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Author
Swanson, David A

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ORIGINAL RESEARCH

A Simplified Version of the Hamilton–Perry Method for Forecasting Population by Age Group and Gender

Jeff Tayman[1] · **David A. Swanson**[2,3,4]

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Abstract
Following the concept of utility, this paper examines a way to reduce further the time and cost associated with an already cost-effective approach to population forecasting, the Hamilton–Perry method (H–P method), which not only has been found to produce reasonably accurate forecasts but has a wide range of applications, including stable population theory and historical demography. The usual application of the H–P method, H–P-Usual, is based on gender-specific CCRs and CWRs, using the female population in the childbearing years to compute the CWRs. H–P-Usual has potential drawbacks. If population forecasts by age are only needed for the total population, additional time and resources are required to assemble and evaluate the gender-specific CCRs and CWRs. More pressing, especially for subcounty areas, is the issue of small population sizes in the age and gender-specific population cells. One potential solution to these issues is reducing the number of input cells required by the H–P model. We propose a simpler H–P method, H–P-Light, that uses non-gender-specific CCRs and CWRs. We analyzed 10-year forecast errors for US counties and census tracts and found no degradation of performance using H–P-Light in both counties and census tracts. We conclude that H–P-Light is a viable alternative to H–P-Usual for producing age-specific population forecasts for the total population and, if needed, by gender.

Keywords H–P-Usual · H–P-Light · Forecast bias · Forecast accuracy · Binary error measure · County · Census tract

Introduction

Yu et al. (2023) report that population forecasts produced by governments at all levels are used in the public sector, the private sector, and by researchers. Population forecasts produced by state demographers, for example, are used by state and local

Extended author information available on the last page of the article

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governments as an important factor in the planning and budgeting of various governmental programs, services, and infrastructure (Kintner et al., 1997; Smith et al., 2013: 6–11; Swanson et al., 2023; Yu et al., 2023). Medicaid, education, and transportation form the largest share of state expenditures, and demand for all three is driven by population change (Sigritz, 2024). Like their counterparts in the private sector and at the national level, state (and local) demographers are constrained by cost and timelines. Because of these constraints, Tayman and Swanson (1996) pointed out the importance of considering the utility concept in producing population forecasts. Swanson et al. (1996) added more specificity to this issue by introducing the "triple constraint" perspective, which can be applied to population forecasting. It has three dimensions:

1. a performance specification—the explanatory/predictive precision sufficient to support a given decision-making situation;
2. time—the schedule requirements under which the performance specification must be accomplished; and
3. resources—the budget requirements under which the performance specification must be accomplished.

Conforming to the triple constraint perspective, the Hamilton–Perry (H–P) method (Hamilton & Perry, 1962) is a short-cut variant of, but algebraically equivalent to, the cohort-component method (CCM). Along with its much smaller data requirements than its more data-intensive CCM cousin, the H–P method provides forecasts of the population by age and gender, race, ethnicity, or other characteristics (e.g., Marquez et al., 2024), if so desired—making it equivalent to the CCM approach regarding output. Instead of specific rates for each component of population change, as used in the CCM, forecasts for all but the youngest age groups are based on Cohort Change Ratios (CCRs) that combine the effects of mortality and migration. Child-woman ratios (CWRs) are used instead of age-specific fertility rates for the youngest age groups. CCRs and CWRs are often obtained from the two most recent censuses, but they can be based on age distributions from any two points in time. The most often-used assumption is that CCRs and CWRs are assumed to be constant over the forecast horizon.

The H–P method requires much less time and resources than the CCM (Baker et al., 2020). Not surprisingly, it has been widely used for subcounty geographic areas where fertility, mortality, and migration data are non-existent, unreliable, or difficult to obtain (Baker et al., 2014; Marquez et al., 2024; Smith et al., 2013: 176; Swanson & Tayman, 2017; Swanson et al., 2010).[1] This method has also gained acceptance among state and local demographers, mainly because research has demonstrated its

[1] A major strength of the H–P method is that it requires only data (census, estimates, surveys, or population registers) collected by age and gender at two time points. Ten-year time points are widely used in places with decennial censuses and produce forecasts in 10-year horizons, and 5-year time points are suitable in places with quinquennial censuses and produce forecasts in 5-year horizons. (e.g., Wilson & Grossman, 2022). We are not aware of H–P applications that produce other than 5-year age group forecasts. Techniques are available for forecasting more detailed age groups and time points not generated with the H–P method (Smith et al., 2013: 272–284).

practical value and that it is capable of producing reasonable forecast error levels (Baker et al., 2020; Chen et al., 2024; Swanson & Tayman, 2017; Wilson, 2016; Wilson & Grossman, 2022). It also has proven helpful in formal demography, where it has been used to explore the field's fundamental canon, stable population theory (Swanson, 2024; Swanson et al., 2016), and its closely related derivative, the stationary population (Swanson & Tedrow, 2012). In addition, the H–P method has been used in the examination of machine learning (Baker et al., 2023), population health (Swanson et al., 2020), and historical demography (Swanson, 2019; Swanson & Verdugo, 2019). Although the H–P method has been primarily used for forecasting the populations of subcounty geographic areas, this brief review shows that it is a tool that can be used in a wide range of settings, theoretical, academic, and applied. In this paper, we evaluate a simplified version of the H–P method for a sub-national forecasting application as a heuristic device to illustrate its utility and applicability to other uses.

Although, as just mentioned, the H–P method has been primarily used for subcounty geographic areas, its minimal data requirements combined with the ability to forecast age and other demographic characteristics make it attractive for use at higher levels of geography, such as states and counties, when information about the components of population change is not needed (Hauer, 2019; Rayer & Wang, 2020; Smith & Tayman, 2003; Swanson & Tayman, 2014; Tayman et al., 2021).

Several lines of research on improving the utility of the H–P method have focused on alternative implementations, such as using synthetic adjustments of the CCRs and CWRs (Baker et al., 2020; Tayman & Swanson, 2017), using cohort change differences (CCD) in conjunction with CCRs (Hauer, 2019; Wilson & Grossman, 2022), incorporating spatial dependencies (Baker et al., 2017: Chapter 14; Baker et al., 2014), and using smoothing techniques for CCRs (Hauer, 2019; Inoue, 2017: Chapter 22; Marquez et al., 2024). In addition, it has been found that the error in H–P forecasts is reduced when the age and sex forecasts are controlled to an independent total population forecast in each geographic area (Baker et al., 2020; Tayman et al., 2021; Wilson & Grossman, 2022).

Here, we examine a new line of research in that the usual application of the H–P method, "H–P-Usual," is based on gender-specific CCRs and CWRs, using the female population in the childbearing years in the CWRs. Following this approach, the total population forecast by age is found by summing male and female forecasts by age. This strategy makes sense demographically for two reasons. First, because gender-specific CCRs indirectly capture differences in age-specific mortality and rates between males and females, and second, the female population in childbearing years used in the CWRs reflects the same population used in computing fertility rates.

However, stratifying the H–P method using gender-specific inputs does have potential drawbacks. If population forecasts by age are only needed for the total population, additional time and resources are required to assemble and evaluate the gender-specific CCR and CWR inputs. More pressing, especially for subcounty areas, is the issue of small population sizes in the age and gender-specific population cells. For example, Baker et al. (2020) eliminated 11.4% (8386) census tracts in the US if a census tract contained one or more age/gender groups with a zero population in any of three census time points used in their study. In addition, small cell sizes can lead to extreme, unrealistic values for the CCRs and CWRs, which is why it is beneficial to impose limits on H–P-Usual inputs and forecasts for small geographic areas (Swanson & Tayman, 2017; Swanson et al., 2010).

One potential solution to these issues is to reduce the number of cells the H–P model inputs require. In pursuit of such a solution, we propose a simpler H–P method, "H–P-Light," which uses CCRs calculated from the total population by age group and CWRs calculated from all adults in the childbearing years and all children, known as the Child Adult Ratio (CAR). H–P-Light reduces the input cells required for the CCRs and CARs by half, producing total population forecasts by age.

H–P-Light can also be used to forecast the population by age and gender based on the total population forecast by age. It uses the age-specific proportion of males to the total population in the launch year to generate male population forecasts by age. The female population forecast by age is derived by subtracting the male population forecast by age from the total population forecast by age. We are unaware of any published studies evaluating the error of the H–P-Light method.[2]

This paper evaluates errors from the H–P-Usual and H–P-Light forecasts. The base period for these forecasts is 1990–2000, with a 10-year forecast horizon year of 2010. Forecast errors are developed by comparing the 2010 forecasts with the 2010 decennial census counts. We examine measures of central tendency for forecast accuracy and bias and a metric that measures the percentage of geographic areas where the H–P-Light error is less than the H–P-Usual error. Previous studies of the H–P method have evaluated counties (Tayman et al., 2021) or census tracts (Baker et al., 2020) across the US. Tayman and Swanson (2017) evaluated the H–P method in the counties of Washington State and census tracts in New Mexico. This study is the first to assess H–P forecast errors for counties and census tracts across the US, allowing a more comprehensive evaluation of the efficacy of H–P-Light in the context of differential population cell sizes in counties and census tracts, a widely used subcounty geographic area.

Data

Counties

The county data came from the National Historic GIS Database (NHGIS) (Manson et al., 2024). Out of a universe of 3140 counties in the US, our data consist of 3106 counties or county-equivalents whose geographic boundaries remained constant

[2] One author used the H–P-Light method to prepare age- and gender-specific population forecasts from 2020 to 2040 for 1274 census tracts in Arizona as input to a model forecasting college students' future supply and demand. A post-hoc analysis of 10-year forecasts was conducted to evaluate whether the H–P-Light forecasts were suitable. That analysis compared H–P-Usual and H–P-Light forecasts using a measure of forecast precision known as the Median Absolute Percent Error (MedApe). The MedApes were similar in the H–P-Usual and H–P-Light forecasts; however, the H–P-Light forecast had greater precision in roughly 80% of total, male, and female population forecasts by age group.

from 1990 to 2010.[3] We collected 1990, 2000, and 2010 census data for 18 5-year age groups (0–4, 5–9…., 80–84, and 85 years and older) for males and females. Aside from boundary changes, implementing the H–P method is impacted by zero population counts. CCRs, CWRs, and CARs are undefined if the denominator of these ratios is zero. At the county level of geography, zero population counts are much less of a problem than for subcounty areas such as census tracts, as discussed in the next section. We encountered only 68 zero cells in the age and gender data for all three census points and assigned them a value of one.

