

COHORT REVENUE & RETENTION ANALYSIS: A BAYESIAN APPROACH

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ABSTRACT. We present a bayesian approach to model cohort-level retention rates and revenue over time. We use bayesian additive regression trees (BART) to model the retention component which we couple with a linear model to model the revenue component. This method is flexible enough to allow adding additional covariates to both model components. This bayesian model allows us to quantify the uncertainty in the estimation, understand the effect of the covariates on the retention through partial dependence plots (PDP), individual conditional expectation (ICE) plots and last but not least forecast the future revenue and retention rates.

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1. INTRODUCTION

Retention and customer lifetime value estimation are one of the most important aspects to understand customer behavior. There are many ways to model retention and revenue by modeling individual-level purchase behavior for both the contractual and the non-contractual setting, see for example the work by Fader and Herd [2] and [1] respectively¹. In real cases, one is interested in modeling retention and revenue at cohort-level. There are (at least) three options to use the techniques mentioned above to model cohort-level retention:

- (1) Pool the cohorts together and model the retention and revenue as a whole.
- (2) Un-pool the cohorts and model each cohort separately.
- (3) Try to model the cohorts jointly.

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¹Our definition of retention is what they call survival curve. See precise definitions below.

See [4] for more details on these approaches. One of the limitations of those approaches is that they are not flexible enough to model seasonality and add external regressors². One can argue that seasonality is not that important when trying to estimate the customer-lifetime-value. Nevertheless, in practice, there are business models on which the customer base is very seasonal.

In this work, we present a bayesian approach to model cohort-level retention rates from a top-down perspective. We do not model the individual-level purchase behavior³ but rather the retention and revenue at cohort matrices. This approach allows for modeling non-linear relationships between cohorts, adding seasonality and external regressors. Concretely, we use bayesian additive regression trees (BART, see [10]) to model the retention component and we couple it with a linear model to model the revenue. The following are the main ingredients behind the model:

Features. The following are the main features used to model the retention and revenue:

- **Cohort age:** Age of the cohort in months.
- **Age:** Age of the cohort with respect to the observation time. This feature is a numerical encoder for the cohort.
- **Month:** Month of the observation time.

In Figure 1 we show an example of a retention matrix. Note that we are removing the diagonal as it is not informative since it has just ones. As an example, let us assume our observation month is *2022-11* and consider the cohort *2022-09*. In this case, the age of this cohort is 2 months as it is always relative to the observation period. This cohort was two observation periods *2022-10* and *2022-11* with cohort age 1 and 2 respectively.

Note that all of these features are accessible for out-of-sample predictions. As we will see below, in practice we can add more covariates to the model. The only requirement for out-of-sample predictions is that the covariates are available for the new observation period.

Model Specification.

- We model the number of active users in the cohort as a binomial random variable $\text{Binomial}(N_{\text{total}}, p)$, where the parameter p represents the retention. We model the latent variable p using a BART model with features cohort age, age and month.
- We model the revenue as a gamma random variable $\text{Gamma}(N_{\text{active}}, \lambda)$. We model the latent variable λ through a linear model with features cohort age, age and a multiplicative interaction. Note that we do not add a seasonality component as we often see most of the seasonality coming from the retention itself. This of course can be added as a feature (plus any other covariates!) to the model.

²Actually, one can add regressors in some cases as described in [3] in the non-contractual case.

³This is a clear limitation if one is interested at customer-level parameters and predictions.

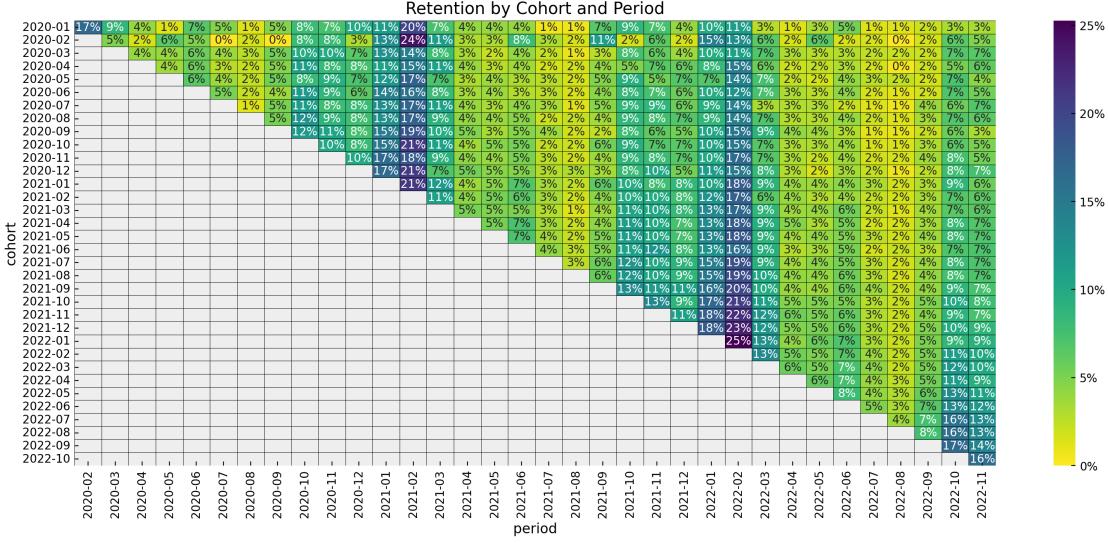


FIGURE 1. Retention matrix example.

- Here is a summary of how the retention and revenue components are coupled together:

$$\begin{aligned}
 \text{Revenue} &\sim \text{Gamma}(N_{\text{active}}, \lambda) \\
 \log(\lambda) &= (\text{intercept}) \\
 &\quad + \beta_{\text{cohort age}} \text{cohort age} \\
 &\quad + \beta_{\text{age}} \text{age} \\
 &\quad + \beta_{\text{cohort age} \times \text{age}} \text{cohort age} \times \text{age}) \\
 N_{\text{active}} &\sim \text{Binomial}(N_{\text{total}}, p) \\
 \text{logit}(p) &= \text{BART}(\text{cohort age}, \text{age}, \text{month})
 \end{aligned}$$

We are interested in estimating the BART parameters and the beta coefficients (plus the intercept) of the linear component simultaneously. Figure 2 summarizes the model structure.

