

A framework for assessing social- and location-based transmission risk as a heuristic for individual decision-making.

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Abstract

This paper provides a framework for the assessment of household-level risk, incorporating both a individual social risk perspective and a location-based perspective. We use this framework as a heuristic to explore the effect of social reintegration choices individuals face, which are not be addressed by current policies. For example, we explore how integrating extended family households during COVID-19 without social distancing may affect household and community risk. The goal is to aid individual decision makers, who are seeking to maintain quality-of-life while navigating local policy, with nuance relating to location-specific behavior and disease prevalence.

1 Introduction

The COVID-19 pandemic has put the brakes on the world, both lives and economies. Now that countries are seeing new cases decline, re-opening economies safely has been on the agenda. How do we make decisions of how to act/where to go as we re-open? What are the ways we can assess our risk to others, others' risk to us, and the public health risk of joining household units?

As we make re-opening decisions, some individuals are informed by state-level policies and politics [1]. But there is a large interpretation gap. In the wake of COVID-19, many papers analyzed individual risk of complications from COVID-19, *e.g.* [10]. They also analyzed risk for broader public policy *e.g.* [6,8]. So far, they have not directly addressed individual concerns as states begin relaxing stay at home orders. While some current news articles have tried to provide some general advice, *e.g.* [11,22], there is little in the way of assessing one's household-level risk of disease transmission when considering visits to friends and family.

The framework presented below is a simplified model which analyzes risk as a function of individual social behavior and location-based factors. This heuristic guide is not meant to override any policy level, and is limited by many simplifying assumptions used throughout. However, it may provide some intuition in how many levels of risk factors can behave together in an overall risk profile which can be used to compare risk across scenarios.

We use the assumption is that risk levels are multiplicative, *i.e* if risks are probabilities, these risks are independent. This assumption is used throughout the calculations below as we calculate a total risk, defined as the social risk * location-based risk.

A spreadsheet which helps organize this information for easy calculation can be found in the following link Risk Tool. To use this Google Spreadsheet and make edits, make a copy of the spreadsheet.

The following sections focus on how to assess calculate the social/behavioral risk and the location-based risk. We use these to calculate a total risk which can be compared across households. We then calculate the relative risk of breaking social distancing to pool or merge with another household as social distancing measures.

2 Individual Social Risk

How do you social distance? What are your working conditions? How does that confer risk? We might assume some general categories of individual risk due to social behavior and then approximate a level of transmission risk from that risk-level.

2.1 Individual social risk levels

We consider 5 risk scenarios. One might also consider defining a continuous function, but for the purpose of easy individual use, individuals may find it easier to pick risk category rather than indicate a value. In the categories below, I attempt to connect a social distancing category with contact rates and transmission probabilities.

- **Risk level 1:** Quarantine with no contact except within the household. (0%)
- **Risk level 2:** Stay-at-home with essential contact only, remote workplace. (low exposure, low risk - 98% safety on contact, one contact/day = 2%)
- **Risk level 3:** Essential worker in an environment practicing strict social distancing measures or in shared housing practicing social distancing measures (high/consistent exposure, but of low risk - 98% safety on contact, 20 contacts/day = 33%)
- **Risk level 4:** Practicing intermittent social distancing (low - medium exposure, but of high risk - 50% safety on contact, 2 contacts/day = 75%)
- **Risk level 5:** Essential worker in an environment practicing no social distancing measures or not practicing social distancing (consistent exposure, high risk - 50% safety on contact, 20 contacts/day = 100%)

Note that nothing is ever 0% risk, but we round for simplification. One could, if desired, assume a 0.1% risk instead.

We use the variable $C_{h,i}$ to define the Social Risk level for household h , individual i . A household is defined as a unit in which there is no social distancing between individuals. Most people may assume it is all people living in a single house, but there are exceptions. For example, if someone is a caretaker for a family member in another household without distancing, this would be considered part of a single household instead of two households. If divorced parents sharing care-taking responsibility of children, we would consider both houses as a single household.

2.2 Examples

Below we consider a few example households. These example households will be used throughout the remainder of the paper.

Household 1: One adult is working from home remotely. Two children are at home, but schools are closed. A second adult is an essential employee in a business

practicing social distancing and sanitation guidelines, and runs all essential errands. Household 1 members 1,2,3 have risk level 1, so $C_{1,1} = C_{1,2} = C_{1,3} = 0$. Household 1 member 4 has risk level 3: $C_{1,4} = 0.33$.