Table 1 contains statistics that measure the population size characteristics in counties by census year. County population size characteristics show modest change over the 20 years. The average population size increase from 1990 to 2010 is similar for the total population and males and females, rising between 23 and 25%. The changes in the percentages for the selected age groups are more stable than those regarding the population size. Small population cell sizes (<25 and 25–49) are relatively infrequent, and over 90% of the age/gender cells have at least 100 persons. The advantage of H–P-Light in terms of cell population size is evident. As expected, there are proportionately more cells with small populations for males and females than the total population. The male and female percentages of the population in cells with under 50 persons are 47% to 280% higher than those for the total population for the three

[3] The 34 excluded counties are (1) all 27 boroughs in Alaska; (2) Adams, Boulder, Broomfield, Jefferson, and Weld counties in Colorado; and (3) Alleghany and Halifax counties in Virginia.

Table 1 County population size, 1990–2010

	Total	Male	Female
1990			
Average	4408	2148	2259
Median	1124	534	640
% under 25	0.4%	1.5%	1.1%
% 25–49	0.7%	2.5%	1.7%
% 50–99	1.9%	6.3%	4.8%
%100+	96.9%	89.7%	92.4%
2000			
Average	4987	2446	2541
Median	1271	615	716
% under 25	0.4%	1.3%	1.0%
% 25–49	0.7%	2.4%	1.7%
% 50–99	1.8%	5.9%	4.6%
%100+	97.1%	90.4%	92.7%
2010			
Average	5470	2689	2781
Median	1359	668	754
% under 25	0.3%	1.3%	1.1%
% 25–49	0.8%	2.4%	1.9%
% 50–99	2.0%	5.5%	4.6%
%100+	96.9%	90.8%	92.4%

Population size in each of the 18 age groupings census time points. Conversely, the percentage of cells with 100 or more persons for the total population is roughly 97%, about seven percentage points higher than the male population and about five percentage points higher than the female population.

Census Tracts

The census tract data also came from NHGIS. This source provides population counts in 5-year age/gender-specific groupings with data for 1990, 2000, and 2010, normalized to 2010 census tract boundaries using block-level re-aggregations and interpolations. The method is described at: https://www.nhgis.org/documentation/time-series.[4] This data set contains 73,057 census tracts covering all 50 states and the District of Columbia. For males and females, we collected census data for 18 5-year age groups (0–4, 5–9…., 80–84, and 85 years and older).

As noted earlier, zero population counts create issues for the H–P method, which are problematic for census tract geography. Zero population cells account for between 1 and 2% of all age/gender-specific cells from 1990 to 2010, but the percentage decreased from 1990, where it was 1.8% (average of the percent for the total, male, and female population) to 1.2% in 2010. In terms of the number of cells involved, in 1990, the sum of the zero population cells for the total and by gender was 67,500. By 2010, that sum has dropped to 43,733. Unlike the counties, we did not change the original data in these zero-population cells to one. If the denominator is zero, we set the CCRs, CWRs, and CARs to zero during the computation of the ratios.

Table 2 contains statistics that measure the population size characteristics of census tracts by census year. Like the counties, population size characteristics for census tracts show modest change over the 20 years. Unlike the counties, the changes in the census tract percentages for the selected age groups are less stable than those regarding the population size. The relative number of cells with small population cell sizes (<25 and 25–49) in 1990 ranges from 16% for the total population to 34% for females. By 2010, these figures dropped to 9% and 30%, respectively—conversely, the relative number of cells with at least 100 persons increased over the 20 years. In 1990, the percentage of all cells ranged from 38% for males to 69% for the total population. By 2010, these figures increase to 49% and 78%, respectively.

The advantage of H–P-Light, in terms of cell population size, is evident for census tracts. As expected, there are proportionately more cells with small populations for males and females than the total population. The male and female percentages of the population in cells with under 50 persons are 58% to 150% higher than those for the total population for the three census time points. Conversely, the percentage of cells with 100 or more persons for the total population averages 74% for the three census years, about 30 percentage points higher than the male population and about 27 percentage points higher than the female population.

[4] At this time, NHGIS's standardized time series tables provide data for 2010 census units. (hgis.org/time-series-tables#nominal-integration).

Table 2 Census tract population size, 1990–2010

Population size in each of the 18 age groupings

	Total	Male	Female
1990			
Average	189	92	97
Median	163	78	85
% Under 25	9.5%	19.4%	15.0%
% 25–49	6.8%	14.5%	13.7%
% 50–99	14.3%	28.4%	30.3%
%100+	69.3%	37.8%	41.0%
2000			
Average	214	105	109
Median	186	90	96
% Under 25	5.9%	15.0%	10.5%
% 25–49	5.8%	13.7%	12.8%
% 50–99	13.4%	27.0%	29.4%
%100+	74.8%	44.6%	47.5%
2010			
Average	235	115	119
Median	203	99	103
% Under 25	3.9%	11.5%	7.9%
% 25–49	5.0%	12.9%	12.2%
% 50–99	12.7%	26.3%	28.3%
%100+	78.4%	49.2%	51.6%

Methods

H–P-Usual

The H–P-Usual method is used to forecast the population by age and gender using gender-specific CCRs and CWRs. Age-specific forecasts are first produced for each gender, which are then added to produce age-specific forecasts for the total population. These initial age- and gender-specific forecasts are controlled to an independent total population forecast for each county and census tract. The controlled age- and gender-specific forecasts are added to create before the age-specific total population forecast.

A CCR is the ratio of a cohort's population to its size 10 years earlier when it was 10 years younger. The CCRs are applied to the appropriate launch year population to move them into the future. As shown by Baker et al. (2017: 45–49), the formula for developing forecasts based on the CCR is:[5]

$$_nCCR_{x,g,t} = {_nP_{x,g,t}} / {_nP_{x-k,g,t-10}}. \quad (1)$$

where $_nP_{x,g,t}$ is the population ages x to $x+n$ for gender (g) at the most recent census (t) (i.e., 2000), $_nP_{x-k,g,t-k}$ is the population ages $x-k$ to $x-k+n$ for gender (g) at the

[5] The width of the age group n does not have to equal the time interval k, but n must be evenly divisible into k.

2nd most recent census (i.e., 1990) ($t-k$), and k is the years between the most recent census at time t and the one preceding it at time $t-k$ (i.e., 10 years).

The formula for moving the population cohorts into the future is:

$$ {}_nP_{x,g,t+k} = {}_nCCR_{x,g,\mathrm{t}} \times {}_nP_{x-k,g,t} \quad (2) $$

where ${}_nP_{x,g,t+k}$ is the population ages x to $x + n$ for gender (g = *1 males* and *2* = *females*) at time $t+k$, ${}_nP_{x-k,g,\mathrm{t}}$ is the population 10 years younger than the CCR age group, and ${}_nCCR_{x,g,t}$ is defined in Eq. (1).

Forecasts for the oldest open-ended age group differ slightly from the forecasts for the age groups beyond age ten up to the oldest open-ended age group. Our terminal age group is ages 85 and older, and calculations for its CCR require the summation of the three oldest age groups (75–79, 80–84, and 85+) to get the population age 75+ at time $t-k$:

$$ CCR_{75+,g,t} = P_{85+,g,t} / P_{75+,g,t-k}. \quad (3) $$

The formula for forecasting the population ages 85+ for gender *(g)* for the year $t+k$ is:

$$ P_{85+,g,t+k} = CCR_{75+,g,t} \times P_{75+,g,t}. \quad (4) $$

Given the nature of the CCRs, 10–14 is the youngest 5-year age group for which forecasts can be made when there are 10 years between censuses. To project the population ages 0–4 and 5–9 with H–P-Usual, we use four CWRs (2 each for males and females), which do not require any data beyond what is available in the decennial census. For the population ages 0–4, the CWR0-4 is defined as the gender-specific population ages 0–4 divided by the female population ages 15–44, and for the population ages 5–9, the CWR5-9 is defined as the gender-specific population ages 5–9 divided by the female population ages 20–49 (Smith et al., 2013: 178). The CWRs are based on the launch year data point, and their formulae are:

$$ CWR0\text{-}4_{1,t} = {}_5P_{0,1,t} / {}_{30}P_{15,2,t}, \quad (5) $$

and

$$ CWR0\text{-}4_{2,t} = {}_5P_{0,2,t} / {}_{30}P_{15,2,t}, \quad (6) $$

$$ CWR5\text{-}9_{1,t} = {}_5P_{5,1,t} / {}_{30}P_{20,2,t}, \quad (7) $$

$$ CWR5\text{-}9_{2,t} = {}_5P_{5,2,t} / {}_{30}P_{20,2,t}. \quad (8) $$

The forecasted gender-specific population ages 0–9 is computed by applying the CWRs to the forecasted female population in the appropriate childbearing ages) at $t+k$ from Eq. (2):

$$ {}_5P_{0,1,t+k} = CWR0\text{-}4_{1,t} \times_{30} P_{15,2,t+k}, \quad (9) $$

$$ {}_5P_{0,2,t+k} = CWR0\text{-}4_{2,t} \times_{30} P_{15,2,t+k}, \quad (10) $$

$$ {}_5P_{5,1,t+k} = CWR5\text{-}9_{1,t} \times_{30} P_{20,2,t+k}, \quad (11) $$

and

$$ {}_5P_{5,g,t+k} = CWR5\text{-}9_{2,t} \times_{30} P_{20,2,t+k}. \quad (12) $$

Finally, the total population forecast by age is:

$$ {}_nP_{x,t+k} =_n P_{x,1,t+k} +_n P_{x,2,t+k} \quad (13) $$

H–P-Light

H–P-Light uses non-gender specific CCRs and CARs instead of CWRs, and, as discussed above, half of the data cells required for the H–P-Usual method are required. The CCR formulas shown in equations (1) through (4) pertain only to the total population and are not specific to gender. The CCR computations for H–P-Light are:

$$ {}_nCCR_{x,t} =_n P_{x,t}/{}_nP_{x-k,t-10} \quad (14) $$

and

$$ CCR_{75+,t} = P_{85+,t}/\, P_{75,t-k}. \quad (15) $$

The forecasts for the total population for ages 10 through 85 and older are given by:

$$ {}_nP_{x,t+k} =_n CCR_{x,t} \times_n P_{x-k,t} \quad (16) $$

and

$$ P_{85+,t+k} = CCR_{75+,t} \times P_{75,t}. \quad (17) $$

To project the total population ages 0–4 and 5–9 with H–P-Light only requires two CARs. For the population ages 0–4, the CAR0-4 is defined as the total population ages 0–4 divided by the total population ages 15–44, and for the population ages 5–9, the CAR5-9 is defined as the total population ages 5–9 divided by the total population ages 20–49:

$$ CAR0\text{-}4_t =_5 P_{0,t}/{}_{30}P_{15,t} \quad (18) $$

and

$$CAR5\text{-}9_t = {}_5P_{5,t}/{}_{30}P_{20,t}. \tag{19}$$

The forecasted total population ages 0–10 is computed by applying the CARs to the forecasted total population) at $t+k$ from Eq. (12) by:

$${}_5P_{0,t+k} = CAR0\text{-}4_t \times {}_{44}P_{15,t+k} \tag{20}$$

and

$${}_5P_{5,t+k} = CAR5\text{-}9_t \times {}_{49}P_{20,t+k}. \tag{21}$$

No further computations beyond equation (14) through (21) are required if only a forecast of the total population by age group is required. We controlled the initial age-specific total population forecast to an independent total population forecast for each county and census tract.

H–P-Light can also be used to forecast the population by age and gender based on a total population forecast by age. It uses the age-specific proportion of males to the total population in the launch year (MALEPROP) and applies it to the total population forecast by age to generate a male population forecast by age.[6] The female population forecast by age is derived by subtracting the male population by age from the total population by age. The equations for generating the gender-specific forecast in H–P-Light are:

$${}_nMALEPROP_{x,t} = {}_nP_{x,1,t}/{}_nP_{x,t}, \tag{22}$$

$${}_nP_{x,1,t+k} = {}_xP_{n,t+k} \times {}_nMALEPROP_{x,t}, \tag{23}$$

and

$${}_nP_{x,2,t+k} = {}_xP_{n,t+k} - {}_nP_{x,1,t+k}. \tag{24}$$

Limits on H–P Inputs for Census Tracts

The variability inherent in small population counts can also lead to abnormally large or small CCRs, CWRs, and CARs.[7] For this study, we make general adjustments

[6] Due to sex differentials at births and in survival rates, the MALEPROP has a typical age pattern. There is an excess of males at the younger ages (<age 20), general parity between the genders (ages 20 to 59), and a non-linear increase in the excess of females after the age of 60. Places with special populations like the military, colleges, and prisons can impact this general pattern.

[7] No adjustments are made to MALEPROP for either counties or census tracts. The MALEPROP ranges from 0.0 to 1.0, and the male forecast by age group is constrained by the forecast of the total population in each age group. Also, the resulting value of MALEPROP has a narrow range. For counties, 98% of the MALEPOPS are between 0.4 and 0.6; for census tracts, the corresponding figure is 93%. A widened range of 0.3 to 0.7 represents 98% of the census tracts.

to the census tract data to address these issues.[8] These are generalized adjustments based on the age and age/gender percentage frequency distributions of the CCRs, CARs, and CWRs. Generally, categories with less than 5% of the observations are raised or lowered to preset values, as described below. The CCRs used in the forecast alternatives are set at a maximum value of 2.5 and a minimum of 0.5 for all but the oldest age group. The minimum for the oldest age group (75+) is set at 0.3 because over 30% of the cells for this age group had CCRs between 0.3 and 0.5. The CWRs and CARs used in the forecast alternatives are set at a maximum value of 0.25 and a minimum of 0.1.

This paper focuses on comparing the errors from H–P-Usual to H–P-Light and not producing the most accurate H–P forecast. Different adjustment strategies and a closer inspection of the census tract H–P inputs would be warranted in the latter case. Such adjustment strategies could include using county-level CCRs, using CCRs from an aggregation of census tracts around the census tract in question, and/or setting upper and lower limits on the total population size used as a control (Swanson et al., 2010; Tayman, 1996).

The number of census tract cells requiring limits on the CCRs is not trivial. Almost 72,000 cells (6.1% of all cells) are adjusted for the CCRs based on the total population used in H–P-Light (see Table 3). More than double the number of cells exceeds the upper limit (2.5) compared to the number below the lower limit (0.5). H–P-Light's advantage in adjusting cells for abnormal CCRs is evident as the number and percentage of cells requiring adjustments for males and females used in H–P-Usual (152,253 = 67,258 + 84,995) is 113% more than adjusted for H–P-Light. More female than male population cells require adjustments of 84,995 and 67,258, respectively. For both genders, the number of cells exceeding the upper limit is greater than those below the lower limit.[9] However, the difference is much greater for males (50,795 above and 16,463 below) than for females (49,741 above and 35,254 below).

Table 3 Adjusted 2000/1990 CCRs, census tracts

CCRs	Total	Male	Female
Cell counts			
<0.5	21,568	16,463	35,254
Over 2.5	50,061	50,795	49,741
All adjustments	71,629	67,258	84,995
Pct. all cells (1,168,912)			
<0.5	1.8%	1.4%	3.0%
Over 2.5	4.3%	4.3%	4.3%
All adjustments	6.1%	5.7%	7.3%

[8] No limits are put on the H–P model inputs for the counties, as very few CCRs, CWRs, and CARs appear to be outside reasonable limits. For example, the CCRs for the 18 age groups are greater than 2.5 in only 131, 148, and 168 cells for the total population, males and females, respectively, representing around 0.3% of all cells. The CWRs are greater than 0.25 in only 48 and 68 cells for males and females, respectively, representing around 0.8% of all cells, while the CARs exceed that value in only 49 cells.

[9] We realize there are more than two genders and that the more inclusive term "all genders" might be preferable by many. We use "both genders" to be consistent with the data that only include "male" and "female" categories for gender.

In percentage terms, more adjustments are made to the CWRs and CARs compared to the CCRs (see Table 4.) Almost 16,000 cells (10.8% of all cells) are adjusted for the CARs used in H–P-Light. However, unlike the CCRs, more adjusted cells are below the lower limit (9833) than are above the upper limit (5915). The advantage of H–P-Light in terms of adjusting cells for abnormal CWRs used in H–P-Usual is evident, as the number of cells requiring adjustments for males and females (37,266 = 21,424 + 15,842) is 136% more than the number adjusted for H–P-Light. Unlike the CCRs, fewer female population cells require adjustment (15,842) than males (21,424). The number of cells exceeding the upper limit is greater for males than those below the lower limit (12,882 above and 8542 below), but the opposite occurs for females (6383 above and 9459 below).

Control Totals

An independent forecast of the 2010 total population for each county and census is needed to create the controlled forecasts. The base period for these forecasts is 1990–2000. An average of multiple extrapolation methods is used to generate the control totals. Though simple in design, trend extrapolation techniques have been found to produce forecasts of the total population that are at least as accurate as those produced by more complex methods (Green & Armstrong, 2015; Smith et al., 2013: 331–336; Rayer et al., 2009), and that a combination of methods often leads to more accurate forecasts than a single method (Armstrong, 2006; Wang et al., 2023).

Five simple extrapolation methods are used to construct an independent 2010 total population forecast for counties. The first method keeps the population constant at its 2000 level. The second method assumes the population from 2000 to 2010 changes at the same numeric amount as during the base period (1990–2000). The third method assumes that the population from 2000 to 2010 changes at the same percentage as during the base period. The fourth method assumes the county's share of the state population change in the base period is the same between 2000 and 2010. The final method assumes that the county change share of the state's population change during the base period will be the same between 2000 and 2010. The 2010 total population control for counties is the average of the five extrapolation methods. The decennial censuses provide the state-level CCRS and CWRs for 1990 and 2000. To represent an actual forecasting situation, we used 2010 state forecasts by age and gender released by the US Census Bureau in 2005 obtained from the Center for Disease Control's WONDER data platform (https://wonder.cdc.gov/population-projections.html).

Table 4 Adjusted 2000 CARs and CWRs, census tracts

Ratio	Total CAR	Male CWR	Female CWR
Cell counts			
< 0.1	9833	8542	9459
Over 0.25	5915	12,882	6383
All Adjustments	15,748	21,424	15,842
Pct. all cells (146,114)			
< 0.5	6.7%	5.8%	6.5%
Over 0.25	4.0%	8.8%	4.4%
All Adjustments	10.8%	14.7%	10.8%

Independent 2010 total population forecasts for census tracts are based on the average of the first two simple extrapolation techniques mentioned above: (1) keeping the population constant at its 2000 level and (2) assuming the linear change from 1990 to 2000 occurs between 2000 and 2010. The 2010 tract total population control total for census tracts is the average of the two extrapolation methods.

Error Measures

Forecast error is the difference between the 2010 forecast alternative and the 2010 census count. We examine the algebraic percent error (ALPE), which measures forecast bias. A negative ALPE indicates the forecast is too low, and a positive ALPE indicates the forecast is too high. We also examine the absolute percent error (APE), which measures forecast accuracy or precision. Percentage errors allow us to summarize errors while minimizing the known effects of population size on ex post facto error calculations (Smith, 1987).

We examine measures of central tendency for forecast accuracy and bias. The arithmetic average of the APEs (MAPE) measures forecast precision in which positive and negative errors do not offset each other. The arithmetic average of the ALPEs (MALPE) measures forecast bias in which the positive and negative errors offset each other. Like any average, the MAPE and, to a lesser extent, the MALPE can be unduly influenced by outlying errors (Baker et al., 2020; Tayman & Swanson, 1999). So, this paper focuses on the median of the ALPEs (MedALPE) and the median of the APEs (MedAPE) as the central tendency measures of forecast bias and precision. Appendix Tables 11 and 12 contain error measures based on the MALPE and MAPE to allow comparison to other studies using these metrics.