Remark 1. This work is the result of a sequence of blog posts where all the details on the code and implementation are presented, see [5], [6] and [7].

2. SYNTHETIC DATA

We illustrate the definitions, concepts and model using a synthetic data set (you can get it as *csv* from [9]). The code to (deterministically!) generate the data set is publicly available in [8].

To start the analysis, let's do some exploratory data analysis. Figure 1 shows the retention matrix per cohort and period. There are two things to note at first glance:

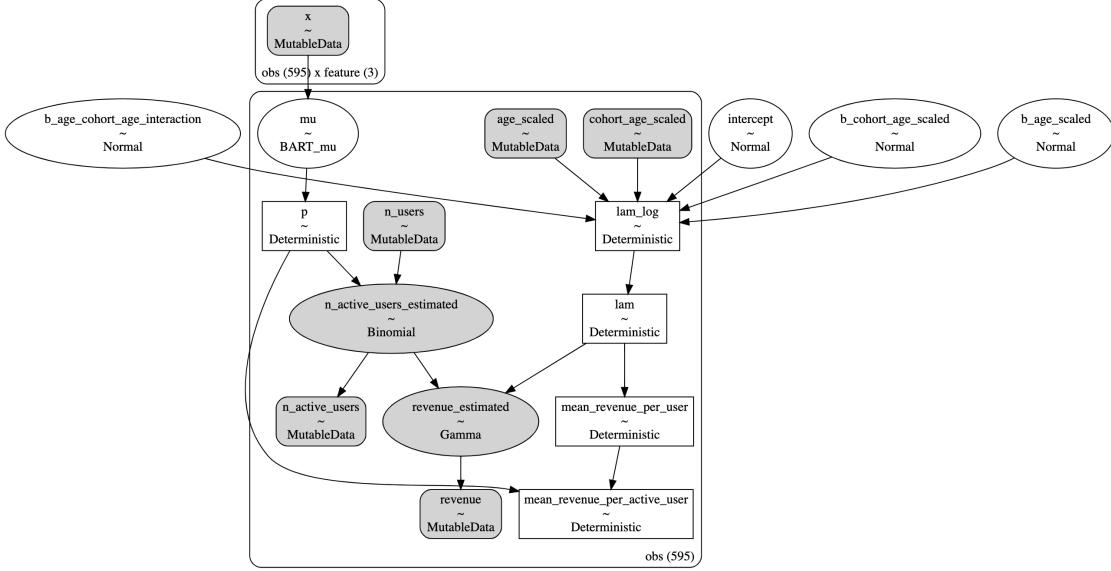


FIGURE 2. Cohort-revenue-retention model structure.

- (1) The retention has a clear seasonal pattern concerning the period. Note it is higher in the last months of the year and lower in the middle of the year. To see the seasonality pattern in a clearer way see Figure 3.
- (2) The retention seems to be increasing as the age decreases. You could see this by comparing the retention values when the period month is November and the cohort age is one.

It is important to keep in mind that the retention metric is a quotient, and therefore the cohort size matters. For example, a retention rate of 0.4 could come from $4/10$ or $4 \times 10^5 / 10^6$. One could argue that the former case carries more uncertainty regarding the estimation. This motivates looking into the number of active users' values. These are shown in Figure 4. We can see that the number of active users increases considerably for newer cohorts. We would like this information to be encoded in the model.

Now, let us look at the revenue. Figure 5 shows the revenue per cohort. We see from the plots how the revenue correlates with the number of active users. This hints that the revenue per user does not change dramatically over time. To see this, we can compute the revenue per user as a function of the age and the period (see Figure 6). We also can compute the revenue per *active* user (see Figure 7). The main difference between the two is that for the former we divide by the cohort size, while for the latter we divide by the number of active users in the given period. Here are some observations:

- The revenue per user shows a clear seasonality pattern. This is expected as the retention has a seasonality pattern.

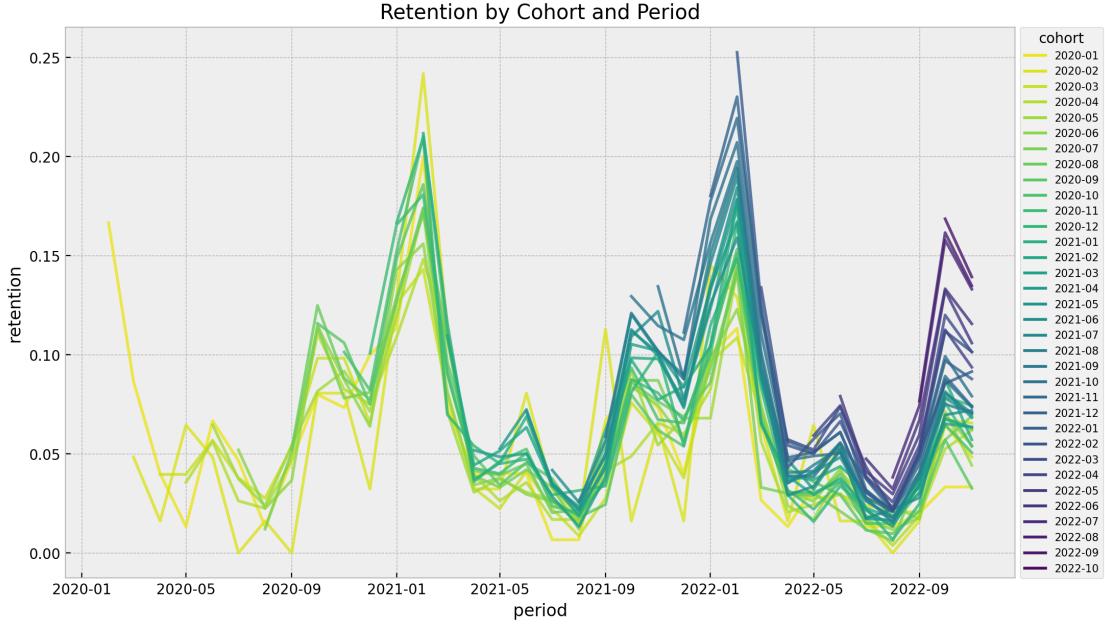


FIGURE 3. Retention as a function of the period. This plot clearly shows the yearly seasonality pattern of the retention values.