Household 2: Two family members in house A, who regularly care-take for child in house B. Because the care-taking is a regular interaction without social distancing, the members of house A and house B together comprise one household. As the child is not going out other than traveling between households, they are level 1. One adult in house A is level 1 and one is level 2 (leaves only for essential errands). The adult in house B is an essential worker at a an essential facility practicing social distancing, and so is level 3. Household members 1 and 2 have risk level 1, so $C_{2,1} = C_{2,2} = 0$. Household member 3 and 4 have risk levels $C_{2,3} = 0.02$ and $C_{2,4} = 0.33$, respectively.

Household 3: Two retired individuals, one of which assumes all essential errand risk. Household members, therefore, have social risk level 1 and 2, $C_{3,1} = 0$ and $C_{3,2} = 0.02$, respectively.

Household 4: Three household members, but all work. One adult works at home, but still runs essential errands ($C_{4,1} = 0.02$). One adult works in a construction workplace that is low-risk and practices social distancing guidelines ($C_{4,2} = 0.33$). The third adult is an essential medical caretaker, but uses all social distancing guidelines ($C_{4,3} = 0.75$).

2.3 Vaccination

On December 14, 2020, the first vaccination was given in the US after FDA approval to a nurse in New York [3]. While rollout is still underway, some frontline workers have already received their second dose, expecting a risk reduction of approximately 95% and 94% over two months of follow-up with the two shot Pfizer-BioNTech and Moderna vaccines, respectively [4, 5].

The effect, in January 2021, of these limited vaccinations on broad public health is too small at this point for herd immunity. However, the effect on individual risk is substantial. We propose a multiplicative correction factor for vaccine efficiency, v_i on C for any individual that has had the vaccine, so that the final individual risk probability is the risk level multiplied by v_i . If the individual has not been vaccinated, then v_i is 1 (no change to risk level).

In order to calculate v_i for vaccinated individuals, we begin with the 94 - 95% vaccinate efficacy rates, which are cumulative over approximately 60 days [4, 5]. Our risks are calculated on a daily estimate, so we solve the following equation:

$$1 - (1 - v_i)^{60} = 0.95$$

$$v_i = 0.0487$$

Repeating this with a 94% efficacy yields a daily risk of 0.0522. For simplification, we estimate $v_i = 0.05$.

In our example of Household 4, this would mean that if our essential medical caretaker is vaccinated, the risk level of that individual should instead be calculated as $C_{4,3} = 0.75 * 0.05 = 0.0375$. The effect of vaccination in that case brings the individual social-risk of a frontlines medical worker to nearly that of a low-risk stay at home individual.

The case of immunity is more nuanced than the vaccination binary assumption we make above. Vaccines will have varying efficacy rates, and the estimated relative risk reduction for the Moderna and Pfizer vaccines are only valid after both doses have been administered [4, 5]. If an individual has contracted the virus and is out of isolation and quarantine, this may also grant at least temporary immunity. However, there are

limited studies about how long this immunity lasts and indications that the immunity might differ based on case severity and other factors [7, 14].

3 Household-level Social Risk

The household-level social risk must amalgamate all of the above practices of individuals within a household. We assume that there is no quarantining going on within a house, but rather the household population is interacting consistently in ways conducive to transmitting any infection.

3.1 Maximum risk conferred

The simplest method is to assume that the risk level of a household is the maximum risk level across all individuals within the household.

$$C_h = \max(C_{h,i} | i \in \text{household } h) \quad (1)$$

Using Eq. 1 for our example households we get the following household-level social risk assessments:

$$\begin{aligned} C_1 &= \max(\{0, 0, 0, 0.33\}) = 0.33 \\ C_2 &= \max(\{0, 0, 0.02, 0.33\}) = 0.33 \\ C_3 &= \max(\{0, 0.02\}) = 0.02 \\ C_4 &= \max(\{0.02, 0.33, 0.75\}) = 0.75. \end{aligned}$$

The advantage to this method is that it is relatively quick to assess as long as you know the risk level of the household member with the highest social risk profile. The disadvantage is that it can underestimate risk in households with multiple members with high social risk levels.

