes effect to provide extra time for manufacturers to develop the new formulation approaches.

California SB 346 was designed to allow vehicle manufacturers to re-engineer vehicle brake systems concurrent with their other periodic vehicle platform re-engineering, which occurs about once every 8 years for most vehicles (BPP 2008; MEMA 2010). Before a newly re-engineered brake system reaches the market, the brakes go through several years of engineering design, product validations, and performance and safety testing by brake pad manufacturers and vehicle manufacturers (BPP 2008; MEMA 2010). The timelines in California SB 346 provided about 4 years for these activities to be conducted in parallel with formulation development (2010-2013), prior to the sales of the first re-engineered less than 5% copper brake pad new vehicles, which under this scenario, was assumed to occur—and indeed did occur—no later than 2014. Because the compliance deadline for brake pads with less then 0.5% copper is only four years after the 5% deadline, within 4 years of the introduction of the less than 5% copper brake pad vehicles (2018), under this scenario, manufacturers are assumed to begin introducing vehicles with less than 0.5% copper brake pads by 2018 so as to completely re-engineer all vehicles to meet the 0.5% standard by 2025.

Although the original equipment brake pad industry appears to be attempting to move directly to the lowest copper brake pads, it appears, based on public information summarized in Section 1, that a few companies are currently bringing brake pads less than 5% copper but more than 0.5% copper to the market in order to provide customers with immediate access to lower copper brake pads. The fraction of the overall brake pad market that makes a two-step transition will largely be determined by the success of each company's product formulators in developing less than 0.5% products that meet their company's and customer's manufacturing, cost, and performance requirements.

For aftermarket brake pads, this scenario is based on the assumption that Washington State requirements will drive the aftermarket transition.

The primary shortcomings of this scenario are:

(1) This scenario is not consistent with early evidence suggesting that the original equipment brake pad industry appears to be attempting to move directly to the lowest copper brake pads (see Section 1).

(2) Washington State might provide broader exemptions when it implements its requirement for brake pads to contain less than 0.5% copper, delaying the aftermarket transition to the lowest copper brake pads.

Scenario 3 – Aftermarket Exemption from 0.5% Copper Standard

Virtually all original equipment (new vehicle) brake pads are reformulated to <5% copper by January 1, 2021 and <0.5% copper by 2025 (California SB 346 compliance deadlines), with minimal use of exemptions and extensions. Higher copper aftermarket (replacement) brake pads for vehicles manufactured prior to compliance dates continue to be sold indefinitely.

> *Variant 3A:* Since the aftermarket exemption for older vehicles is based on the premise that aftermarket brake pads should be designed to be similar to the original equipment brake pads, this variant assumes that aftermarket brake pads for pre-2025 vehicles that originally have low copper or copper free brake pads will have the same copper content as the originals.
>
> *Variant 3B:* Since the California law's aftermarket exemption does not require aftermarket brake pads to be designed to be similar to the original equipment brake pad, this variant assumes that aftermarket brake pad installations are unconstrained by copper content. Under this scenario, copper content for pre-2025 vehicles remains unchanged after 2025, i.e., that aftermarket brake pads containing <5% but >0.5% copper ("low copper") continue to be available indefinitely for pre-2025 vehicles.

Like Scenario 2, this scenario assumes that original equipment brake pad manufacturers will implement a two-step transition to the lowest copper brake pads in accordance with the compliance dates in California SB 346. Where it differs from Scenario 2 is in the aftermarket. This scenario assumes that Washington State deviates from the policy in its current law and provides a broad aftermarket brake pad exemption similar to the exemption in California SB 346 when it implements its requirement for brake pads to contain less than 0.5% copper. The exemption in California SB 346 is a permanent exemption for all aftermarket brake pads designed to fit vehicles manufactured prior to California's compliance deadlines in 2021 and 2025. Such an exemption would delay the aftermarket transition to the lowest copper brake pads by allowing high copper replacement brake pads to be sold for vehicles manufactured prior to compliance deadlines.

