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Authors
Kear, Tom P.
Eisinger, Douglas
Niemeier, Debbie A.
et al.

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US vehicle emissions: Creating a common currency to avoid model comparison problems

Tom Kear [a], Douglas Eisinger [b,*], Deb Niemeier [b], Mike Brady [c]

[a] *Dowling Associates Inc., 428 J Street, Suite 500, Sacramento, CA 95814, USA*
[b] *UC Davis-Caltrans Air Quality Project, Department of Civil and Environment Engineering, University of California, One Shields Avenue, Davis, CA 95616, USA*
[c] *California Department of Transportation, Air Quality and Conformity Coordination, Division of Transportation Planning, MS-32, 1120 N Street, Sacramento, CA 94274, USA*

Abstract

Emission inventory models are a key input to regional air quality plans, called State Implementation Plans (SIPs) in the US. These plans frequently include emissions caps, or ‘‘budgets,’’ to which transportation system emissions must be compared. When emissions models and vehicle fleet-related planning assumptions change substantially, but for a variety of reasons the State Implementation Plan and its emissions budgets do not, a mismatch arises. The SIP Currency approach addresses problems that arise when the latest emissions and transportation modeling tools and planning assumptions are used to estimate on-road vehicle emissions, but the resulting estimates are compared to outdated emissions targets. Translating emissions estimates into the currency of emissions estimates included in older air quality plans provides a way to ensure continued improvement in air quality while preventing unintended disruption of transportation planning. The article illustrates how carbon monoxide, volatile organic compound and oxides of nitrogen emissions may be translated into the currency of outdated emissions models.

Keywords: Transportation conformity; Emissions budgets; On-road vehicle emissions; Air quality

1. Introduction

Use is made of SIP Currency to compare air pollution emission estimates produced by different modeling tools. This approach translates emissions estimated using one modeling tool into the ‘‘currency’’ or estimates produced by a different model version or tool. Development of the new approach was motivated by US ‘‘transportation conformity’’ regulations that mandate periodic comparisons between forecasted vehicle emissions and allowable emissions levels. Although this article describes SIP Currency using US conformity and

* Corresponding author.
E-mail address: doug@sonomatech.com (D. Eisinger).

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on-road vehicle examples, the concept may be applied to any emission source category in any location where new emission estimates are compared to emission targets produced with outdated tools.

2. Background

In the US, two modeling tools have traditionally been used to estimate on-road vehicle emissions: EMFAC (a name derived from "**em**ission **fac**tor"), developed by the California Air Resources Board for use in California, and MOBILE (a name derived from its applicability to mobile sources), developed by the US Environmental Protection Agency (EPA) for use in the rest of the US. As EMFAC and MOBILE are updated, newer model versions produce emission estimates different than those of their predecessors, complicating comparisons between old and new emissions estimates. The model comparison problem is not unique to the US; emission modeling tools are periodically updated around the world, triggering the need for a methodology to help compare results that span model versions. For example, the COPERT model, a commonly used European on-road vehicle emissions model, was updated in 1997 and again in 2000 (Ahlvik et al., 1997; Bellasio et al., 2007; Ntziachristos et al., 2000). Individual countries have also created emission estimation tools, and these evolve over time; German on-road vehicle emissions modeling tools, for example, are periodically updated to reflect incremental changes similar to those made to US tools (National Research Council, 2000).

Transportation conformity requires coordinated transportation and air quality planning. US metropolitan area air quality management plans, called "state implementation plans" or SIPs, cap allowable emissions from on-road motor vehicles. Transportation plans, which are updated more frequently than SIPs, must demonstrate that they conform to regional SIP goals. In US metropolitan areas, many transportation projects are contingent upon receipt of federal transportation funding, and delivery of these funds are themselves contingent upon successful conformity determinations. Thus, by requiring periodic checks against emission reduction goals, the conformity process has become an important lever to ensure collaborative regional planning as well as ongoing progress towards regional air quality goals (e.g., see Transportation Research Board, 2002). However, the conformity exercise can become problematic once modeling tools and planning assumptions are updated, making SIP assumptions obsolete. During a conformity demonstration, transportation plan emissions must be estimated with the latest modeling tools and planning assumptions (Wykle et al., 2001), regardless of the tools used to establish the SIP. SIP updates could correct potential problems. However, given the political and technical complexities involved with changing a SIP, this solution is often impractical in the short-term. Once established, SIP goals can remain in place for several years without adjustment; SIP amendments, if they are pursued, typically take one or two years to achieve (Eisinger et al., 2002).