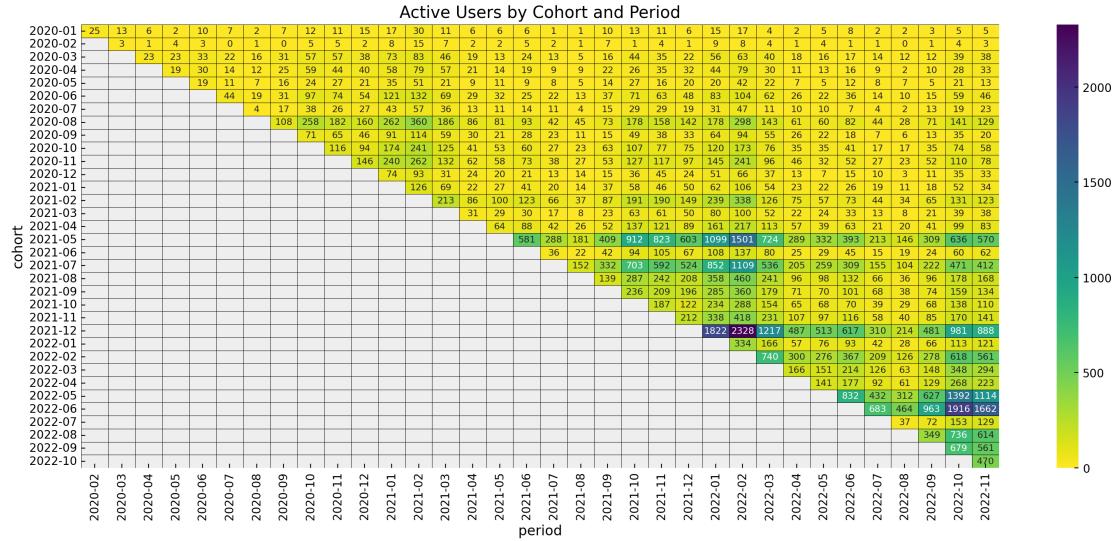


FIGURE 4. Active users' values.

- The revenue per active user does now the seasonality pattern as it's already encoded in the denominator. In addition, we see that the revenue per active user seems to be decreasing as the cohort age increases.

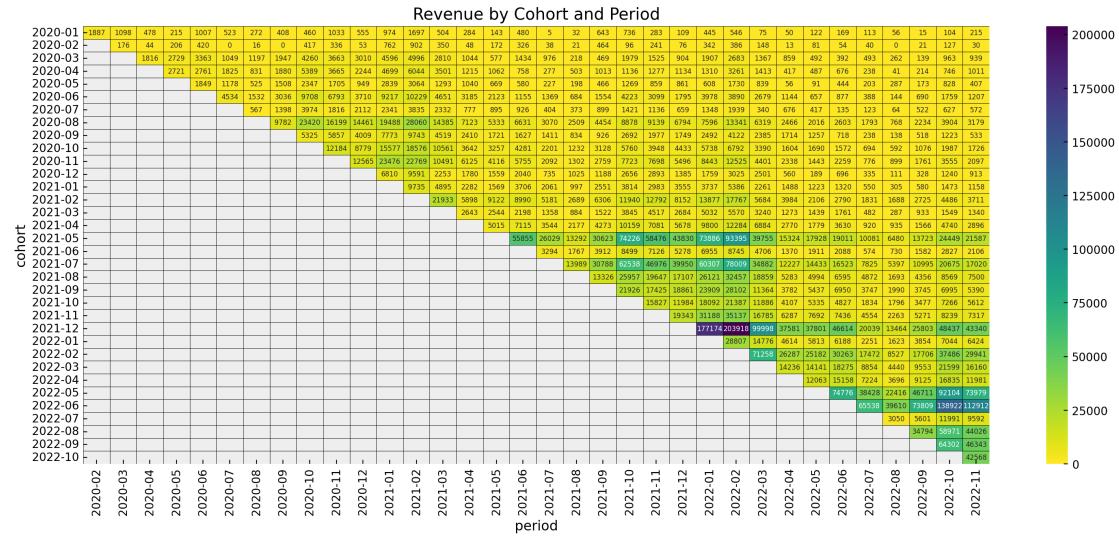


FIGURE 5. Revenue per cohort.

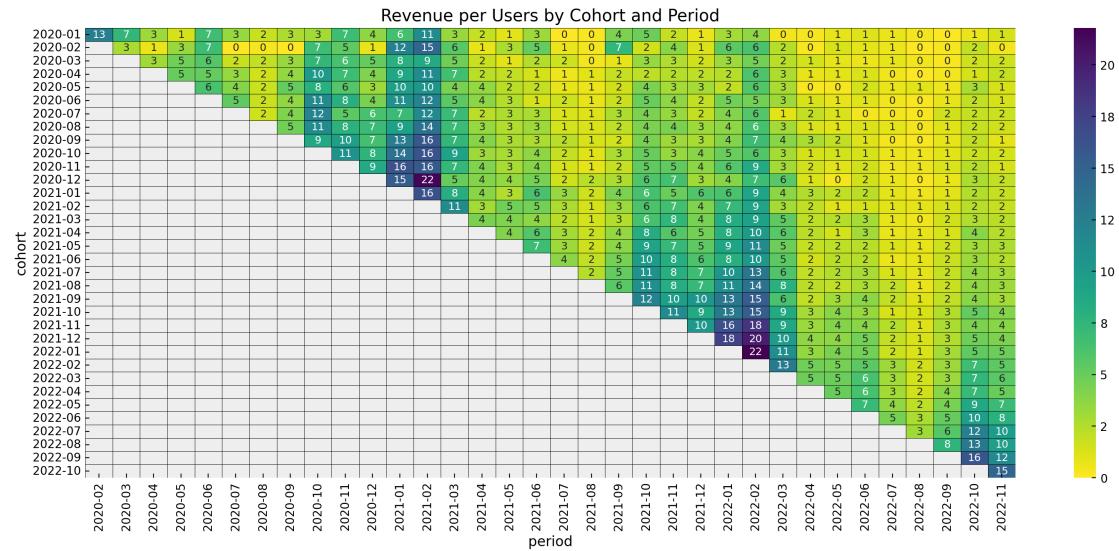


FIGURE 6. Revenue per cohort.

