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A physics-informed learner for decoding societal mobilization in epidemic transmission

Epidemic dynamics depend not only on contact-driven transmission but also on when individuals become mobilized into the effective susceptible pool. We formalize this process with the susceptibility mobilization function (SMF), a single time-resolved curve learned directly from case data. Using a physics-informed, covariate-free neural learner embedded in an extended SIR framework, we estimate SMFs for 210 COVID-19 waves across 30 Chinese provinces from 2020 to 2022. Despite substantial geographic and variant heterogeneity, SMFs exhibit consistent morphological structure that can be summarized using functional principal components. A hierarchical Bayesian alignment model links these morphological modes to societal-context domains such as mobility, population structure, urban form, and economic capacity, and reveals strong period sensitivity. During Delta waves, high-context settings displayed later and broader mobilization. Translating morphology into intervention guidance, we identify a robust principle: advancing actions slightly before the SMF peak reduces epidemic size more reliably than increasing intervention strength later. We also develop a two-axis provincial scorecard that separates current performance (SRS) from longitudinal progress (LPI), allowing fairer comparison across structurally diverse settings. By transforming diverse social determinants into an interpretable temporal function, the SMF provides a generalizable methodological tool for analyzing context-driven transmission and supporting adaptive epidemic response.