SIP Currency offers an interim solution when SIP updates cannot be readily accomplished. SIP Currency is analogous to equating temperature in degrees Fahrenheit to temperature in degrees Celsius. Although the approach described here is not as rigorous as a SIP update, it is a clear improvement over the current US conformity approach, which directly compares outdated SIP goals to emissions estimated using the latest tools and information.

3. US conformity case study

The case of the Minneapolis–St. Paul, Minnesota metropolitan area illustrates how model updates can create conformity problems. The Minneapolis–St. Paul area last violated US air quality standards for carbon monoxide (CO) in 1991 (Minnesota Pollution Control Agency, 2005). In 1998, the state established a CO SIP using what was, at that time, the latest available EPA on-road emissions model, called "MOBILE5a." Based on MOBILE5a, Minneapolis–St. Paul planners established 1114 tons per day (tpd) of CO as the maximum allowable motor vehicle CO emissions (Kelso and Lynn, 1998). The region experienced conformity trouble when EPA released MOBILE6, an updated version of its emissions model. Although there was no real air quality problem (CO violations ended in 1991), updated planning assumptions and use of the MOBILE6 model resulted in estimated year 2009 on-road CO emissions of 1311 tpd, well above the 1114 tpd allowed. Thus, conformity failure loomed, threatening future approvals of Minneapolis–St. Paul transportation plans. Faced with a regulatory, not a real, air quality problem, more than a dozen staff representing local, state, and federal agencies, together with a team of consultants, collaborated over many months to revise the CO SIP.

Using MOBILE6 and updated planning assumptions, the multi-agency group revised the SIP emissions cap – finding that, to ensure acceptable air quality, motor vehicle CO emissions could not exceed 1961 tpd (Tamura et al., 2004; US Environmental Protection Agency, 2004). The SIP amendment process enabled transportation plan approval but was time-consuming and expensive. If an alternative analytical approach had been available, such as SIP Currency, the state could have more rapidly completed its conformity determination.

A SIP documents that air quality standards will be attained by a date certain. The SIP employs an air quality model to recreate historic concentration data based upon estimated emissions. Then, once the relationship between emissions and observed concentrations is understood, the model is used to estimate emission reductions necessary to attain air quality goals. The attainment demonstration is the basis for establishing allowable on-road emissions (called "conformity emission budgets" in the US).

Consider an example where, subsequent to the approval of a SIP, new planning assumptions change the emission inventories (Fig. 1). For this example, assume concentrations were observed during two historic pollution episodes, represented by lines 1 and 2. Assume that, when the SIP was developed, analysts modeled emissions for both episodes, as represented by points A and B in Fig. 1. As illustrated, SIP modeling estimated that a 10% emissions reduction resulted in a 10% reduction in pollutant concentrations. Using this emissions-to-concentration relationship, the SIP estimated that a 30% reduction in the emissions that occurred during the first episode was needed to bring the region into attainment (Fig. 1, point C). Assume that subsequent to SIP approval, a new set of planning assumptions or a new version of the emissions model is released. As a result, episode emissions are re-modeled and found to be greater than the original estimates. These new findings are illustrated in Fig. 1 by the concentration and emission values plotted as points D and E. Note that our measured concentrations are not changing, rather, the way in which we model their associated emissions is changing.