After this exploratory analysis, we can start the modeling phase.

3. MODEL SPECIFICATION AND DIAGNOSTICS

4. PREDICTIONS

4.1. In-Sample Predictions.

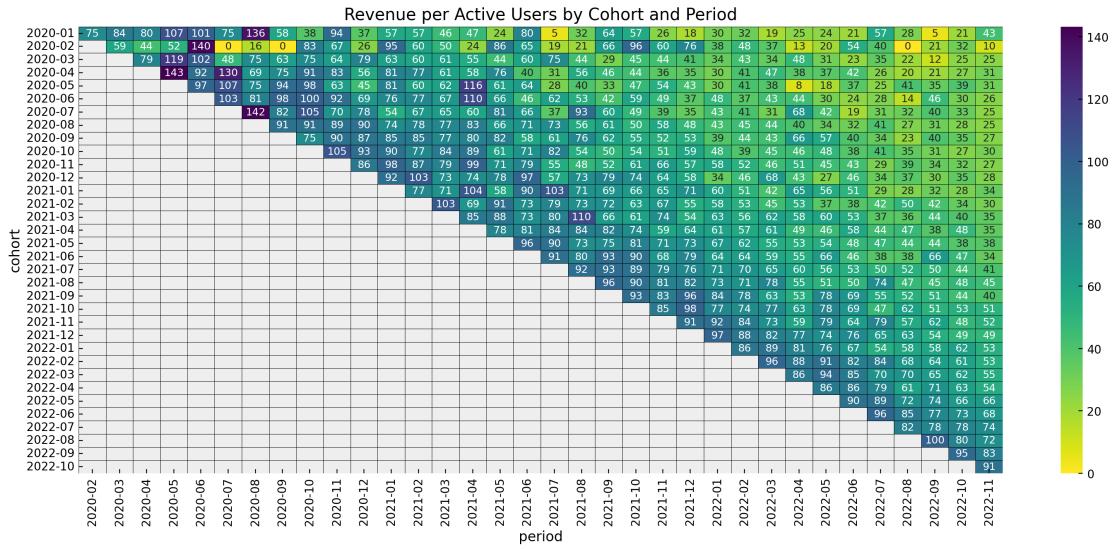
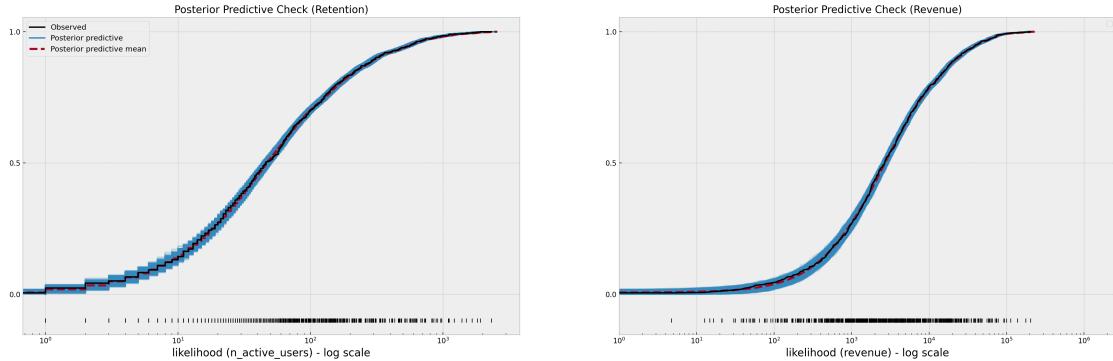


FIGURE 7. Revenue per cohort.