We also examine the relative performance of H–P-Usual and H–P-Light using a binary non-parametric measure that quantifies the number and percentage of counties or census tracts where the APE in H–P-Usual is greater than or equal to the APE in H–P-Light or the APE in H–P-Usual less than the APE in H–P-Light. Tayman et al. (2021) used the same binary comparison measure.

Forecast Error Analysis

We begin the analysis by examining forecast errors for the total population to show the differences between errors between population controls and population totals if controls are not instituted. This analysis uses the uncontrolled total population forecast from the two H–P alternatives. The remainder of the analysis uses only the controlled forecast to explore forecast errors by age and gender and, finally, forecast errors by population size and growth rate.

Total Population Forecast Error

County

Not surprisingly, the total population control has less bias and greater precision than the population totals from the uncontrolled H–P alternatives for the counties (see Table 5). The control total MALPE (1.7%) is 60% lower than the MALPEs for H–P-Usual and H–P-Light, and the controlled MAPE (6.0%) is 23% lower than the MAPEs for H–P-Usual and H–P-Light. There is no difference in the amount of forecast bias and level of forecast precision in the total population between H–P-Usual and H–P-Light, as the MAPEs and MALPEs are virtually identical. Notable is that the MAPEs for all alternatives are significantly lower than the typical MAPE for 10-year forecasts for counties (12%) (Smith et al., 2013: 365).

The control total has fewer outlying errors than either H–P alternative. Regarding bias, the MALPE is only 0.1 percentage point or 9% larger than the MedALPE, smaller than the differences seen in H–P-Usual, 55% larger MALPE, and H–P-Light, 48% larger MALPE. The impact of outliers is more significant in precision measures, consistent with APEs having only a positive range starting at zero. The control total MAPE is only 1.6 percentage points or 36% larger than the MedAPE, smaller than the 50% differences seen in H–P-Usual and H–P-Light. The absolute percent error distribution further highlights the impact of outliers between the control total alternative and the H–P alternatives. The error distributions are virtually identical for H–P-Usual and H–P-Light, which have a greater proportion of larger errors than the control total. Seven percent of the APEs are 15% or higher for the total population control, compared to around 12% for the two H–P alternatives. Conversely, 84% of the APEs in the population control alternative are less than 10%, compared to 75% for the two H–P alternatives.

Table 5 County total population forecast errors, control total, H–P-usual, and H–P-light

	Bias[a]				Precision[b]		
	Control[c]	H–P-Usual	H–P-Light		Control[c]	H–P-Usual	H–P-Light
MALPE	1.7%	4.3%	4.3%	MAPE	6.0%	7.8%	7.8%
MedALPE	1.6%	2.8%	2.9%	MedAPE	4.4%	5.2%	5.2%

	Absolute percent error distribution		
	Control[c]	H–P-Usual	H–P-Light
Under 5%	56.0%	48.9%	48.6%
5.0–9.9%	27.8%	25.8%	25.9%
10.0–14.9%	9.1%	12.7%	13.0%
15.0–19.9%	5.5%	8.9%	8.7%
20.0–29.9%	0.7%	1.2%	1.3%
30%+	0.8%	2.6%	2.6%
	100.0%	100.0%	100.0%

Based on the H–P model not adjusted to the county total population control total

[a]Based on the algebraic percentage error

[b]Based on the absolute value of the algebraic percentage error

[c]Based on the average of five simple extrapolation techniques described in the control total section

Census Tract

The population control has less bias and greater precision than the population totals from the uncontrolled H–P models for the census tracts (see Table 6). Still, not surprisingly, there is more bias and less precision in the census tract forecasts compared to the county forecasts. The control total MALPE (1.8%) is dramatically lower than the MALPEs for H–P-Usual (11.1%) and H–P-Light (11.3%), and the control total MAPE (15.2%) is 33% lower than the MALPEs for H–P-Usual and H–P-Light (22.7%). There is no difference in the amount of forecast bias and level of forecast precision in the total population between H–P-Usual and H–P-Light, as the MAPEs and MALPEs are virtually identical. The MAPE for the population control alternative is somewhat lower than the typical MAPE for 10-year forecasts for census tracts (18%) (Smith et al., 2013: 365), but the MAPEs for both H–P alternatives are roughly 28% larger than the typical MAPE for census tract.

Outlying errors are a more significant issue for census tracts. The control total has fewer outlying errors than either H–P alternative. Regarding bias, the MALPE is one percentage point or 125% larger than the MedALPE, smaller than the differences seen in H–P-Usual, 214% larger MALPE, and H–P-Light, 247% larger MALPE. The impact of outliers is more significant in precision measures, consistent with APEs having only a positive range starting at zero. The control total MAPE is 8.1 percentage points, or 114%, larger than the MedAPE slightly lower than the 120% differences seen in H–P-Usual and H–P-Light. The absolute percent error distribution further highlights the impact of outliers between the control total alternative and the H–P alternatives. The error distributions are virtually identical for H–P-Usual and H–P-Light, which have a greater proportion of larger errors than the control total. Thirteen percent of the APEs are 25% or higher for the total population control, compared to around 22% for the two H–P alternatives. Conversely, 63% of the

Table 6 Census tract total population forecast errors, control total, H–P-usual, and H–P-light

	Bias[a]				Precision[b]		
	Control[c]	H–P-Usual	H–P-Light		Control[c]	H–P-Usual	H–P-Light
MALPE	1.8%	11.3%	11.1%	MAPE	15.2%	22.7%	22.7%
MedALPE	0.8%	3.6%	3.2%	MedAPE	7.1%	10.3%	10.3%

	Absolute percent error distribution		
	Control[c]	H–P-Usual	H–P-Light
Under 5%	38.4%	27.3%	27.4%
5.0–9.9%	24.2%	21.6%	21.6%
10.0–14.9%	13.1%	14.0%	14.0%
15.0–24.9%	11.8%	15.2%	15.2%
25.0–49.9%	8.4%	13.4%	13.2%
50%+	4.1%	8.6%	8.6%
	100.0%	100.0%	100.0%

Based on the H–P model not adjusted to the census tract total population control total

[a]Based on the algebraic percentage error

[b]Based on the absolute value of the algebraic percentage error

[c]Based on the average of two simple extrapolation techniques described in the control total section

APEs in the population control are less than 10%, compared to 49% for the two H–P alternatives.

Age Group and Gender Forecast Error

We initially constructed the forecast for 17 5-year age groups and a terminal age group of 85 years and older, but we evaluated forecast errors using a reduced set of seven groups. These groups cover the entire age spectrum, adequately capture the age-specific performance of the alternatives, and make the analysis easier to follow. The seven age groups are younger than age 10 (hereafter < 10), 10–19, 20–34, 35–54, 55–64, 65–74, and 75 years and older (hereafter 75 +). As a composite measure of the age group accuracy and bias, we also compute the arithmetic average of the ALPEs and APEs across the seven age groups for each county and census tract.

County

Table 7 presents the MedALPE and MedAPE by age group for the total population, males and females for the county population forecasts. This table also contains summary statistics for the average error across age groups and the total population. Appendix Table 11 includes the corresponding table showing the MALPE and MAPE.

The amount of bias in the age-specific county forecasts for the total population is comparable between H–P-Usual and H–P-Light; except for age group < 10, the numeric differences in MedALPE range from 0.0 to 0.3 percentage points, but the MedALPE for H–P-Light is never larger than the MedALPE for H–P-Usual. The largest variance is in the age group < 10, where the MedALPE for H–P-Light is 57% lower. A similar pattern of bias is seen in the male population, but the differences between H–P-Usual and H–P-Light are larger than seen in the total population. Except for the age group 75 +, the differences range from 0.1 to 1.1 percentage points; the difference for the age group 75 + is 4.8. Unlike the total population, the bias in H–P-Light is larger for the age group 55–64 (MedALPE 0.4% vs. 0.3%) and the average over the age groups (MedALPE 0.7% vs. 0.1%). In general, the amount of bias in the female population is also comparable between H–P-Usual and H–P-Light, but the differences between H–P-Usual and H–P-Light fall between the total and male population. The differences range from 0.2 to 2.6 percentage points. Also, the bias is less for H–P-Usual in all age groups, except for age group < 10 and the average across age groups.

The amount of precision in the age-specific county forecasts for the total population is more comparable between H–P-Usual and H–P-Light compared to bias; the numeric differences in MedAPE range from 0.0 to 0.2 percentage points, but the MedAPE for H–P-Light is never larger than the MedAPE for H–P-Usual. A similar pattern of precision is seen in the male population, but the differences between H–P-Usual and H–P-Light are larger than in the total population. Except for the age group 75 +, the differences range from 0.2 to 1.3 percentage points; the difference for the age group 75 + is 3.7. For males, the MedAPE for H–P-Light is never larger than the MedALPE for H–P-Usual. In general, the amount of precision in the female population is comparable between H–P-Usual and H–P-Light, but the differences