Using our new emissions estimates and our historic concentration data, we now find that the original SIP assumption, that a 10% reduction in emissions results in a 10% reduction in pollutant concentrations, no longer holds. Instead, we find that, based on the latest information, a 20% drop in emissions is needed to achieve a 10% reduction in pollutant concentrations (Fig. 1, points D and E). What might account for this change? Perhaps the original model relied on a mischaracterized vehicle fleet or inaccurate mileage accrual rates. Regardless of the reasons, the latest modeling results show that a 60% reduction in first-episode emissions is required to achieve the desired 30% reduction in concentrations. This is illustrated in Fig. 1 by moving from point D to point F. The new information invalidates the SIP emission budgets. The updated planning assumptions change the emission-to-concentration relationship, or the currency, used to prepare the original SIP.

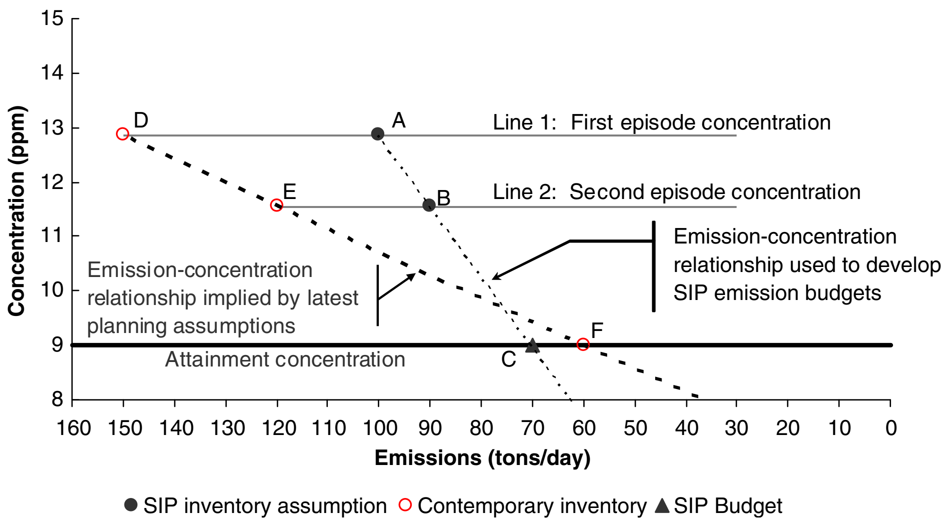

Fig. 1. Example altered emission-to-concentration relationships based on new information. Note: In this example, the SIP emission budget (point C) is more than what the latest modeling tools and assumptions estimate is acceptable.

4. Applying SIP currency

To understand how the SIP Currency framework can be applied, we provide three examples. The first example illustrates how to translate a single year's up-to-date emissions estimate into a value equivalent to an already approved SIP emission budget. The need for this might occur when modeling a near-term conformity milestone. In the second example, we describe how to formulate a mathematical relationship that relates up-to-date emission estimates for any analysis year into a SIP-equivalent value. The second approach is more applicable to real-world situations, since conformity analyses involve multiple analysis years. The first two examples use CO data. In the third example, we extend the concept to evaluate ozone precursor pollutants: volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). The currency concepts are applicable anywhere, although the examples use California data and models.

4.1. Example 1: a simplified currency illustration

In this first example, we present a simplified case where the region has already attained the air quality standard and allowable on-road emissions are capped to not exceed the estimated emissions at the time of attainment (in the US, such a cap would be the "conformity budget"). Assume a CO SIP was prepared using a now-outdated version of the California on-road emissions model (referred to as *EMFAC7f*) and that, following approval of the CO SIP, an updated tool, *EMFAC 2002*, became available. The now-outdated tool (EMFAC7f) estimated that a 27% reduction in CO emissions occurred between 1998 and 2003 to reach 8.85 ppm CO. However, EMFAC 2002, the latest tool, estimates that a 34% reduction in 1998 CO emissions occurred to reach the 8.85 ppm CO goal (Table 1).

Even though the 2003 CO concentration was 8.85 ppm, the attainment goal, the 2003 emission estimate produced by the newest tool (EMFAC 2002) exceeds the allowable conformity budget (9768 tpd exceeds the allowable 5400 tpd). A conformity problem has arisen not because there is an air quality problem, but because we have to compare emissions-to-concentration relationships produced using different tools and assumptions.

A three-step SIP Currency process is used to solve the conformity problem (Table 1).