4.2. Out-of-Sample Predictions.

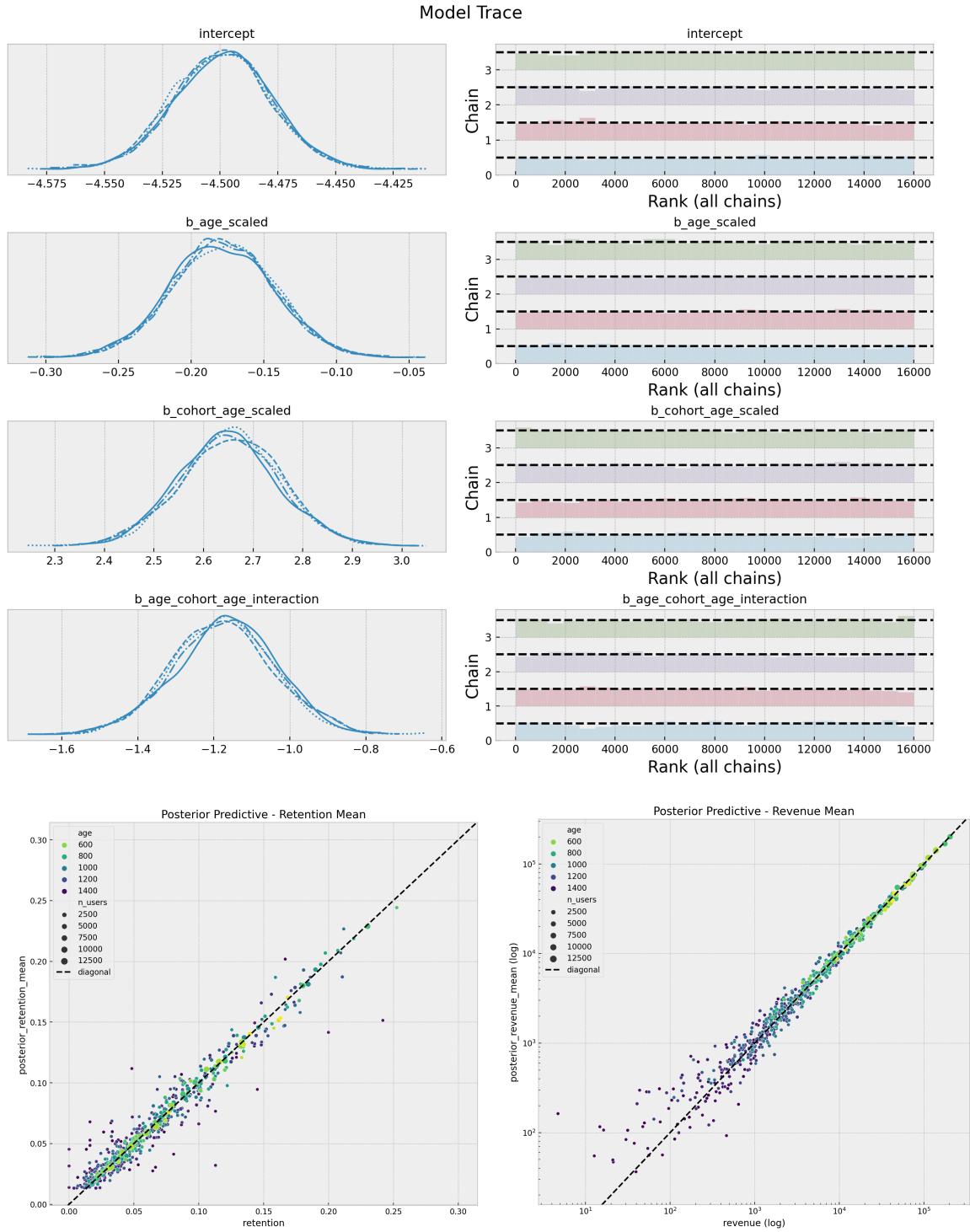


FIGURE 8. My caption