Under this scenario, aftermarket brake pad manufacturers would maintain the current copper content in their brake pads that are made for use in vehicles manufactured prior to 2021 and 2025. This would avoid the need for manufacturers to develop lower copper brake pads that meet the same performance characteristics as the higher copper brake pads. Variant 3A assumes that the

industry follows its stated design preference of replacing "like for like" brake pads in terms of copper content. Variant 3B assumes that this stated practice is not followed, perhaps because copper-free and copper containing replacement brake pads offer the same performance characteristics. This would mean that brake pads with copper content <5% but >0.5% to be used in pre-2025 vehicles until those vehicles are no longer on the road.

The primary shortcomings of this scenario are:

(1) This scenario is not consistent with early evidence suggesting that the original equipment brake pad industry appears to be attempting to move directly to the lowest copper brake pads (see Section 1).

(2) When establishing regulatory requirements, states ordinarily rely on the precedents established in their state's own authorizing legislation.

This scenario is pessimistic. It is included to show the latest reasonable dates for achievement of brake copper reductions and to provide insight into the water quality implications of Washington Department of Ecology's upcoming decision about potential requirements that all brake pads contain <0.5% copper.

Section 5: Results

Using the assumptions in Section 3, copper reductions were estimated for three scenarios. An attached Excel spreadsheet contains the detailed calculations.

5.1 Estimation Approach

Reduction estimates were made using the percent reduction approach, i.e., estimating reduction in the source (brake pad copper) and translating that source reduction into its associated urban runoff reduction. This straightforward approach is based on BPP modeling, which used detailed estimates of all urban runoff copper sources and intricate modeling to create an overall average estimated brake pad copper contribution to total copper in runoff from highly urbanized watersheds (Donigian 2009).

Another possible approach for estimating brake pad copper release reductions involves estimating the average brake pad wear rate and multiplying this estimate with estimated brake pad copper content (the "composition/wear" approach). The BPP explored this ground-up approach, but abandoned it due to the high uncertainties in the input data for wear rate, which varies tremendously among on-road vehicles due to differences in pad sizes among vehicle classes and vastly different wear rates among brake pad formulations (Rosselot 2006a). The BPP also explored a third estimation approach based on brake pad particle emission factors multiplied by estimated brake pad copper content (the "composition/emissions factor" approach, but abandoned this as well based on the high uncertainties in the input values. Ultimately, the BPP estimated brake pad copper releases from vehicle emissions studies in tunnels (where fleet wide average releases can be captured and quantified) and brake pad wear debris distribution data from BPP laboratory tests (Rosselot 2006a). The BPP's estimation approach, involved two separate emissions factors – an air emissions factor and a road emissions factor – that were summed to estimate total copper emissions. The air emissions factor (from the one-time vehicle tunnel studies), uniquely and advantageously melded vehicle fleet-wide average copper content and wear rates into a single value, reducing uncertainty. The BPP found that all three methods yielded relatively similar copper release estimates.

This percent reduction estimation approach based on BPP modeling provides brake pad copper content reductions and estimated copper reductions in urban runoff. These estimates are not necessarily translatable directly into surface water copper reduction estimates, as they do not account for response lag times in surface waters, which may be affected by accumulated copper from past brake and non-brake discharges, copper sources other than urban runoff, rainfall volumes and intensity, and site-specific watershed conditions like channel length, shape, channel bottom material, and sediment loads (Donigian 2009).

5.2 Results

The estimates include three sets of values. First, the average copper concentration in brake pads manufactured each year was estimated. Using these data, replacement rates, inventory turnover rates, and vehicle fleet age data, the on-road average brake pad copper concentration was estimated. Finally, assuming that lower copper concentrations in on-road brake pads are directly proportional to reduction in bake pad copper's contribution to urban runoff copper content, the urban runoff copper reduction from brake pads alone was estimated. To account for the watershed lag time, the urban runoff copper reductions are estimated to occur one year after the brake pad copper reductions. Based on BPP modeling, the maximum urban runoff copper reduction from brake pads is about 61%.