- *First*, we assume the latest modeling tools are the best representation available of the emission inventory at the time when the air quality standard was met.
- *Second*, we acknowledge that, even using the latest tools and assumptions, the actual emission inventory at the time of attainment is unknown and each set of tools and assumptions produces only a "best estimate" of actual emissions ("X" tpd). We can define the emission estimates from the two models in relation to the actual emission inventory, X, at the time of attainment,
  $X =$ the actual emission inventory (unknown) at attainment
  $X_{7f} =$ 5400 tpd estimated from EMFAC7f (outdated tool)
  $X_{2002} =$ 9768 tpd estimated from EMFAC 2002 (newest tool)
- *Third*, we have established through the SIP process that the target concentration is 8.85 ppm (for this example). Thus, any emission inventory modeled to result in 8.85 ppm (i.e., inventories less than or equal to 9768 tpd from EMFAC 2002, or less than or equal to 5400 tpd from EMFAC7f) should be acceptable. Under this construction, any EMFAC 2002-based inventory that was less than 9768 tpd would satisfy the 5400 tpd budget set with the outdated tool, EMFAC7f.

Table 1
CO data for SIP Currency examples, based on two sets of planning assumptions

Emissions model version used as basis for modeled concentrations	1998 (base year)		2003 (attainment year)		1998–2003
	Emissions (tpd)	Concentration (ppm)	Emissions (tpd)	Concentration (ppm)	Percent emissions reduction needed to reach 8.85 ppm CO
Outdated tool (EMFAC7f)	7400	9.71	5400[a]	8.85	27%
Updated tool (EMFAC 2002)	14,800		9768		34%

[a] SIP cap on allowable emissions (also referred to as the conformity emissions budget).

4.2. Example 2: capturing changes over time

In the second example, a mathematical relationship is developed between the emissions-to-concentration relationships created by two different models. This allows us to establish a common SIP Currency over multiple analysis years. The data in Table 1 is again used; we also continue to use California's EMFAC model to illustrate the use of outdated (EMFAC7f) and recent (EMFAC 2002) modeling tools.

Assume the region is now attempting to demonstrate conformity for its 2030 transportation plan. Using SIP Currency principles, year 2030-modeled CO emissions need to be at or below 9768 tpd to demonstrate conformity, if EMFAC 2002, the newest tool, is used. In this example, we use SIP Currency to create a linear relationship that maps the base year 14,800 tpd (EMFAC 2002) to 7400 tpd (EMFAC7f) and maps the attainment year 9768 tpd (EMFAC 2002) to 5400 tpd (EMFAC7f). This relationship can be derived using the general equation for a line, $y = mx + b$, to establish a linear conversion (Eqs. (1)–(3)), where a line connects the 1998 and 2003 episode data, with the x-axis representing the EMFAC 2002 inventory and the y-axis representing the EMFAC7f inventory

$$7400 = (m)(14800) + b \quad (1)$$

$$5400 = (m)(9768) + b \quad (2)$$

$$y = (0.3975)(x) + 1517 \quad (3)$$

where, x is the EMFAC 2002 emissions estimate, and y is the SIP Currency equivalent

In this example, the analyst would develop the linear conversion given by Eq. (3), and then use it to show that the resulting value of y is less than or equal to 5400 tpd. Fig. 2 illustrates this concept. For example, if the analyst modeled year 2030 CO emissions of 8000 tpd using EMFAC 2002, SIP Currency would be used to translate that estimate into an EMFAC7f-equivalent 4697 tpd, based on Eq. (3). Note that, in this example, the translated SIP currency value is below the 5400 tpd emission budget and acceptable for conformity, whereas the original 8000 tpd estimate would create a conformity failure.

Example 2 assumes the relationship between the two sets of assumptions is linear. However, linearity is not certain, and the differences between model versions and planning assumptions can vary across analysis years.