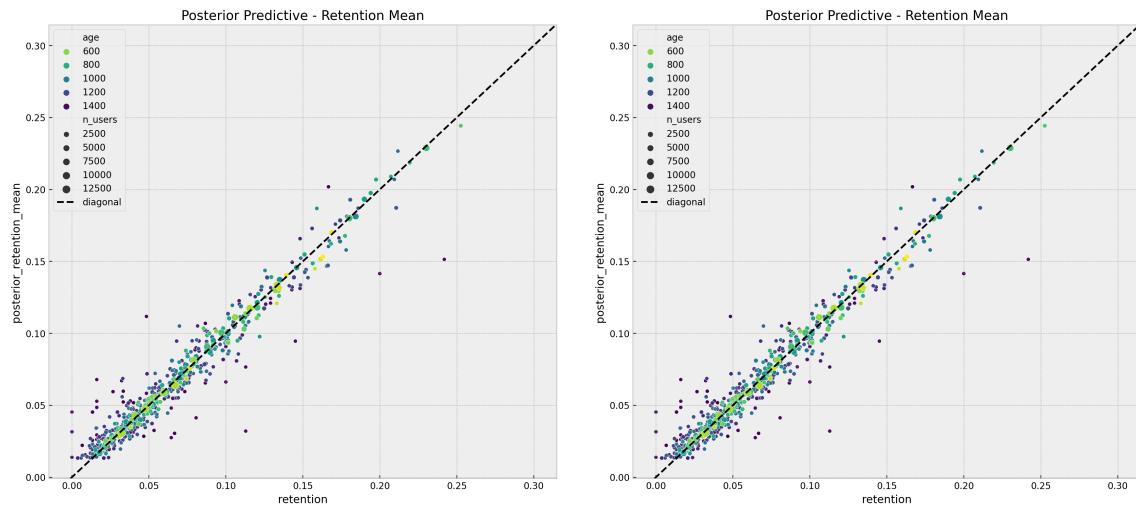
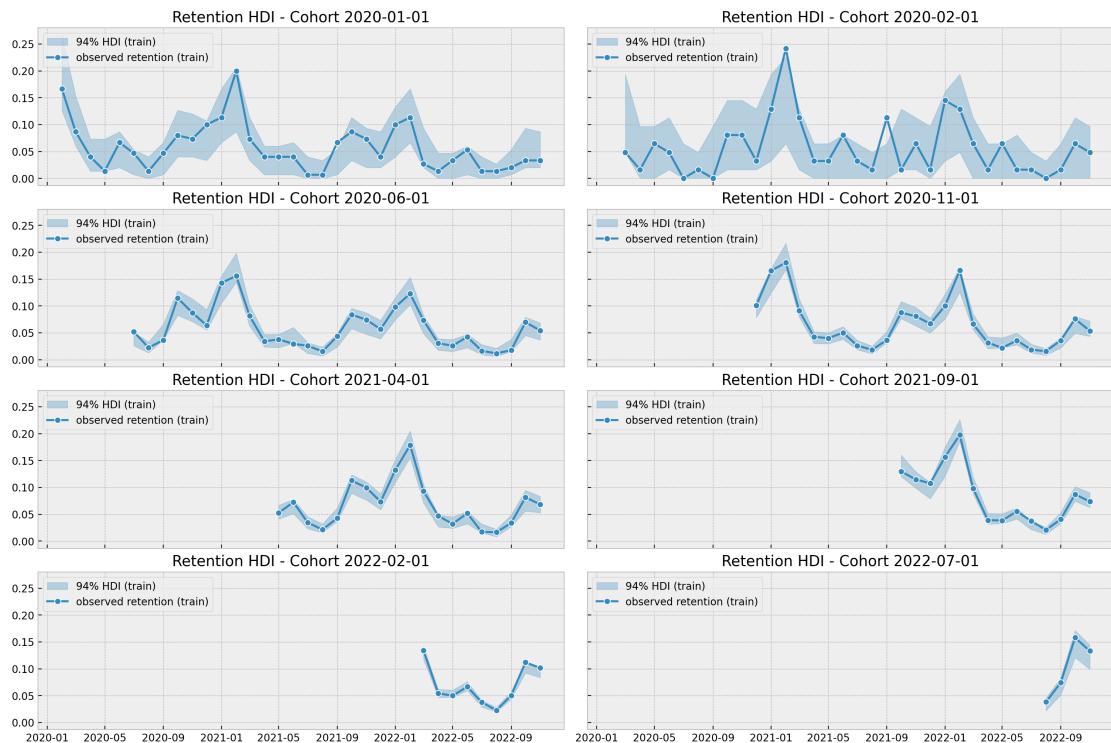
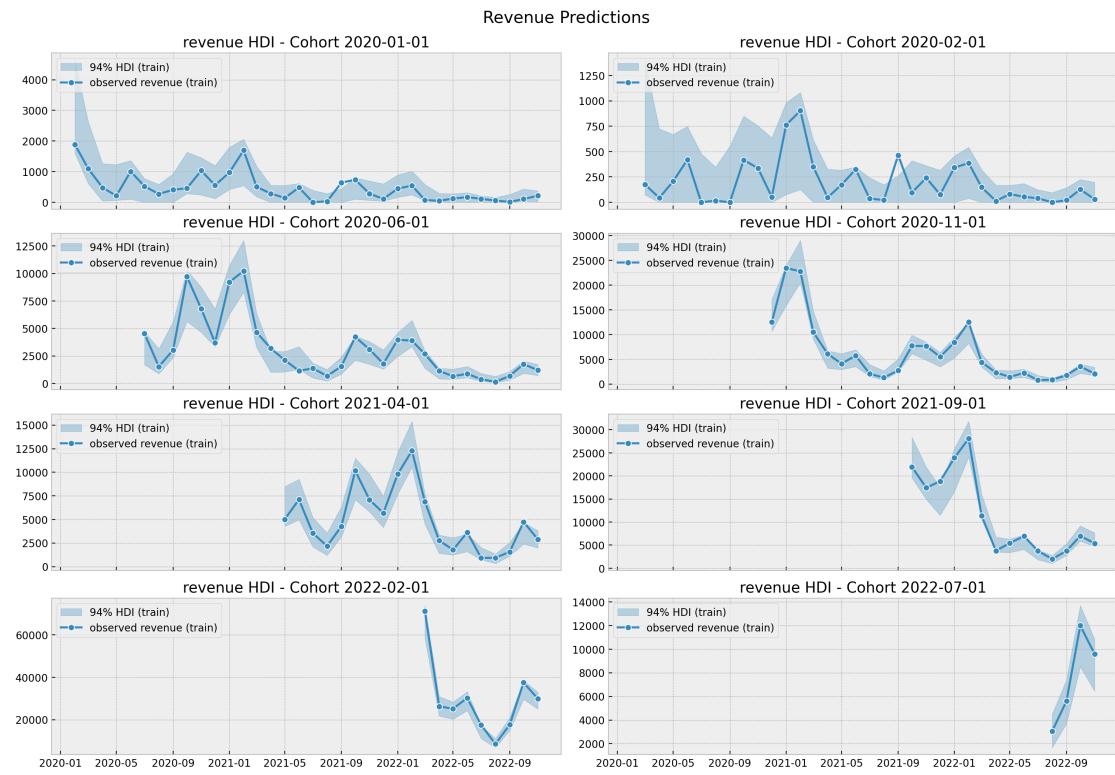