Table 7 County forecast error by age and gender

Age group	MedALPE			MedAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
Total population						
< 10	− 2.1%	− 0.9%	− 57.1%	7.3%	7.1%	− 2.7%
10–19	3.5%	3.4%	− 2.9%	6.2%	6.1%	− 1.6%
20–34	4.7%	4.4%	− 6.4%	8.4%	8.3%	− 1.2%
35–54	2.7%	2.6%	− 3.7%	5.1%	5.0%	− 2.0%
55–64	0.5%	0.4%	− 20.0%	4.4%	4.3%	− 2.3%
65–74	− 2.6%	− 2.6%	0.0%	4.6%	4.6%	0.0%
75 +	− 4.0%	− 3.8%	− 3.8%	6.1%	5.9%	− 3.3%
Avg age groups[a]	0.7%	0.7%	0.0%	6.6%	6.6%	0.0%
Total	1.6%	1.6%	0.0%	4.4%	4.4%	0.0%
Male population						
< 10	− 2.0%	− 1.0%	− 50.0%	7.4%	7.1%	− 4.1%
10–19	3.6%	3.4%	− 5.6%	6.4%	6.1%	− 4.7%
20–34	4.8%	4.4%	− 8.3%	9.1%	8.3%	− 8.8%
35–54	3.1%	2.6%	− 16.1%	5.8%	5.0%	− 13.8%
55–64	0.3%	0.4%	33.3%	4.8%	4.3%	− 10.4%
65–74	− 3.7%	− 2.6%	− 29.7%	5.7%	4.6%	− 19.3%
75 +	− 8.8%	− 4.0%	− 54.5%	9.6%	5.9%	− 39.1%
Avg age groups[a]	0.1%	0.7%	600.0%	7.8%	6.5%	− 8.3%
Total male	1.4%	1.7%	21.4%	4.6%	4.4%	− 4.3%
Female population						
< 10	− 2.2%	− 1.0%	− 54.5%	7.5%	7.1%	− 4.7%
10–19	3.2%	3.4%	6.3%	6.2%	6.1%	− 1.6%
20–34	4.2%	4.5%	7.1%	7.8%	8.3%	6.4%
35–54	2.1%	2.6%	23.8%	4.8%	5.0%	4.2%
55–64	0.2%	0.4%	100.0%	4.5%	4.3%	− 4.4%
65–74	− 2.0%	− 2.6%	30.0%	4.5%	4.6%	2.2%
75 +	− 0.9%	− 3.5%	288.9%	5.7%	6.0%	6.2%
Avg age groups[a]	1.1%	0.8%	− 27.3%	6.6%	6.6%	0.0%
Total female	1.6%	1.5%	− 6.3%	4.2%	4.3%	2.4%

Average of the APEs over the seven age categories in each county

between H–P-Usual and H–P-Light fall between the total and male population. The differences range from 0.0 to 0.5 percentage points. Also, for females, the precision is greater for H–P-Usual in most comparisons, except for age groups < 10, 10–19, and 55–64.

We next examine the relative performance of H–P-Usual and H–P-Light using a non-parametric measure that quantifies the percentage of counties where APE in H–P-Light is less than or equal to the APE in H–P-Usual. It is clear from Fig. 1 that using this criterion, H–P-Light outperforms H–P-Usual in the total and male populations but less so for females. The percentage is above 50% in all categories for the total population (54% to 70% of the counties) and male population (55% to 82%). For females, the percentage is at or below 50% in 5 categories (44% to 50% of all counties) and is marginally above 50% in 3 categories (54% to 56%).

Fig. 1 Percentage of counties with lower H–P-Light APE by age

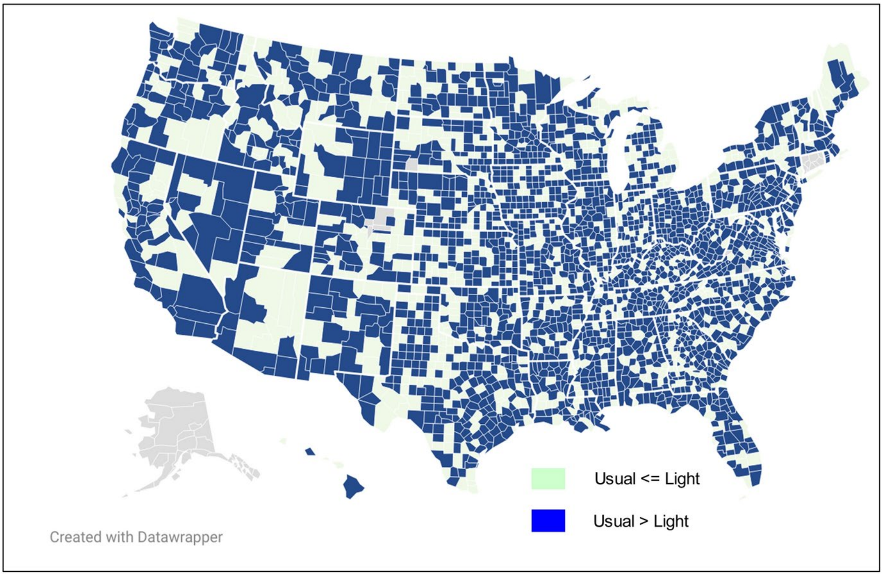

Fig. 2 Comparing H–P-Usual and H–P-Light, total population average age group APE

To provide a geographic perspective on the relative performance in terms of precision of H–P-Usual and H–P-Light, we present three choropleth maps of US counties containing information for the total population (See Fig. 2), male population (see Fig. 3) and female population (see Fig. 4). These maps are based on the average of APEs across the age groups and show counties where this average is larger for H–P-Usual compared to H–P-Light or less than or equal for H–P-Usual compared to H–P-Light.

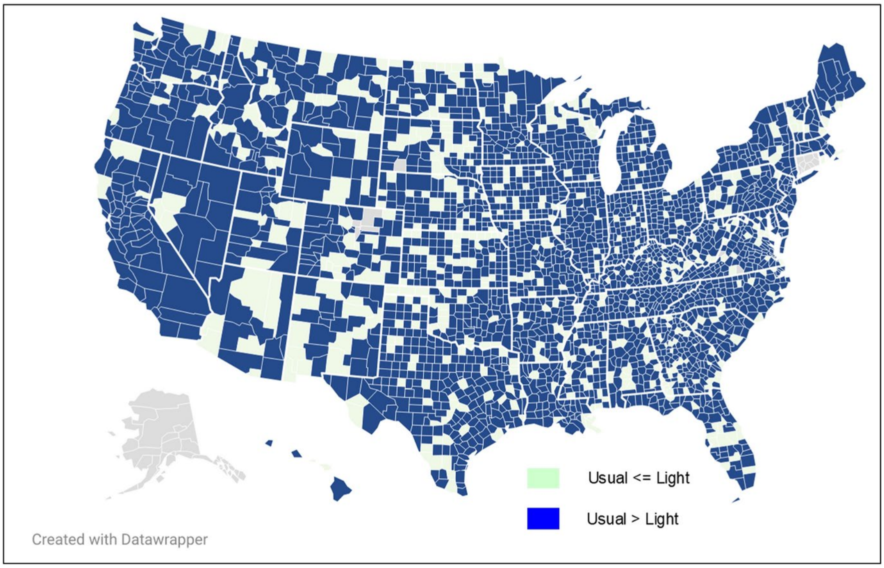

Fig. 3 Comparing H–P-Usual and H–P-Light, male population average age group APE

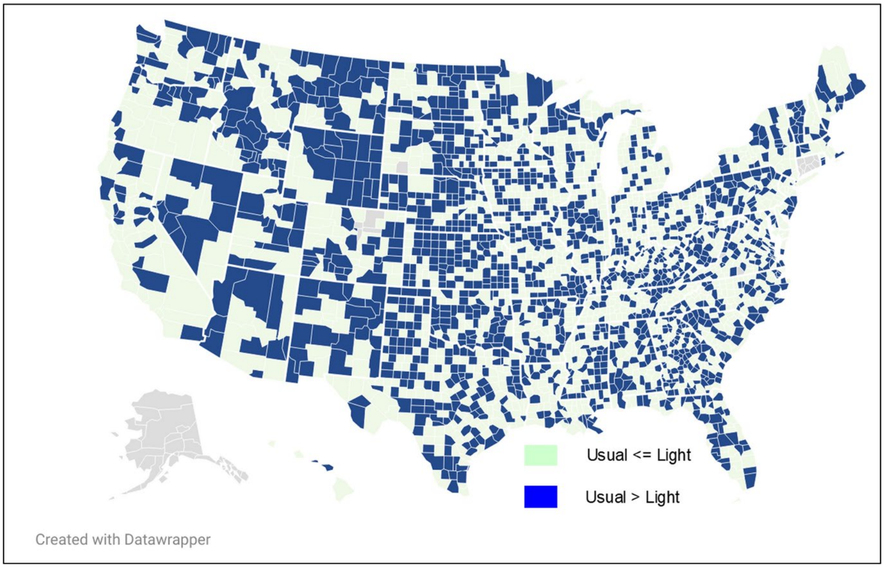

Fig. 4 Comparing H–P-Usual and H–P-Light, female population average age group APE

For the total population, H–P-Light has greater precision across age groups in 70% of the counties. Figure 2 shows a relatively random pattern of these counties across the US. For the male population, H–P-Light has greater precision across age groups in 82% of the counties. Figure 3 also shows a relatively random pattern of these counties across the US. The improvement of H–P-Light for males compared to the total population is widespread across the U.S. Delaware, Mississippi, West Virginia, New Mexico, and Rhode Island are the only states with more counties showing less precision for H–P-Light for males than for the total population, ranging from 3.7% to 9.1% of the counties in these states. Counties in 44 states show greater precision for H–P-Light, ranging from 20 to 39% of the counties in 10 states, 10% to 20% in 18 states, and less than 10% in 16 states.

H–P-Light has greater precision across age groups in 50% of the counties for the female population. Figure 4 also shows a relatively random pattern of these counties across the US, but clearly, there is a much greater predominance of counties where the H–P-Usual has greater precision across age groups. The improvement of H–P-Usual for females is widespread. Only 11 states have more counties with greater or equal precision for H–P-Light for females than the total population, ranging from 2 to 29% of the counties in these states. Counties in 38 states show less precision for H–P-Light for females than the total population, ranging from 20 to 50% of the counties in 27 states, 10% to 20% in 11 states, and less than 10% in 11 states.

Census Tract

Table 8 presents the MedALPE and MedAPE by age group for the total population, males, and females for the census tract population forecasts. This table also contains summary statistics for the average error across age groups and the total population. Appendix Table 12 includes the corresponding table showing the MALPE and MAPE.