3.2 Multiplicative risk

Another variation is calculate the risk as a probability of contamination given that risk is like a probability of having a disease. To calculate, one would assume that the probability each individual is not contagious is $1 - C_{h,i}$ and define risk as 1- the probability that no individuals within the household are infected.

$$C_h = 1 - \prod(1 - C_{h,i} | i \in \text{household } h) \quad (2)$$

Using Eq. 2 for our example households we get the following household-level social risk assessments:

$$\begin{aligned} C_1 &= 1 - (1 - 0)^3(1 - 0.33) = 0.33 \\ C_2 &= 1 - (1 - 0)^2(1 - 0.02)(1 - 0.33) = 0.3434 \\ C_3 &= 1 - (1 - 0)(1 - 0.02) = 0.02 \\ C_4 &= 1 - (1 - 0.02)(1 - 0.33)(1 - 0.75) = 0.84. \end{aligned}$$

Comparing two risk methods, there is little difference for households with most members at Level 1 or 2. Making the simplifying assumption about a maximum risk conferred has more effect on the risk of household with few at home members.

4 Location-based Risk

Two households such as Household 1 and Household 2, even with approximately the same social risk levels may be different in total risk due to a number of location-based factors. This includes disease prevalence as well as location-based social distancing behaviors, which could be a function of policy, but not necessarily. For example: About what percent of the population is using social distancing? What are the state or county guidelines for the level of openness? How well are the other residents in that county adhering to guidelines?

We define total location-based risk = Location-based risk level * Prevalence of disease at location. Below we introduce ascertainment rate as important in estimating both location based risk and prevalence. We also propose relative location-based risk levels and discuss how to consistently calculate location-based prevalence in a way that incorporates ascertainment certainty.

4.1 Ascertainment Rate

When assessing risk, we have to understand certain aspects of data certainty. For example, often we discuss prevalence and case rate by referring to the number of positive tests. However this is not necessarily the same as the number of infected individuals. A comprehensive Spanish serology study indicated that one out of every 10 individuals with COVID-19, was correctly identified through testing [13]. This result was replicated in France as well [19]. Therefore, we must correct our disease prevalence data with a parameter, $a \in (0, 1]$ which reflects the ascertainment rate, the ratio of recorded cases to actual cases.

More specifically, ascertainment rates are variable across space, time, and case severity. In the case of Spain, although the average ascertainment rate, a was 0.10, it varied across regional areas, with hard hit urban areas having both a higher incidence as well as a lower ascertainment. Another study in Japan [18], estimated their average ascertainment early in the pandemic at 0.44 for non-severe cases, as it is assumed that severe cases would be identified in the hospitalization. A comparison of October 2020 serology results with cumulative case estimates show a range of values of the ascertainment bias correction factor, $1/a_j$ of 1.0 in low prevalence states such as Vermont for states and 8.5 in states like New York with early uncontrolled cases [9, 12]. Therefore, it makes sense to allow for a more nuanced ascertainment rate at each location any location j , a_j .

We might assume that in ideal scenarios such as residential colleges which employed at least twice-weekly census testing to identify asymptomatic or pre-symptomatic cases, the ascertainment rate would be close to 1. In states with robust testing and contract tracing and low incidence rates, ascertainment might also be quite high. This would mitigate overall location-based risk levels, because if cases are promptly identified and quarantined, we can assume public workplaces and retail locations have lower rates than would be in the state overall. We assume as a starting default that ascertainment rates are 0.5, similar to that in the Japanese study in early 2020 which was a relatively well-controlled situation [18].

4.2 Location-based Risk Levels

A straightforward and user-friendly way to quantify location-based risk might be through some sort of risk level analogous to the social-risk levels. For simplification, we present risk levels the same as considered above, with the same way of conceptualizing the numerical risk score.

- **Risk level 1:** Strict stay at home, enough testing, contact tracing, quarantine of all contacts and suspected cases. (0%)
- **Risk level 2:** Stay-at-home with essential contact only, remote workplace, no schools in session, all essential businesses with strict social distancing and disinfecting measures. (low exposure, low risk - 98% safety on contact, one contact/day = 2%)
- **Risk level 3:** Business open but all practicing social distancing or predominately stay at home with a non-negligible percent of the population not social distancing (high/consistent exposure, but of low risk - 98% safety on contact, 20 contacts/day = 33%)
- **Risk level 4:** Only partial practicing of social distancing (low - medium exposure, but of high risk - 50% safety on contact, 2 contacts/day = 75%)
- **Risk level 5:** Business as usual - Not practicing social distancing and no testing/quarantining (consistent exposure, high risk - 50% safety on contact, 20 contacts/day = 100%)

Again, note that nothing is ever 0% risk, but we round for simplification. One could, if desired, assume a 0.1% risk instead.