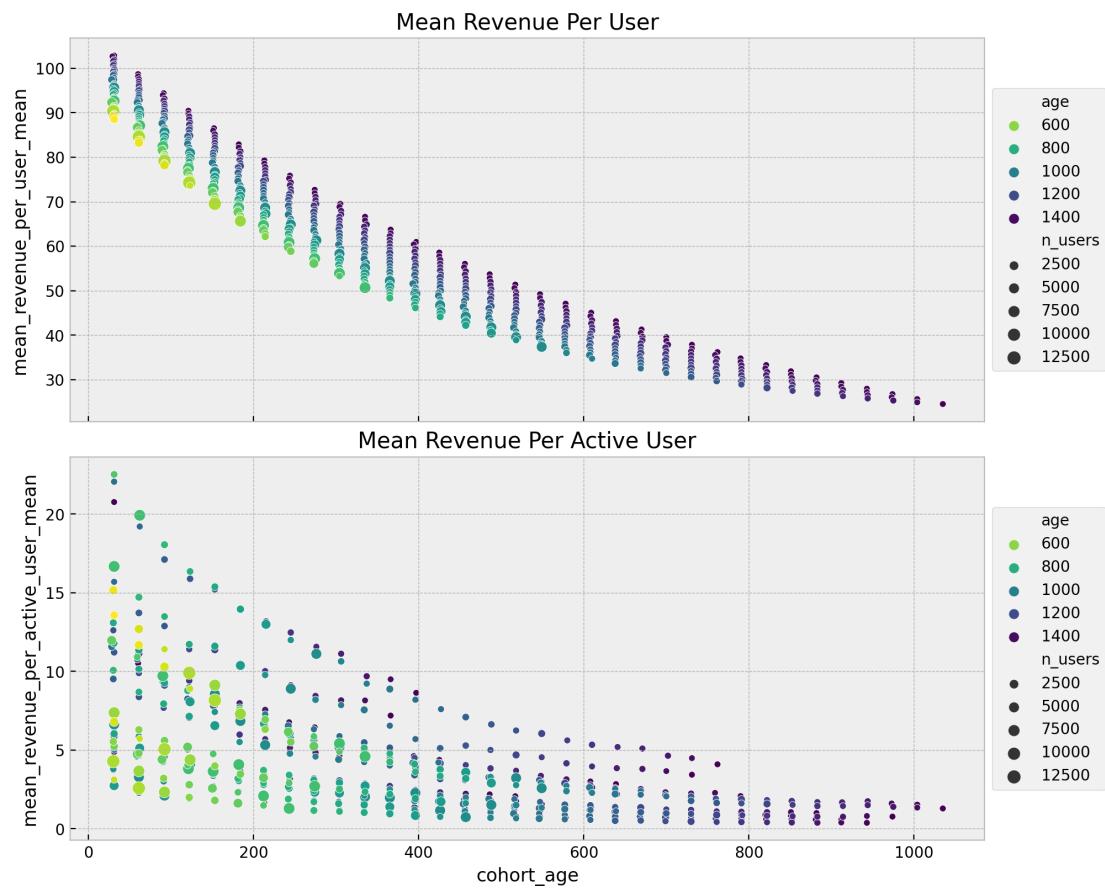
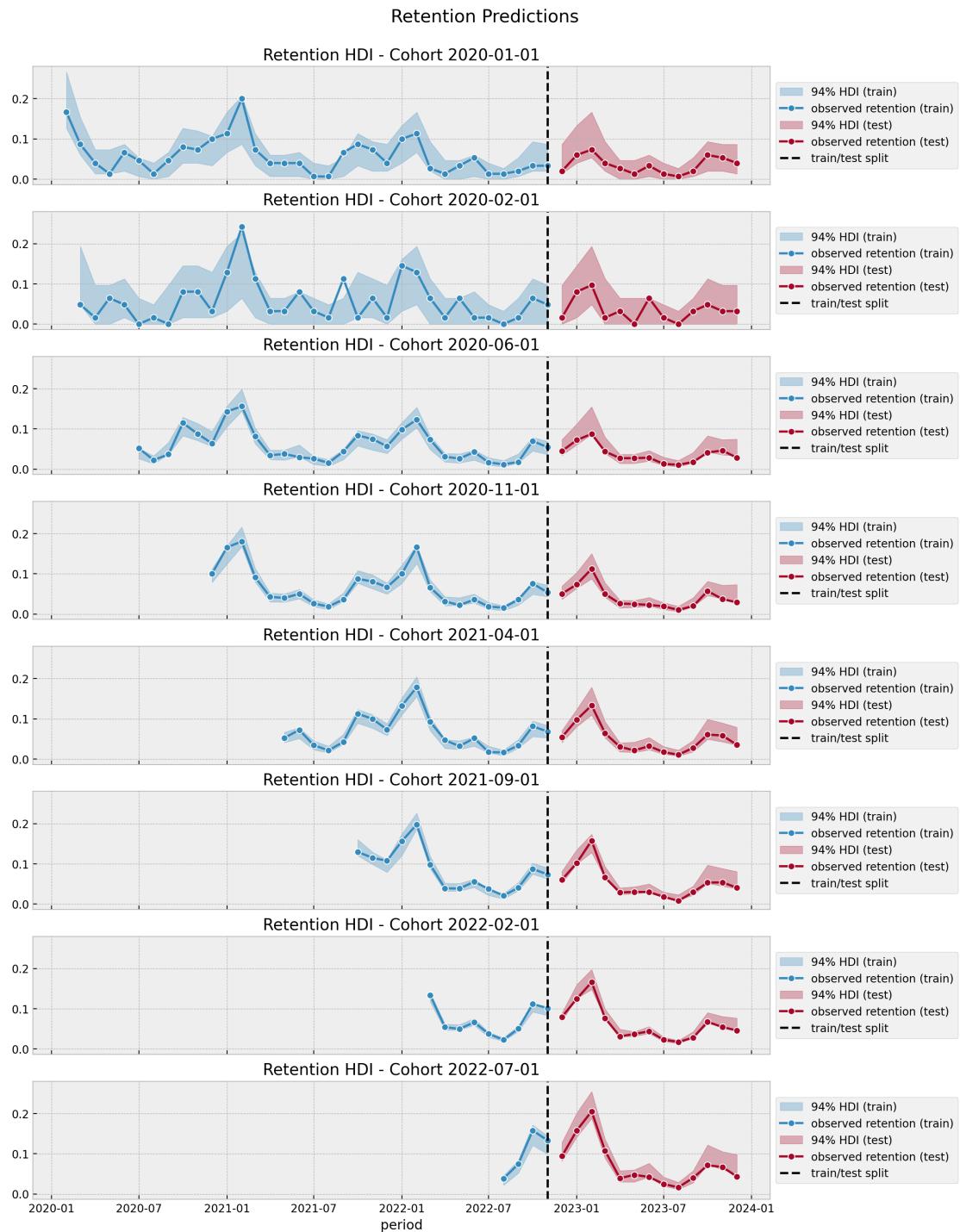