The amount of bias in the age-specific census tract forecasts for the total population is comparable between H–P-Usual and H–P-Light. Except for age groups < 10 and 75 +, the numeric differences in MedALPE range from 0.1 to 0.3 percentage points; the difference for the age group < 10 is 0.9 percentage points, and for 75 +, it is 1.6 percentage points. The MedALPE for H–P-Light is smaller than the MedALPE for H–P-Usual in all age groups except for age group < 10 (1.3% vs. 0.4%) and age group 65–74 (− 3.1% vs. − 3.0%). A similar pattern of bias is seen in the male population, but the differences between H–P-Usual and H–P-Light are larger than seen in the total population. Except for the age group 75 +, the differences range from 0.1 to 1.2 percentage points; the difference for the age group 75 + is 5.5 percentage points. The MedALPE in H–P-Light is larger than the MedALPE for H–P-Usual in four age groups, < 10 (1.5% vs. 0.4%), 10–19 (2.7% vs. 2.5%), 55–64 (3.6% vs. 3.2%), and 65–74 (-5.6% vs. -4.7%). In general, the amount of bias in the female population is also comparable between H–P-Usual and H–P-Light, but the differences between H–P-Usual and H–P-Light are comparable to those seen in the male population. Except for the age group 75 +, the differences range from 0.2 to 1.0 percentage points; the difference for the age group 75 + is 3.0 percentage points. The MedALPE in H–P-Light is larger in four age groups: < 10 (1.1% vs. 0.3%), 10–19 (2.7% vs. 2.5%), 20–34 (2.1% vs. 1.3%), 75 + (3.9% vs. 0.9%), and the average across age groups (2.8% vs. 1.8%).

The amount of precision in the age-specific census tract forecasts for the total population is more comparable between H–P-Usual and H–P-Light compared to bias; the numeric differences in the MedAPE are 0.0 to 0.1 percentage points, and

Table 8 Census tract forecast error by age and gender

Age group	MedALPE			MedAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
Total population						
< 10	0.4%	1.3%	208.2%	14.8%	14.7%	− 0.9%
10–19	2.8%	2.8%	− 0.2%	12.5%	12.5%	0.0%
20–34	1.9%	1.7%	− 7.4%	14.1%	14.0%	− 0.3%
35–54	− 0.3%	− 0.3%	− 16.3%	8.7%	8.7%	− 0.6%
55–64	− 2.6%	− 2.6%	− 0.5%	9.4%	9.3%	− 0.3%
65–74	− 3.0%	− 3.1%	2.7%	11.1%	11.1%	0.0%
75 +	1.6%	0.0%	− 100.0%	13.9%	13.8%	− 1.0%
Avg age groups[a]	1.6%	1.5%	− 6.3%	13.4%	13.4%	− 0.5%
Total	0.8%	0.8%	0.0%	7.0%	7.0%	0.0%
Male population						
< 10	0.4%	1.5%	238.4%	15.7%	15.7%	0.6%
10–19	2.5%	2.7%	7.0%	13.8%	13.5%	− 2.2%
20–34	1.4%	1.0%	− 27.8%	15.5%	14.5%	− 6.2%
35–54	− 0.5%	− 0.4%	− 19.5%	10.0%	9.3%	− 7.2%
55–64	− 3.4%	− 3.6%	7.4%	10.8%	10.9%	1.1%
65–74	− 4.7%	− 5.6%	20.7%	12.8%	13.6%	6.2%
75 +	1.3%	− 6.8%	− 613.2%	15.4%	16.8%	9.2%
Avg age groups[a]	1.5%	0.3%	− 80.0%	15.0%	14.9%	− 0.8%
Total male	0.6%	0.2%	− 67.4%	7.7%	7.3%	− 5.2%
Female population						
< 10	0.3%	1.1%	232.7%	15.9%	15.6%	− 1.6%
10–19	2.5%	2.7%	5.4%	13.7%	13.6%	− 0.5%
20–34	1.3%	2.1%	60.4%	14.9%	14.7%	− 1.3%
35–54	− 0.7%	− 0.3%	− 60.7%	8.9%	9.0%	1.5%
55–64	− 2.4%	− 2.0%	− 15.9%	10.4%	11.0%	5.4%
65–74	− 2.3%	− 1.7%	− 29.2%	12.3%	12.6%	2.3%
75 +	0.9%	3.9%	335.7%	15.0%	15.7%	4.8%
Avg age groups[a]	1.8%	2.8%	55.6%	14.6%	14.8%	1.5%
Total female	0.7%	1.4%	88.3%	7.4%	7.4%	− 0.3%

Average of the APEs over the seven age categories in each census tract

the MedAPE for H–P-Light is never larger than the MedAPE for H–P-Usual. A similar pattern of precision is seen in the male population, but the differences between H–P-Usual and H–P-Light are larger than in the total population. The differences range from 0.0 to 1.4 percentage points. Unlike the total population, the MedAPE for H–P-Light is larger than the MedALPE for H–P-Usual in the three oldest age groups, 55–64 (10.9% vs. 10.8%), 65–74 (13.6% vs. 12.8%), and 75 +(16.8% vs. 15.4%). Generally, the amount of precision in the female population is more similar between H–P-Usual and H–P-Light than in the male population. The differences range from 0.2 to 0.9 percentage points. Also, the precision is greater for H–P-Usual in the three age groups 35 years and older.

We next examine the relative performance of H–P-Usual and H–P-Light using a non-parametric measure that quantifies the percentage of census tracts where the APE in H–P-Light is less than the APE in H–P-Usual. Figure 5 shows that using this

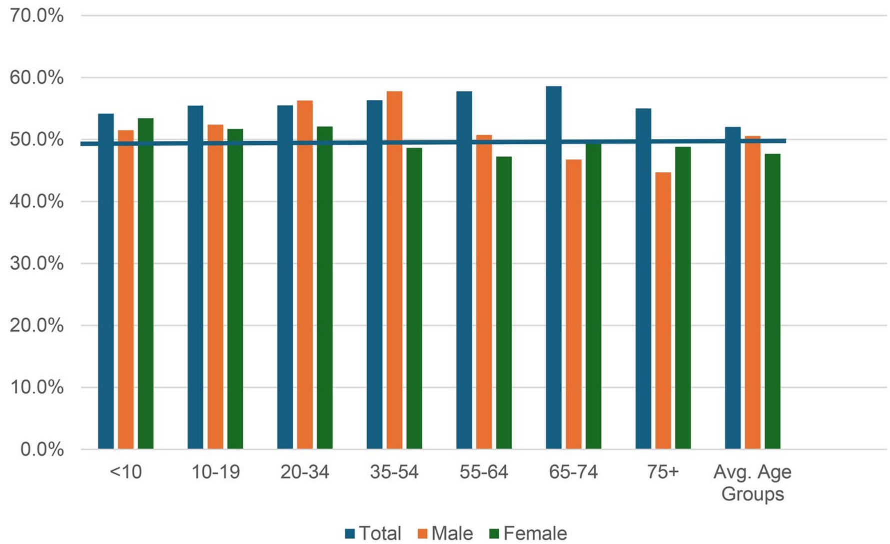

Fig. 5 Percentage of census tracts with lower H–P-Light APE by age

criterion, H–P-Light outperforms H–P-Usual in the total and male populations but less so for females. The percentage is above 50% in all categories for the total population (52% to 59% of the census tract. For the male population, the percentage is above 50% in all but two categories (51% to 58% of the counties). The male percentages for the two oldest age groups (65–74 and 75+) are 45% and 47% of the census tracts, respectively. For females, the percentage is below 50% in four age groups (47% to 49% of all counties) and is 50% or more in the same number of age groups (50% to 53% of all census tracts).

Population Size and Growth Rate Forecast Precision

In this final section of the analysis, the often-studied relationships between forecast precision and population size and growth rate are examined (e.g., Rayer, 2008; Smith et al., 2013: 338–342; Tayman et al., 2021). Population size is the county or census tract population in the year 2000, and the 1990–2000 decade is used to compute the growth rate, measured as the percent change over that period. The measure of precision in this analysis is the MedAPE of the average of the APEs across age groups for each size and growth rate category.

County

Table 9 shows the county forecast precision by population size and growth for the total, male and female populations for both H–P alternatives, which exhibit the well-known direct relationship between population size and forecast precision for the total, male and female populations (Tayman et al., 2011). This direct relationship is not linear but tends to weaken or disappear once a certain size threshold is reached,

Table 9 County forecast error by population size and growth rate

Size	2000 population size								
	Total			Male			Female		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
<5000	11.9%	11.8%	− 0.8%	13.2%	11.9%	− 9.8%	13.1%	12.1%	− 7.6%
5000–9999	8.4%	8.4%	0.0%	9.8%	8.4%	− 13.8%	8.7%	8.4%	− 3.4%
10,000–14,999	7.5%	7.3%	− 2.7%	8.5%	7.3%	− 14.1%	7.8%	7.3%	− 5.8%
15,000–24,999	6.6%	6.5%	− 1.5%	7.7%	6.5%	− 15.6%	6.5%	6.5%	0.0%
25,000–49,999	5.8%	5.7%	− 1.7%	6.9%	5.7%	− 16.8%	5.5%	5.6%	1.8%
50,000–99,999	5.2%	5.1%	− 1.9%	6.3%	5.1%	− 18.4%	4.9%	5.2%	5.1%
100,000–149,999	5.3%	5.3%	0.0%	6.4%	5.3%	− 17.2%	4.9%	5.3%	8.2%
150,000+	4.7%	4.6%	− 2.1%	5.6%	4.6%	− 17.9%	4.4%	4.6%	4.5%
Growth rate	1990–2000 population growth rate								
	Total			Male			Female		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
<− 5%	9.0%	9.0%	0.0%	10.0%	8.9%	− 11.0%	10.0%	9.0%	− 10.0%
− 5.0 to − 1.1%	6.0%	5.9%	− 1.7%	7.2%	5.9%	− 18.8%	6.1%	5.9%	− 3.3%
−1.1 to 1.9%	5.2%	5.3%	1.9%	6.1%	5.3%	− 13.1%	5.5%	5.3%	− 3.6%
2.0–4.9%	5.1%	5.1%	0.0%	6.3%	5.1%	− 18.4%	5.0%	5.1%	2.0%
5.0–9.9%	5.6%	5.6%	− 0.9%	6.7%	5.5%	− 17.9%	5.4%	5.5%	1.9%
10.0–14.9%	6.2%	6.2%	0.0%	7.3%	6.2%	− 15.1%	6.1%	6.2%	1.6%
15.0–19.9%	6.9%	6.8%	− 2.2%	8.2%	6.8%	− 17.2%	6.5%	6.8%	3.8%
20.0–29.9%	8.4%	8.2%	− 2.4%	9.2%	8.3%	− 9.8%	7.7%	8.2%	7.2%

Median of the average of the APEs over the seven age categories around 50,000 persons. For the total population, the MedAPEs for H–P-Usual and H–P-Light are close in value, differing by at most 0.2 percentage points across size categories. The MedAPE for H–P-Light is not higher than the MedAPE for H–P-Usual in any size category. The differences in MedAPEs for H–P-Light and H–P-Usual are farther apart for males than for the total population; the differences have a narrow range from 1.0 to 1.4 percentage points. MedAPE for H–P-Light is lower than the MedAPE for males in all size categories. For females, the differences in MedAPEs for H–P-Light and H–P-Usual are between the total and male differences. They range from 0.0 to 1.0 percentage points. Unlike the total and male population, female MedAPEs for H–P-Light are slightly larger than those for H–P-Usual in the four largest size categories, with differences ranging from 0.1 to 0.3 percentage points.