We define the variable K_j as the location-based risk level in location j . A location could be a zip code, a city/town, a county, or a state. For all calculations that follow for a particular location, be sure to make scope of that location consistent.

4.3 Examples

Below we consider a few example locations. These example locations will be used throughout the remainder of the paper. The estimates of risk level and the conditions described throughout the paper were current as of May 15th, 2020.

Location 1: Cumberland County, Maine. Maine records disease data at the county level and makes policy both at the town, county, and state level. The state is on a stay-at-home order, with minimal exceptions for essential work at locations employing recommended social distancing and sanitation practices. Essential food shopping, health care, and limited outdoor quality-of-life activities are also permitted. Some rural counties were allowed to ease restrictions more significantly than some higher impacted counties. Cumberland County is considered a county with community transmission and as such, no major restrictions were lifted. Cumberland County might be considered a risk level of 2, $K_1 = 0.02$.

Location 2: Hancock County, Maine. Hancock County is one of the rural counties in Maine that has lifted additional restrictions due to low case prevalence. Socially-distant shopping and in-restaurant dining are now permitted. Due to the low case numbers and density, some residents are not employing measures such as mask-wearing and social distancing. We categorize this as a risk level 4, $K_1 = 0.75$.

Location 3: Warwick, Rhode Island, zip code 02889. Rhode Island data has been shared on their Health Department website at both the city/town and zip code levels. Rhode Island has had a higher case incidence overall than Maine, and many restrictions are in place, but not all residents in 02889 are following guidelines, sometimes congregating in groups without masks. We categorize this as a risk level 3, $K_1 = 0.33$.

4.4 Location-based Prevalence

Disease prevalence is the number of cases of infected individuals at a given time. In order to be able to compare prevalence across many locations, we will use the number of

active positive cases per capita, or I_j/N_j where I_j is the number of infecteds and N_j is the number of residents in location j .

We define disease prevalence, P in location j as the number of active cases reported per capita/ascertainment rate, or

$$P_j = (I_j/N_j) * (1/a_j). \quad (3)$$

Using Eq. 3, current active case data from the Maine website [15] and 2019 population data [16], and assuming $a_j = 0.5$ we get the following per capita prevalence estimates for location 1 and 2 in Maine:

$$P_1 = 823/295003 * (1/0.5) = 0.00558$$

$$P_2 = 10/54811 * (1/0.5) = 0.000365.$$

The Rhode Island data already provides per capita case estimates, in the form of the number of confirmed positive cases per 100,000 individuals [21]. The issue with this data for comparison with Maine is that we do not know how many cases are active versus recovered or deceased. While imperfect, we make the assumption that half the cases are active. Another possibility would be to new active cases over the last 14 dates, and while an automated tool might be able to do this, to make this as user friendly for the individual, we use the first technique. In this case, we get a per capita prevalence estimate for location 3:

$$P_3 = 607/100000 * 0.5 * (1/0.5) = 0.00607.$$

4.5 Total Location-Based Risk

The total location-based risk in location j , L_j , is a combination of both local social behaviors as well as disease prevalence. We do not treat this as a probability calculation as the location-based risk alone does not transmit the disease. You have to have both risk in the environment as well as a method to transmit that risk.

$$L_j = K_j * P_j. \quad (4)$$

Using Eq. 4 in our example locations, we get the following total location-based risk estimates:

$$L_1 = K_1 * P_1 = 0.0001116$$

$$L_2 = K_2 * P_2 = 0.0002737$$

$$L_3 = K_3 * P_3 = 0.0020031.$$

See the spreadsheet calculator in Supplementary information for all calculation detail.

5 Assessing Household Risk for Pooling

As we begin to relax our social behaviors, particularly where they relate to quality-of-life, we may be considering scenarios which merge households, either short-term or long-term. If these households are in the same location, we could compare just household-level risk. However, in cases where two households might span counties or even state-lines, such as traveling to see grandparents and give hugs, traveling to a new location brings local-level risk, mediated by their socially-distancing practices.