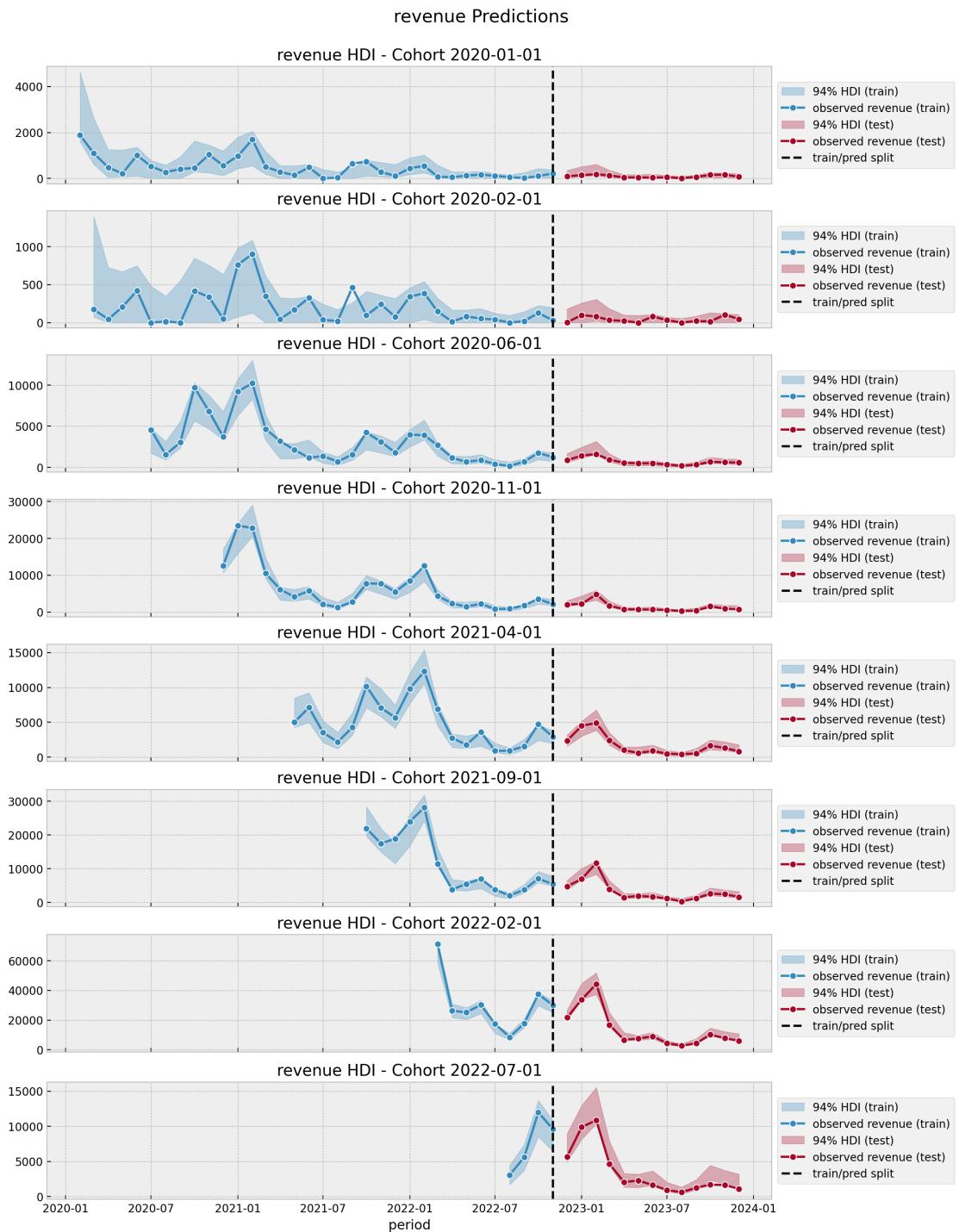
FIGURE 9. My caption











Appendix: Python Code

LISTING 1. Python example

```

1 import pymc_bart as pmb
2 import pymc as pm
3
4
5 with pm.Model(coords={"feature": features}) as model:
6
7     # --- Data ---
8     model.add_coord(name="obs", values=train_obs_idx, mutable=True)
9     age_scaled = pm.MutableData(
10         name="age_scaled", value=train_age_scaled, dims="obs"
11     )
12     cohort_age_scaled = pm.MutableData(
13         name="cohort_age_scaled", value=train_cohort_age_scaled, dims="obs"
14     )
15     x = pm.MutableData(name="x", value=x_train, dims=("obs", "feature"))
16     n_users = pm.MutableData(name="n_users", value=train_n_users, dims="obs")
17     n_active_users = pm.MutableData(
18         name="n_active_users", value=train_n_active_users, dims="obs"
19     )
20     revenue = pm.MutableData(name="revenue", value=train_revenue, dims="obs")
21
22     # --- Priors ---
23     intercept = pm.Normal(name="intercept", mu=0, sigma=1)
24     b_age_scaled = pm.Normal(name="b_age_scaled", mu=0, sigma=1)
25     b_cohort_age_scaled = pm.Normal(name="b_cohort_age_scaled", mu=0, sigma=1)
26     b_age_cohort_age_interaction = pm.Normal(
27         name="b_age_cohort_age_interaction", mu=0, sigma=1
28     )
29
30     # --- Parametrization ---
31     # The BART component models the image of the retention rate under the
32     # logit transform so that the range is not constrained to [0, 1].
33     mu = pmb.BART(name="mu", X=x, Y=train_retention_logit, m=50, dims="obs")
34     # We use the inverse logit transform to get the retention rate
35     # back into [0, 1].
36     p = pm.Deterministic(name="p", var=pm.math.invlogit(mu), dims="obs")
37     # We add a small epsilon to avoid numerical issues.
38     p = pt.switch(pt.eq(p, 0), eps, p)
39     p = pt.switch(pt.eq(p, 1), 1 - eps, p)
40
41     # For the revenue component we use a Gamma distribution where we
42     # combine the number of estimated active users with the average
43     # revenue per user.
44     lam_log = pm.Deterministic(
45         name="lam_log",

```

```

46     var=intercept
47     + b_age_scaled * age_scaled
48     + b_cohort_age_scaled * cohort_age_scaled
49     + b_age_cohort_age_interaction * age_scaled * cohort_age_scaled,
50     dims="obs",
51 )
52
53 lam = pm.Deterministic(name="lam", var=pm.math.exp(lam_log), dims="obs")
54
55 # --- Likelihood ---
56 n_active_users_estimated = pm.Binomial(
57     name="n_active_users_estimated",
58     n=n_users,
59     p=p,
60     observed=n_active_users,
61     dims="obs",
62 )
63
64 x = pm.Gamma(
65     name="revenue_estimated",
66     alpha=n_active_users_estimated + eps,
67     beta=lam,
68     observed=revenue,
69     dims="obs",
70 )
71
72 # --- Derived Quantities ---
73 mean_revenue_per_user = pm.Deterministic(
74     name="mean_revenue_per_user", var=(1 / lam), dims="obs"
75 )
76 pm.Deterministic(
77     name="mean_revenue_per_active_user",
78     var=p * mean_revenue_per_user,
79     dims="obs"
80 )

```

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