Figures 4 through 7 and tables 15 through 18 present the estimated average on-road brake pad copper content, the estimated reduction as compared to 2013 (baseline) levels, and the estimated subsequent reduction in copper levels in urban runoff. Figures 4 and 5 include copper content data reported to Washington Ecology (Washington Department of Ecology 2015a). Figure 5, which focuses on the current decade, shows that actual reduction trends are falling between Scenarios 1 and 2, suggesting that many manufacturers are making a one-step reduction to the lowest copper brake pad formulations, instead of creating "low-copper" interim products.

Figure 4. Average Brake Pad Copper Content by Year Manufactured: Reported Data Compared to Estimates

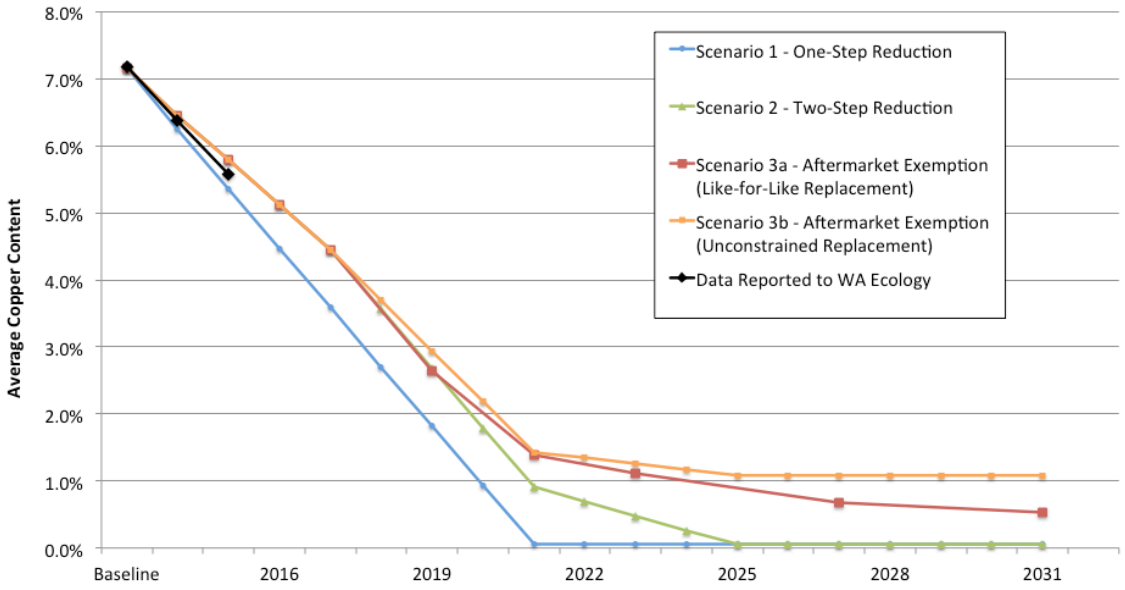

Figure 5. Average Brake Pad Copper Content by Year Manufactured: Reported Data Compared to Estimates (Baseline through 2019)