Both H–P alternatives exhibit the well-known u-shaped relationship between population growth and forecast precision for the total, male and female populations (Tayman et al., 2011). As shown in Table 9, the fastest declining and growing areas, ignoring the sign, tend to have higher MedAPEs than areas with more stable growth patterns. For the total population, the MedAPEs for H–P-Usual and H–P-Light are close in value, differing by at most 0.2 percentage points across growth rate categories. The MedAPE for H–P-Light is not higher than the MedAPE for H–P-Usual in any size category. The differences in MedAPEs for H–P-Light and H–P-Usual are farther apart for males than for the total population. The differences range from 0.8 to 1.4 percentage points. MedAPE for H–P-Light is lower than the MedAPE for H–P-Usual for males in all growth rate categories. For females, the differences in MedAPEs for H–P-Light and H–P-Usual are between the total and male differences. They range from 0.2 to 1.0 percentage points. Unlike the total and male population, female MedAPEs for H–P-Light are slightly larger than those for H–P-Usual in counties with growth rates of 2% or more, with differences ranging from 0.1 to 0.6 percentage points.

Census Tract

Table 10 shows the census forecast precision by population size and growth for the total, male and female populations for both H–P alternatives. Both H–P alternatives exhibit the well-known direct relationship between population size and forecast precision for the total, male and female populations (Tayman et al., 2011). This direct relationship is not linear but tends to weaken or disappear once a certain size threshold is reached, about 4,600 persons. For the total population, the MedAPEs for H–P-Usual and H–P-Light are close in value, differing by at most 0.3 percentage points across size categories. The MedAPE for H–P-Light is not higher than the MedAPE for H–P-Usual in any size category. For males, the differences in MedAPEs for H–P-Light and H–P-Usual are somewhat farther apart than for the total population. The differences have a range from 0 to 1.0 percentage points. For males, MedAPE for H–P-Light is lower than or equal to the MedAPE for H–P-Usual for all but the largest size category. For census tracts with 6500 or more persons, the MedAPE for H–P-Light is 0.3 percentage points larger. The differences in MedAPEs for females for H–P-Light and H–P-Usual are similar to those in males. They range from 0.1 to 0.7

Table 10 Census tract forecast error by population size and growth rate

Size	2000 population size								
	Total			Male			Female		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
< 1800	27.4%	27.1%	− 1.2%	30.7%	29.7%	− 3.4%	29.4%	30.1%	2.4%
1800–2399	16.3%	16.2%	− 0.9%	18.8%	18.4%	− 2.3%	17.9%	18.2%	1.7%
2400–2999	14.1%	14.1%	− 0.6%	16.1%	15.9%	− 1.4%	15.5%	15.7%	1.6%
3000–3799	13.0%	12.9%	− 0.6%	14.7%	14.5%	− 1.6%	14.1%	14.4%	1.9%
3800–4599	12.3%	12.2%	− 0.6%	13.6%	13.6%	0.0%	13.3%	13.5%	1.0%
4600–5499	11.9%	11.8%	− 0.8%	13.1%	13.1%	0.4%	12.7%	12.9%	1.1%
5500–6499	11.7%	11.6%	− 0.1%	12.9%	12.9%	0.4%	12.4%	12.5%	0.9%
6500+	12.3%	12.3%	− 0.2%	13.1%	13.4%	1.8%	12.9%	13.0%	0.8%
Growth rate	1990–2000 population growth rate								
	Total			Male			Female		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
< − 8.0%	16.2%	16.0%	− 1.2%	18.7%	17.7%	− 5.4%	17.1%	17.9%	4.7%
−8 to −3.0%	10.8%	10.7%	− 1.8%	12.6%	12.3%	− 2.0%	12.1%	12.6%	3.8%
− 2.9 to 1.9%	10.5%	10.4%	− 1.2%	12.1%	12.0%	− 1.0%	11.8%	12.1%	2.6%
2.0–7.9%	11.1%	11.0%	− 1.2%	12.6%	12.6%	− 0.2%	12.3%	12.4%	1.0%
8.0–19.9%	12.5%	12.4%	− 0.6%	13.8%	13.9%	1.0%	13.5%	13.6%	0.9%
20.0–39.9%	15.4%	15.4%	0.1%	16.8%	17.0%	1.0%	16.3%	16.3%	0.1%
40.0–89.9%	21.3%	21.4%	0.5%	22.2%	22.5%	1.1%	22.3%	22.3%	0.0%
90.0+%	33.2%	33.5%	0.9%	34.3%	34.0%	− 0.9%	33.7%	34.6%	2.8%

[a]Median of the average of the APEs over the seven age categories

percentage points. Unlike the total and male populations, female MedAPEs for H–P-Light are larger than those for H–P-Usual in all size categories.

Both H–P alternatives exhibit the well-known u-shaped relationship between population growth and forecast precision for the total, male and female populations (Tayman et al., 2011). As shown in Table 10, the fastest declining and growing areas, ignoring the sign, tend to have higher MedAPEs than areas with more stable growth patterns. For the total population, the MedAPEs for H–P-Usual and H–P-Light are close in value, differing by at most 0.3 percentage points across growth rate categories. The MedAPE for H–P-Light is not higher than the MedAPE for H–P-Usual in all but the top two fastest growth rate categories. For census tracts growing at least 40%, the MedAPEs for H–P-Light are 0.1 and 0.3 percentage points higher. The differences in MedAPEs for H–P-Light and H–P-Usual are farther apart for males than for the total population. The differences range from 0.1 to 1.0 percentage points. For males, the MedAPE for H–P-Light is lower than the MedAPE for H–P-Usual in five of the eight growth rate categories. For census tracts growing between 8 and 90%, the MedAPEs for H–P-Light are between 0.1 and 0.3 percentage points higher. The differences in MedAPEs for females for H–P-Light and H–P-Usual are similar to those in males. They range from 0.1 to 0.9 percentage points. Unlike the total and male populations, female MedAPEs for H–P-Light are larger than those for H–P-Usual in all size categories.

Discussion

This paper proposes a simpler H–P method, H–P-Light, that uses CCRs calculated from the total population by age group and CWRs calculated from all adults in the childbearing years and all children, known as the Child Adult Ratio (CAR), as opposed to the usual H–P method, H–P-Usual, which requires gender-specific inputs. H–P-Light has reduced the impact of small population sizes in age- and gender-specific cells, most notably prevalent in subcounty areas such as census tracts. For the years used to compute the CCRs (i.e., 1990 and 2000) and the year (i.e., 2000) used to calculate the CWRs and CARs, the total population has 202,300 age-specific cells (age group 0–4 to age group 85+) with a population less than 25. This number represents around 8% of the total population of age-specific cells for all census tracts. For the male and female populations, the number of cells with fewer than 25 persons balloons to 788,000 or 15% of the gender-and age-specific cells. The effect of smaller cell population size is reflected in the number of overrides made to the census tracts to treat abnormally large or small CCRs, CWRs, and CARs. The ratios based on the total population are overridden in 87,000 census tracts compared to 189,500 census tracts, more than twice as many as the gender-specific ratios.

Using non-gender-specific inputs, H–P-Light initially produces an age-specific forecast for the total population. Suppose, however, age-specific forecasts by gender are also needed. In that case, they can be derived from the total population age-specific forecast using the age-specific proportion of males to the total population in the launch year (MALEPROP). While this is a new input to an H–P model, it is not nearly as susceptible to small cell size and abnormal values as are age- and gender-specific CCRs and CWRs. Also, MALEPROP required no census tract overrides. As discussed in Footnote 3, the MALEPROP ranges from 0.0 to 1.0, and its computations are constrained by the forecast of the total population in each age group. The resulting MALEPROP value also has a narrow range. For counties, 98% of the MALEPOPS are between 0.4 and 0.6; for census tracts, the corresponding range is 0.3 to 0.7.

The advantages of H–P-Light over H–P-Usual regarding resource requirements and mitigating abnormal values of H–P inputs are clear. However, these advantages are not beneficial unless the forecast performance of H–P-Light is on par with that of H–P-Usual. We analyzed forecast errors for the total population to show the differences between errors between population controls and population totals if controls are not instituted. The remainder of the analysis explored forecast errors by age and gender and finally forecast errors by population size and growth rate. Based on summary measures of forecast bias and precision, the analysis found no performance degradation using H–P-Light for counties and census tracts. H–P-Light has a slightly lower bias and a somewhat greater precision than H–P-Usual in most comparisons. Similar conclusions are reached using a non-parametric measure of forecast performance that counted counties and census tracts where H–P-Usual's forecast precision is greater than H–P-Light based on the average of APEs across age groups.