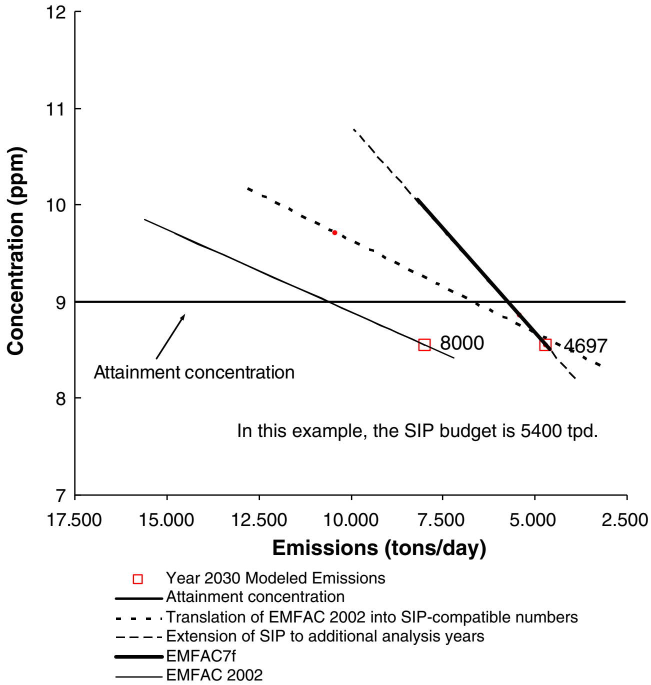

Fig. 2. Linear conversion to equate outdated (EMFAC7f) and newly-modeled (EMFAC 2002) emissions.

Although SIP Currency can be used to approximate these changing relationships, a SIP update is still the most robust method for recalibrating emissions-to-concentration relationships.

4.3. Example 3: ozone and precursor inventories

The third example applies SIP Currency concepts to tropospheric ozone problems, which occur as a function of NO_x and VOC precursor emissions. The example is based on the 1999 and 2001 San Francisco Bay Area Ozone Attainment Plans; where the 1999 plan, developed using a now-outdated version of EMFAC (*EMFAC7g*), is used to represent baseline assumptions, and the 2001 plan, developed using a more recent version of EMFAC (*EMFAC2000(beta)*), represents updated assumptions (Bay Area Air Quality Management District, 1999, 2001). The example also shows how a non-linear relationship can be approximated with SIP Currency.

Table 2 summarizes the emission inventory information from the 1999 ozone SIP; it includes emission inventory information for the 1995 and 2000 calendar years. The 1999 SIP used data from a real-world 1995 high-ozone episode to model the relationship between VOC and NO_x emissions, and ozone concentra-

Table 2
San Francisco Bay Area 1999 ozone attainment plan

	Estimated on-road emissions (tpd)	Other emissions (tpd)	Estimated total emissions (tpd)
1995 observed 1-h ozone level of 138 ppb			
VOC	273.7	288.3	562
NO_x	326.3	299.7	626
2000 estimated emissions to attain air quality goals; on-road emissions represent the maximum allowable (referred to as the conformity emissions budgets)			
VOC	175.2	258.8	434 (78% of 1995)
NOx	247.1	286.9	534 (85% of 1995)

On-road emissions based on a now-outdated model: EMFAC7g.