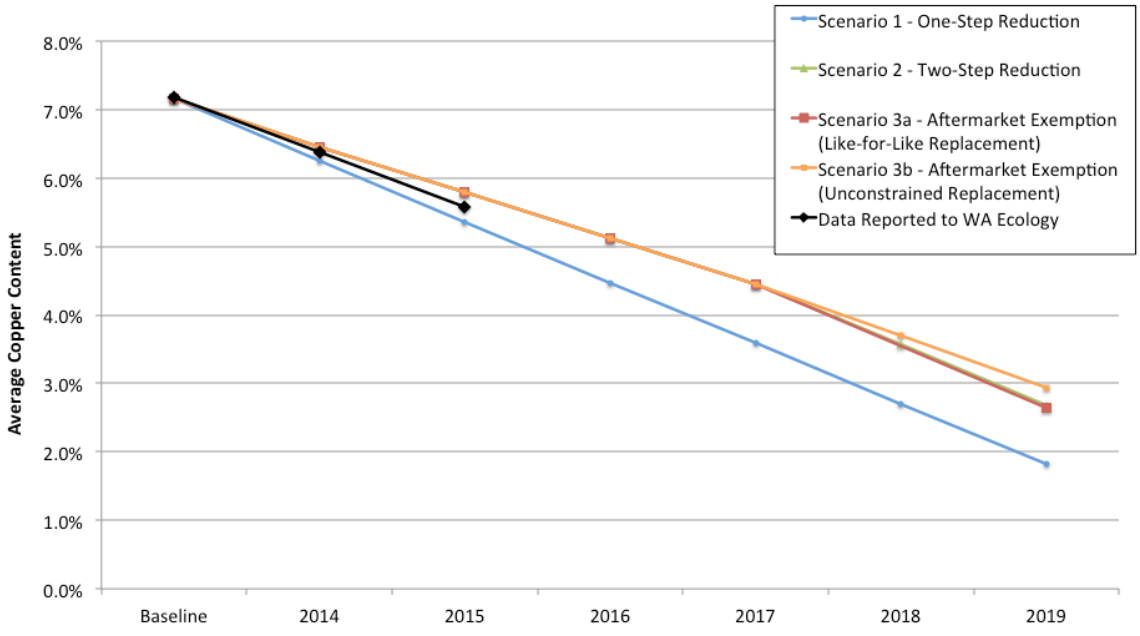

Figure 6. On-Road Brake Pad Copper Content Projections

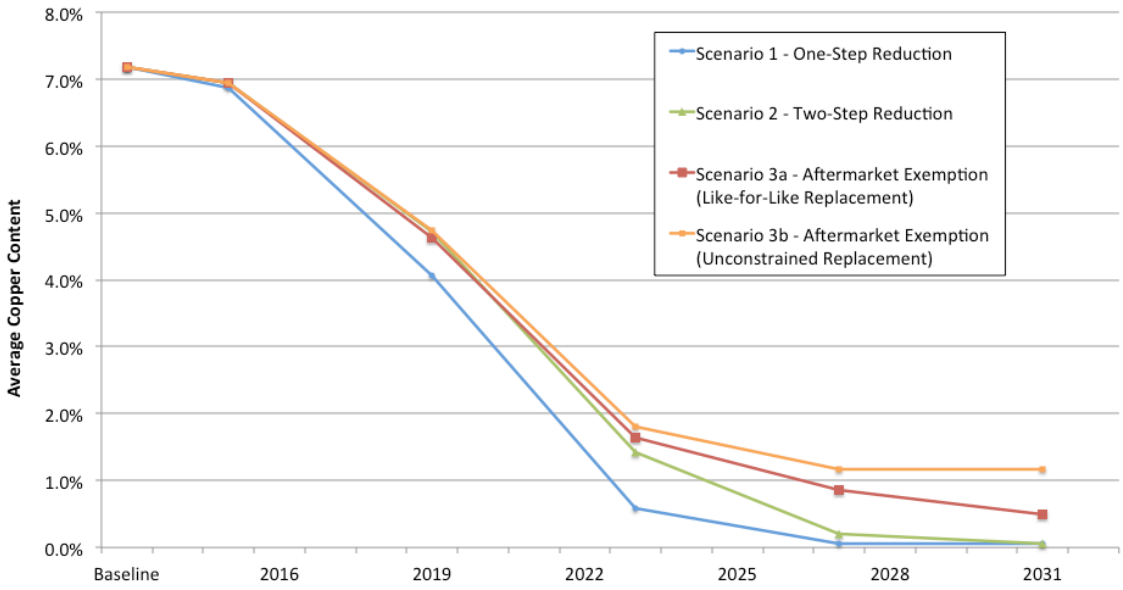

Figure 7. Urban Runoff Copper Reduction Projections

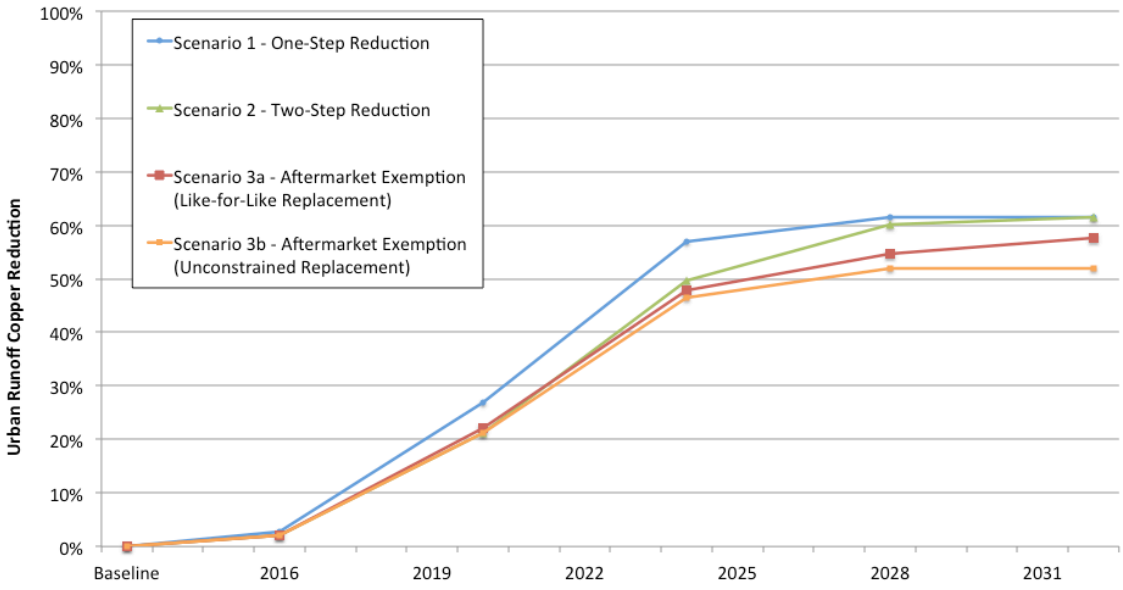

Table 15. Scenario 1 – Estimated Copper Reductions

Year*	Scenario 1 – One-Step Reduction			
	Manufactured Average Brake Pad Copper	On-Road Average Brake Pad Copper	Estimated Brake Pad Copper Reduction	Estimated Urban Runoff Copper Reduction from Brake Pads Alone
Baseline (2013 and prior years)	7.2%	7.2%	--	
2014	6.2%			
2015	5.4%	6.9%	4%	
2016	4.5%			**2.8%**
2017	3.6%			
2018	2.7%			
2019	1.8%	4.1%	44%	
2020	0.9%			**27.0%**
2021	0.05%			
2022	0.05%			
2023	0.05%	0.6%	92%	
2024	0.05%			**57.0%**
2025	0.05%			
2026	0.05%			
2027	0.05%	0.05%	99%	
2028	0.05%			**61.6%**
2029	0.05%			
2030	0.05%			
2031	0.05%	0.05%	99%	
2032				**61.6%**

*Estimation years are highlighted.