Generally, H–P-Light's performance relative to H–P-Usual is better for the total and male populations than for females. For the 32 age and gender comparisons (8 age groups, bias and precision, and county and census tract), H–P-Light has less forecast error than H–P-Usual for the total population 78% of the time. The corresponding figures for males and females are 69% and 43%, respectively. For the 32 population size and growth comparisons (eight size groups, eight growth rate groups, precision, and county and census tract), H–P-Light has less forecast error than H–P-Usual for the total and male populations 78% of the time. The corresponding figure for females is 19%. A similar pattern also occurs in the share of counties and census tracts where H–P-Light has greater precision than H–P-Usual. For example, for the average APE over the age groups, H–P-Light has greater precision in 70%, 82%, and 50% of the counties for the total population, males, and females, respectively. For census tracts, the corresponding figures are much closer: 52% for the total population, 51% for males, and 48% for females.

Although not a key focus of the paper, the results provide additional evidence of the value of controlling H–P forecasts to a total population control for each geographic area (Baker et al., 2020; Tayman et al., 2021; Wilson & Grossman, 2022). There is little difference in forecast errors for the total population between uncontrolled H–P-Usual and H–P-Light, but the error for both H–P alternatives is greater than the error for the population control total. The value of controlling is greater for census tracts than for counties in terms of both forecast bias and precision. For counties, the bias and precision based on MedALPE and MedAPE in the H–P alternatives are 75% and 18% higher, respectively, than the bias and precision in the control total. The corresponding figures for the census tracts are 515% higher for bias and 45% higher for precision.

Conclusion

The H–P method has gained acceptance as research has demonstrated its practical value and reasonable error levels in forecasting populations. The H–P-Usual method uses gender-specific CCRs and CWRs, which have two key shortcomings. If population forecasts by age are only needed for the total population, additional time and resources are required to assemble and evaluate the gender-specific CCR and CWR inputs. More pressing, especially for subcounty areas, is the issue of small population sizes in the age and gender-specific population cells. The approach we propose and analyze in this paper, H–P-Light, uses non-gender-specific inputs to address H–P-Usual's shortcomings. Moreover, the age-specific forecasts produced by H–P-Light do not degrade the forecast precision and bias levels from H–P-Usual. While the differences in forecast errors between H–P-Light and H–P are generally small, H–P-Light outperforms H–P-Usual more often than not in the total and male population and less so in the female population. These gender differences were not due to the order in which the age/gender forecasts were made in H–P-Light. The age-specific forecasts were identical for males and females regardless of whether male or female forecasts were done first and the forecasts for other genders were done second. Additional research into the mechanics of H–P-Light is needed to understand better the differences in performance between the male and female forecasts.

H–P-Light is a viable alternative to H–P-Usual for producing population forecasts by age and gender. It is a worthwhile addition to the current toolkit for generating these forecasts. This statement does not mean that H–P-Light forecasts by age and gender are superior or preferred to those generated from H–P-Usual, but H–P-Light does address the key shortcomings of H–P-Usual. It is evident that if forecasts are only needed by age and not by age and gender or if there are time and resource constraints, it would make more sense to use H–P-Light. The various H–P alternatives studied here and in other studies would benefit from additional research on smaller geographic areas, such as block groups, to investigate forecast horizons over 10 years (Smith & Tayman, 2003, and to analyze other demographic characteristics, such as race and Hispanic Origin (e.g., Marquez et al., 2024).

As is the case for H–P-Usual (Swanson & Tayman, 2014), uncertainty intervals can be generated using H–P-Light forecasts. Importantly, because both H–P-Usual and H–P-Light are algebraically equivalent to the CCM approach (Baker et al., 2017: 100–101), the procedure developed by Swanson and Tayman (2025) to generate uncertainty intervals for forecasts made using the CCM approach can be applied to both H–P-Light and H–P-Usual. Their approach uses ARIMA models to place low and high values around total population forecasts and then translates these relative interval widths to a total population forecast from a CCM.

Following the "triple constraint" perspective (Swanson et al., 1996), H–P-Light offers an improvement in utility for the population forecasting arena. In addition, our findings suggest H–P-Light may also be of use in other arenas, such as stable population theory (Swanson, 2024; Swanson et al., 2016), stationary populations (Swanson & Tedrow, 2012), machine learning (Baker et al., 2023), population health (Swanson et al., 2020), and historical demography (Swanson, 2019; Swanson & Verdugo, 2019).

Appendix

See Tables 11 and 12.

Table 11 County forecast error by age and gender

Age Group	Total population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
< 10	− 1.8%	− 0.6%	− 67.7%	9.5%	9.6%	1.3%
10–19	4.0%	3.9%	− 2.6%	8.2%	8.2%	−0.8%
20–34	5.2%	4.9%	− 5.6%	11.2%	11.0%	−1.6%
35–54	3.3%	3.1%	− 8.3%	7.4%	7.2%	−2.9%
55–64	1.3%	1.2%	− 7.4%	6.3%	6.2%	−0.7%
65–74	− 2.6%	− 2.6%	− 1.0%	6.3%	6.4%	1.0%
75 +	− 3.6%	− 3.4%	− 4.7%	7.7%	7.7%	−0.9%
Avg age groups[a]	0.8%	0.9%	12.5%	8.1%	8.0%	−0.7%
Total	1.7%	1.7%	− 0.2%	6.0%	6.0%	0.0%
Age group	Male population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
< 10	− 1.6%	− 0.6%	− 64.9%	9.8%	9.6%	−2.3%
10–19	4.2%	3.9%	− 6.4%	8.8%	8.2%	−7.4%
20–34	5.6%	4.8%	− 13.1%	12.9%	11.0%	− 14.5%
35–54	4.0%	3.1%	− 23.9%	8.9%	7.2%	− 19.3%
55–64	1.5%	1.2%	− 22.7%	7.0%	6.2%	− 10.7%
65–74	− 3.2%	− 2.4%	− 24.0%	7.4%	6.5%	− 12.5%
75 +	− 8.3%	− 3.7%	− 55.4%	10.9%	7.6%	− 30.2%
Avg age groups[a]	0.3%	0.9%	200.0%	9.4%	8.0%	− 14.3%
Total male	1.8%	1.8%	− 2.1%	6.6%	6.1%	−8.3%
Age group	Female population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
< 10	− 1.8%	− 0.6%	− 67.3%	9.9%	9.6%	−3.0%
10–19	4.0%	3.9%	− 1.8%	8.6%	8.2%	−5.4%
20–34	4.8%	4.9%	2.1%	10.6%	11.0%	4.3%
35–54	2.5%	3.0%	23.9%	6.6%	7.1%	8.2%
55–64	1.1%	1.2%	7.7%	6.5%	6.3%	−4.2%
65–74	− 1.9%	− 2.6%	34.2%	6.4%	6.3%	−1.0%
75 +	− 0.3%	− 3.2%	1045.3%	7.8%	7.7%	−1.3%
Avg age groups[a]	1.2%	1.0%	− 16.7%	8.1%	8.0%	−0.4%
Total female	1.6%	1.7%	5.8%	5.8%	5.8%	0.8%

[a]Average of the APEs over the seven age categories in each county

Table 12 Census tract forecast error by age and gender

Age Group	Total population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
<10	41.4%	47.6%	14.9%	60.2%	65.4%	8.8%
10–19	5.0%	5.1%	2.3%	21.0%	21.1%	0.4%
20–34	8.8%	9.0%	1.7%	28.0%	28.2%	0.9%
35–54	6.4%	5.5%	− 14.8%	21.3%	20.3%	−4.7%
55–64	− 0.7%	− 1.0%	51.3%	16.2%	15.9%	−1.8%
65–74	− 1.0%	− 1.5%	50.3%	17.8%	17.6%	−1.4%
75+	9.4%	7.0%	− 26.0%	26.1%	25.2%	−3.4%
Avg age groups[a]	15.2%	14.9%	− 2.0%	32.7%	32.6%	−0.4%
Total	2.0%	1.9%	− 3.9%	15.1%	15.1%	−0.4%
Age group	Male population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
<10	25.7%	27.0%	5.4%	45.0%	45.4%	1.1%
10–19	5.1%	5.2%	2.6%	22.2%	21.9%	−1.3%
20–34	4.9%	3.8%	− 22.1%	25.1%	23.6%	−5.7%
35–54	8.8%	7.0%	− 21.1%	25.0%	22.3%	− 10.9%
55–64	− 0.4%	− 1.5%	234.2%	18.0%	17.2%	−4.5%
65–74	− 1.7%	− 3.0%	83.3%	19.6%	19.7%	0.7%
75+	8.7%	− 1.2%	− 114.0%	26.3%	24.9%	−5.2%
Avg age groups[a]	11.3%	8.4%	− 25.7%	30.0%	28.3%	−5.7%
Total male	1.9%	1.5%	− 23.9%	15.6%	15.1%	−3.1%
Age group	Female population					
	MALPE			MAPE		
	H–P-Usual	H–P-Light	% Diff	H–P-Usual	H–P-Light	% Diff
<10	34.5%	42.8%	24.1%	54.0%	61.6%	14.0%
10–19	4.6%	4.7%	2.3%	21.8%	21.6%	−0.6%
20–34	5.0%	5.5%	11.0%	25.2%	25.1%	−0.4%
35–54	3.5%	3.8%	9.4%	18.8%	18.9%	0.6%
55–64	− 1.1%	− 0.4%	− 62.4%	16.5%	17.3%	5.1%
65–74	− 0.6%	0.4%	− 162.1%	18.6%	19.1%	2.8%
75+	8.4%	11.4%	36.1%	26.8%	27.9%	4.2%
Avg age groups[a]	11.0%	13.9%	n/a	29.4%	31.7%	8.0%
Total female	2.2%	8.0%	271.6%	15.7%	21.0%	34.0%

[a]Average of the APEs over the seven age categories in each census

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Declarations

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Authors and Affiliations

Jeff Tayman[1] · David A. Swanson[2,3,4]

✉ Jeff Tayman
jtayman@san.rr.com

David A. Swanson
dswanson@ucr.edu

1 Tayman Demographics, 2142 Diamond St., San Diego, CA 92109, USA

2 Population Research Center, Portland State University, Portland, OR, USA

3 Center for Studies in Demography and Ecology, University of Washington, Seattle, WA, USA

4 Department of Sociology, University of California Riverside, Riverside, CA, USA