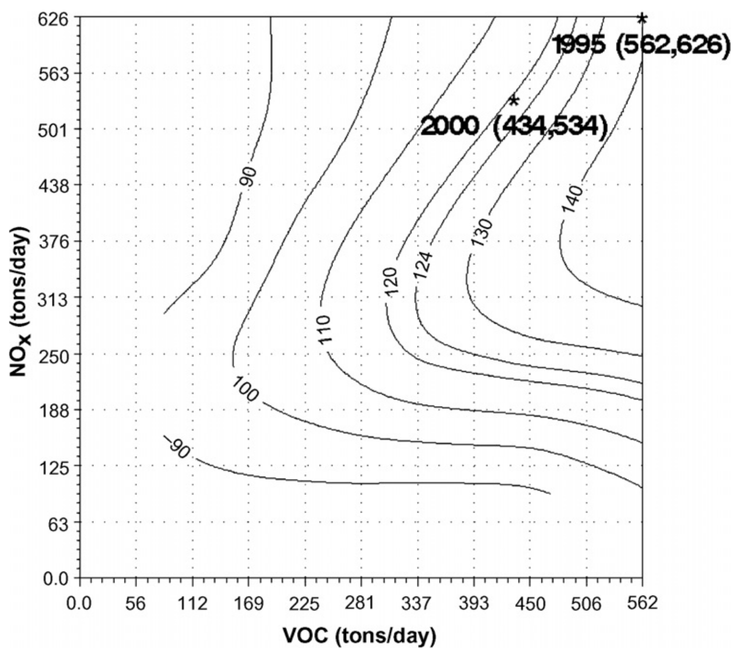

Fig. 3. Ozone isopleths from the 1999 Bay Area ozone plan depicting the attainment demonstration for 2000 (less than 124 ppb of ozone) and associated VOC and NO_x emissions.

tions. Fig. 3 illustrates this relationship as an "ozone isopleth" diagram, which is analogous to a topographic map. The contour intervals, or isopleths, depicted in the figure show how ozone concentrations vary with differing VOC and NO_x emission levels. The upper right corner of the diagram represents the peak ozone value observed during the episode. The contour intervals represent predicted ozone concentrations for various combinations of reduced VOC and NO_x emissions.

During the 1995 episode used as the basis for Fig. 3, peak ozone concentrations reached 138 ppb. Thus, the upper right corner of Fig. 3 is the point at which ozone concentrations are 138 ppb, and the VOC and NO_x emissions (562 tpd and 626 tpd, respectively) are those estimated to have occurred during the episode (Table 2). For comparison, values over 124 ppb exceeded the US one-hour ozone air quality standard.

In the 1999 SIP, the Bay Area modeled the emission reductions needed to attain air quality goals by year 2000. Table 2 includes the 2000 attainment inventory, and identifies the maximum allowable on-road emissions, or transportation conformity budgets. The on-road emission numbers included in Table 2 and Fig. 3 are based on a now-outdated model (EMFAC7g).

The Bay Area updated the ozone SIP in 2001 and the on-road inventory was developed using a new model (EMFAC2000(beta)). Table 3 and Fig. 4 show results from the 2001 plan that correspond to information in Table 2 and Fig. 3. The 2001 plan also estimated emissions and concentrations for 2006. In the 2001 ozone plan, the new emission inventory assumptions increased year 1995 VOC and NO_x (peak ozone episode) emissions by 21% and 20%, respectively, compared to the 1999 ozone plan estimates. Fig. 4 is a rescaled version of the isopleth chart to account for the new inventories. The upper right corner of the figure represents the 138 ppb peak ozone value observed during the 1995 episode, and the updated episode inventory: 681 tpd VOC, 752 tpd NO_x. The VOC and NO_x tpd numbers along the horizontal and vertical axes are 21% and 20% greater, respectively, than the comparable numbers in Fig. 3, to account for the updated emission estimates.

The need for SIP Currency becomes apparent when one compares the emissions budgets established by the 1999 SIP (Table 2) with the inventory prepared for the 2001 plan (Table 3). The more recent calendar year 2000 VOC and NO_x estimates exceed the allowable budgets.

Eqs. (4) and (5) capture the relationship between the emission inventories from the two plans. These relationships assume that the ozone concentrations shown on the isopleths must match at the origin (representing natural background) and at the calibration point based on 138 ppb observed in 1995. The numerators in Eqs. (4) and (5) come from Table 2 while the denominators come from Table 3.

$$(\text{1999 plan VOC}) = (\text{2001 plan VOC}) \times (562/681) \tag{4}$$

$$(\text{1999 plan NO}_x) = (\text{2001 plan NO}_x) \times (626/752) \tag{5}$$

Table 3
San Francisco Bay Area 2001 ozone attainment plan

	Estimated on-road emissions (tpd)	Other emissions (tpd)	Estimated total emissions (tpd)
1995 observed 1-h ozone level of 138 ppb			
VOC	339.5	341.5	681
NO_x	434.2	317.8	752
2000 estimates (air quality attainment demonstration)			
VOC	238.1	315.9	554 (81% of 1995)
NO_x	352.1	295.9	648 (86% of 1995)
2006 estimates (air quality attainment demonstration)			
VOC	168.5	276.5	445 (65% of 1995)
NO_x	271.0	254.0	525 (70% of 1995)
For comparison: maximum allowable (conformity emission budgets) from Table 2			
VOC	175.2		
NO_x	247.1		

The 1995, 2000 and 2006 on-road emissions are based on an updated model (EMFAC2000(beta)), while the maximum allowable emissions are based on the outdated model (EMFAC7g).