Table 16. Scenario 2 – Estimated Copper Reductions

Year*	Scenario 2 – Two-Step Reduction			
	Manufactured Average Brake Pad Copper	**On-Road Average Brake Pad Copper**	**Estimated Brake Pad Copper Reduction**	**Estimated Urban Runoff Copper Reduction from Brake Pads Alone**
Baseline (2013 and prior years)	7.2%	7.2%	--	
2014	6.5%			
2015	5.8%	6.9%	3%	
2016	5.1%			**2.2%**
2017	4.5%			
2018	3.6%			
2019	2.7%	4.7%	34%	
2020	1.8%			**21.3%**
2021	0.9%			
2022	0.7%			
2023	0.5%	1.4%	80%	
2024	0.3%			**49.8%**
2025	0.05%			
2026	0.05%			
2027	0.05%	0.2%	97%	
2028	0.05%			**60.3%**
2029	0.05%			
2030	0.05%			
2031	0.05%	0.05%	99%	
2032				**61.6%**

*Estimation years are highlighted.

Table 17. Scenario 3a – Estimated Copper Reductions

Year*	Scenario 3a - Aftermarket Exemption (Like-for-Like Replacement)			
	Manufactured Average Brake Pad Copper**	On-Road Average Brake Pad Copper	Estimated Brake Pad Copper Reduction	Estimated Urban Runoff Copper Reduction from Brake Pads Alone
Baseline (2013 and prior years)	7.2%	7.2%	--	
2014	6.5%			
2015	5.8%	6.9%	3%	
2016	5.1%			**2.2%**
2017	4.5%			
2018				
2019	2.6%	4.6%	36%	
2020				**22.1%**
2021	1.4%			
2022				
2023	1.1%	1.6%	77%	
2024				**47.9%**
2025				
2026				
2027	0.7%	0.9%	88%	
2028				**54.6%**
2029				
2030				
2031	0.5%	0.5%	93%	
2032				**57.7%**

*Estimation years are highlighted.

**Due to computational effort required, not estimated for all years.

Table 18. Scenario 3b – Estimated Copper Reductions

Year*	Scenario 3b - Aftermarket Exemption (Unconstrained Replacement)			
	Manufactured Average Brake Pad Copper	On-Road Average Brake Pad Copper	Estimated Brake Pad Copper Reduction	Estimated Urban Runoff Copper Reduction from Brake Pads Alone
Baseline (2013 and prior years)	7.2%	7.2%	--	
2014	6.5%			
2015	5.8%	6.9%	3%	
2016	5.1%			**2.2%**
2017	4.5%			
2018	3.7%			
2019	2.9%	4.7%	34%	
2020	2.2%			**21.2%**
2021	1.4%			
2022	1.3%			
2023	1.3%	1.8%	75%	
2024	1.2%			**46.4%**
2025	1.1%			
2026	1.1%			
2027	1.1%	1.2%	84%	
2028	1.1%			**51.9%**
2029	1.1%			
2030	1.1%			
2031	1.1%	1.2%	84%	
2032				**52.0%**

*Estimation years are highlighted.

5.3 Comparison to Washington Department of Ecology Estimates

Washington Department of Ecology used the wear rate approach to estimate the brake pad copper release reduction that would occur if all on-road vehicles had brake pads manufactured in 2021 (Washington Department of Ecology 2013). These estimates only examined copper releases into the environment—not the ultimate reductions in urban runoff. The estimation scenario is purely theoretical, since brake pads across the vehicle fleet are replaced about every 3-5 years (see Table 9). Because Washington assumed that only brake pad copper content would change (wear rate and vehicle miles traveled were held constant), Washington's reduction estimate effectively estimated reduction in manufactured brake pad copper as compared to its 2011 baseline data.

Washington estimated about an 87% reduction in the copper content of brake pads manufactured in 2021 as compared to those manufactured in 2011. This reduction estimate is consistent with the manufactured brake pad copper content reduction estimated in Scenario 2 (see Table 19).

Table 19. Estimated Average Copper Content of Brake Pads Manufactured in 2021: Comparison among Scenarios 1-3 and Washington Ecology Estimate

Scenario	Baseline Copper Content	2021 Copper Content	Estimated Reduction
1	7.2%	0.05%	99%
2	7.2%	0.9%	87%
3a	7.2%	1.4%	81%
3b	7.2%	1.4%	81%
Washington Ecology	[Varies by vehicle type]		87%

Source: Tables 14-17 and Washington Department of Ecology 2013.

5.4 Uncertainties

Although every effort was made to develop scenarios that bracket the range of possible copper reduction schedules and to base reduction estimates on reasonable assumptions, these estimates may not account for all possibilities. For example, if high copper brake pads continue to be used in the small populations of exempted vehicles (e.g., motorcycles), the ultimate reduction levels could be slightly less than the anticipated maximum reduction of 61%. In the relatively unlikely event that California DTSC allows substantial extensions, the pace of reductions could be slower than estimated in any of the scenarios.

Although these estimates are based on the best available information, they are uncertain. The most significant uncertainties are in brake pad copper content (particularly market volumes for each brake pad copper content level, which are unavailable), future changes in vehicle miles traveled, and watershed response

times. As the brake pad reformulation process unfolds, additional data will become available from Washington State that will reduce the uncertainties in brake pad copper content estimates.

These estimates are designed to cover ordinary, highly urbanized California watersheds. They do not address watersheds unusual local copper sources (e.g., marine antifouling paint removal activities, copper mines), where brake pad-related copper reductions would be lower.

5.5 Monitoring Progress

In the long term, ambient monitoring data will reflect brake pad copper reductions. Based on the projections in Figure 7, reductions will likely be too small to measure until the 2020s. Measuring reductions will require a robust long-term monitoring program with sufficient samples to differentiate copper reductions from ordinary variability in environmental samples. The California State Water Board Surface Water Ambient Monitoring Program Stream Pollution Trends Program (SWAMP SPoT) intends (assuming funding remains available) to provide long-term measurements of copper reductions in sediments from California urban watersheds. SWAMP SPoT's robust monitoring plan, which includes several dozen sites influenced by urban runoff, used statistical power analysis to determine sufficient sampling frequency for measuring anticipated reductions.[6] Its long-term baseline data set, combined with its relatively large number of sampling sites, puts this program in the unique position to identify trends early and track them effectively.

[6] Watershed copper reductions were estimated on the basis of an earlier version of these reduction predictions (Moran 2013).

Section 6: Conclusions

Newly manufactured vehicle brake pads contain, on average, significantly less copper than they did in the early 2010s.

Brake pads available today have an average copper content of about 5.6%, a 32% reduction as compared to the BPP 2006 estimate and a 22% reduction as compared to Washington's 2011 baseline data.

In mid-2015, 44% of brake pad formulations contained <0.5% copper.

The lowest copper content brake pads are widely available, both in the original equipment and aftermarkets.

Brake pads manufactured in 2021 are expected to contain 81-99% less copper than they did in the early 2010s.

By 2019, newly manufactured brake pads are expected to contain 60% to 75% less copper than they did at the start of this decade.

Based on brake pad copper content data reported to Washington Department of Ecology, the actual reduction trend appears to be falling between the most optimistic one-step reduction (Scenario 1) and the two-step reduction (Scenario 2).

Under all scenarios, the pace of reductions is anticipated to slow after 2020, when all high-copper brake pads will be out of the market.

On-road brake pad copper content is dropping, but more slowly than manufactured brake pad copper content. A 35% to 43% reduction in on-road brake copper content should occur by 2019.

The slower pace of on-road brake pad copper reductions is due to the combination of brake pads' three to five year average lifetimes on vehicles and the inventory turnover times at wholesalers and retailers

Due to the slower change in on-road brakes and watershed lag times, urban runoff copper levels are slower. They are anticipated to drop by 21-27% by 2020 and by 46-57% by 2024.

Because environmental monitoring data have natural variability, it is likely that the urban watershed response to brake pad copper reduction requirements will first be measurable in the mid-2020s.