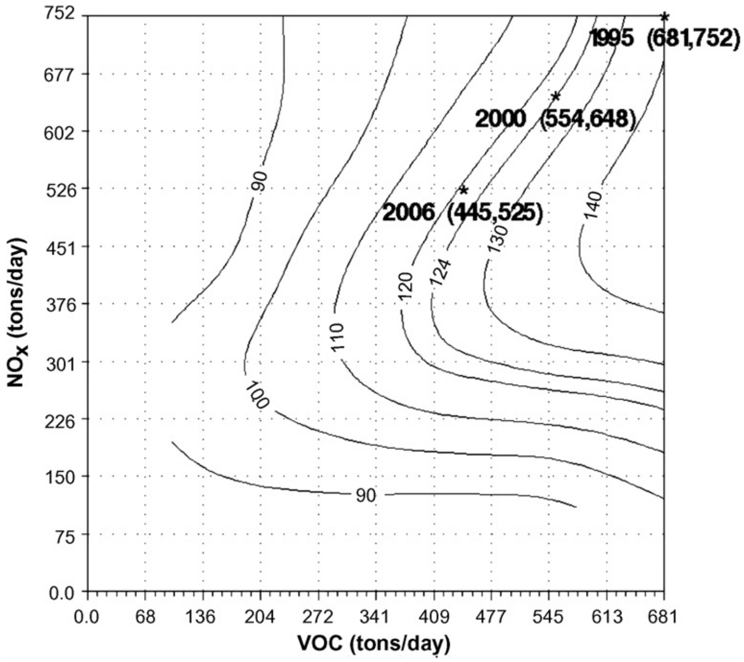

Fig. 4. Ozone isopleths from the 2001 Bay Area ozone plan depicting attainment for 2000 and 2006 (at or less than 124 ppm of ozone), and associated VOC and NOx emissions.

Table 4
SIP Currency applied to an updated Bay Area emission inventory

	VOC	NO_x
Given information		
• 2000 on-road emissions, based on outdated tool (EMFAC7g); these represent maximum allowable emissions (conformity budgets)	175	247
• 2000 on-road emissions, based on updated tool (EMAC2000(beta)); note that these emissions exceed allowable levels	238	352
Calculated information		
• 2000 on-road emissions, translating updated emissions into the "currency" of the outdated tool [derived from Eqs. (4) and (5)]	196	293

In this case, the relationships established by Eqs. (4) and (5) are used to translate the 2001 plan's emission inventory into the "currency" of the 1999 SIP. Table 4 presents the translated numbers.

Before applying SIP Currency, year 2000 on-road VOC emissions in the 2001 plan exceeded the allowable budget by 63 tons per day (238 tpd vs. 175 tpd allowable). Adjusting the newest model's (EMFAC2000(beta)) emissions back into the currency of the 1999 SIP reduced the excess emissions to 21 tpd. Note that SIP Currency did not automatically translate to meeting conformity. In this example, conformity was not met; however, the need for additional control measures was reduced once the excess emissions were scaled.

5. Conclusions

In the US, once planning assumptions and modeling tools are updated, there is a risk that transportation conformity will be impossible to demonstrate without changing the SIP. SIP amendments, however, are difficult to achieve in the short-term. The SIP Currency concepts discussed in this article offer an interim approach to improve conformity and other assessments while progress is made to amend the SIP. The examples provided here are based on creating simplified relationships between SIP budgets developed with outdated planning assumptions or models and results produced using more recent information. Although SIP Currency does not replace the need for SIP amendments, it can improve the technical quality of transportation conformity and other emissions assessments.

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