Washington State's upcoming decision about implementing requirements that all brake pads contain <0.5% copper has important water quality implications in California and the rest of the nation.

Due to the nature of the vehicle parts supply chain, the same brake pads are sold across all of North America. Consequently, one state's regulatory requirements affect the entire nation. Washington State has the most restrictive approach to aftermarket exemptions. The difference between Scenario 2 and Scenario 3 predictions show the importance of Washington's continuation of its approach to exemptions for aftermarket brake pads for older vehicles.

If Washington maintains its current approach and follows its legislative precedent, full urban runoff copper reductions are expected to be achieved in the early 2030s. If Washington's approach were to diverge from its precedents, the pace of reduction would start to drop off in the early 2020s. By 2028 there would be as much as a 15% difference between copper reductions with a narrow aftermarket exemption and copper reductions with a broad aftermarket exemption. In the worst case (Scenario 3b), full reductions might never be achieved. These differences may have implications for compliance with water quality standards and achievement of Total Maximum Daily Loads (TMDLs).

Section 7: Recommendations

Recommendation 1: Share these projections with Washington State and with the vehicle industry.

Washington State will soon make a decision about implementing requirements that all brake pads contain <0.5% copper. Washington's law delegates this decision to the Washington Department of Ecology. Through its three scenarios, this report estimates the difference in water quality outcomes that could occur as a consequence of the Washington decision. If Washington continues, as expected, to follow its legislative precedent, which has a narrow aftermarket exemption (only brake pads supplied to dealers under an "original equipment service contract" are exempt), Scenarios 1and 2 would provide the best projections of future copper reductions. If Washington unexpectedly abandons its precedent—and offers a broad exemption for aftermarket parts for pre-2025 vehicles, Scenarios 3a and 3b illustrate that the pace of copper reduction would be significantly slower and total reductions by 2032 would be lower.

Recommendation 2: Update these copper reduction estimates in 2018 using data from implementation of California SB 346 and Washington State law.

Washington State's collection of brake pad formulation data provides an ongoing tracking of brake pad copper content. Updated information can be used not only to update the estimates, but also to refine the assumptions to reduce uncertainties in the copper reduction estimates. The Washington data set links to brake pad certifications that expire every 3 years. Most current certifications expire in 2016 or 2017. The first set of certifications in 2013-14 likely included every formulation in the marketplace at that time, including many formulations developed long before adoption of copper restrictions. By the time these formulations are up for renewal in 2016-17, manufacturers may have sufficient updated formulations to abandon legacy high copper products. An update in 2018 would reflect these changes and could include sufficient additional new information to provide a meaningful update to these 2015 estimates.

Recommendation 3: Use the California State Water Board "SWAMP SPoT" sediment monitoring to track brake pad copper reductions.

Measuring reductions will require a robust long-term monitoring program with sufficient samples to differentiate copper reductions from ordinary variability in environmental samples. The California State Water Board Surface Water Ambient Monitoring Program Sediment Pollution Trends Program (SWAMP SPoT) has the unique capacity to track these trends.

Recommendation 4: Use the urban runoff copper reduction estimates in this report, in combination with local data, for urban runoff management planning purposes, doing so in a manner that recognizes that uncertainties in the estimates and unique local watershed characteristics.

This report was prepared to provide information to support urban runoff management planning. Using local monitoring data and knowledge of watershed characteristics, both water quality regulators and the regulated community can use the estimates in this report to support development of quantitative local copper reduction projections and to examine the magnitude and timing of anticipated vehicle brake pad copper reductions in relationship to targets in local and regional plans (e.g., copper TMDLs). Organizations using these data should evaluate the applicability of these estimates to their specific watersheds carefully and should recognize the uncertainties inherent in these estimates as well as their generic nature. Use of these estimates should be accompanied by an examination of the watershed for the presence of any unusual local copper sources (e.g., marine antifouling paint removal activities, copper mines).

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