5.1 Total Location-based Household-level Risk

We now define the total location-based household-level risk as a layered combination of household-level social risk and total location-based risk. As in the above section, we do not treat this as a probability calculation as the total location-based risk alone does not transmit the disease. You have to have both risk in the environment as well as a method to transmit that risk.

$$T_{h,j} = C_h * L_j \quad (5)$$

Assume that Household 1 is in Location 1, Households 2 and 3 are in Location 2, and Household 4 is in Location 3. Using Eq. 5 for our example households we get the following household-level social risk assessments:

$$T_{1,1} = C_1 * L_1 = 0.0000368$$

$$T_{2,2} = C_2 * L_2 = 0.000940$$

$$T_{3,2} = C_3 * L_2 = 0.0000055$$

$$T_{4,3} = C_4 * L_3 = 0.0016743.$$

5.2 Pooled Risk

Now suppose you want to travel to visit extended family or want to invite people over for a birthday party, without social distancing. When you do this, you assume the risk of their household. We will call this pooling households. If you combine or pool households, even temporarily, what is the effect?

As in the above pooling of individuals into a household, likewise, we treat the households as individuals in a larger pool. This assumes that each household has some risk probability, and we are calculating the complement of the probability that none of them bring infection.

$$T_{pool} = 1 - \prod(1 - T_{h,j} | h \text{ households} \in \text{pool}) \quad (6)$$

In our example, if we pool Households 1, 2, 3, and 4, the pooled risk is $T_{pool} = 0.0018103$.

6 Risk Assessment for Individual Decision Making

The risk levels calculated in the prior section are approximately a probability of a household having an infected member each day. According to our calculations above, Household 1 has about a 1-2 % chance of being infected within a year, while Household 4 has a 46% chance. However, these probability calculations should not be too strictly interpreted. There are variations to work pattern, state mandates, and underlying disease prevalence, as well as the use of general risk categories which all make these calculations more of a heuristic than a prediction.

Despite the aforementioned shortcomings, the value of these calculations are in comparing relative risks across households and locations and/or across decision scenarios. In the latter case, comparing alternative scenarios for a single household helps us better assess the risk reduction or amplification based on changing behaviors. Below we consider a few such alternative scenarios and calculate relative risk, risk reduction, and risk amplification/multiplier as a result of modifying social risk. This heuristic for relative risk assessment could then be used to guide individual decision-making.

6.1 Relative Risk

In our examples, as expected, Household 3 has the lowest risk relative to all other households because of the low prevalence in in Location 2 and the lack of household exposure due to low household-level social risk. While Household 2 is in the same Location 2, its Household 1's risk is lower. The disease prevalence is higher in Location 1, but the social-risk, due to occupation, ability to socially distance and stay home, and the local mandates, all make this household relatively safer.

Household 2 and 4 have higher relative risks on the whole for different reasons. Where Household 2 benefits from low disease prevalence, local social and having frontline service workers in their household counterbalance the low disease prevalence. Household 4, has the highest risk, due to both occupation as well as location-based disease prevalence.

To assess the risk of having a slightly larger household with a frontline service workers, we calculate the *relative risk* of Household 2 in comparison to Household 3, both in Location 2 as the ratio of the total risks:

$$T_{3,2}/T_{2,2} = 0.0000055/0.0000940 = 0.06.$$

In other words, Household 3 has 6% of the risk of Household 2.

6.2 Risk Reduction and Risk Multiplier

If Household 1 was able to move its essential worker to working from home and only out for essential shopping, this would reduce the risk level by 94%. This would be called a *relative risk reduction*. However, this option is not possible for many service, laboratory or healthcare settings. As vaccines for healthcare workers become available in the first tier of vaccine distribution plans [3], one strategy would be to wait to gather until the frontline worker is vaccinated. For example, when the healthcare worker in Household 4 receives a full vaccination, reduces the total household risk 56%.

Another option is to reconfigure pods or household pools, even temporarily during spikes in disease activity. If Household 2 was able to shift all adults to working from home or sever the caregiving relationship which effectively pools two households until vaccination was possible, we would expect that would reduce the risk to the level of Household 2. This would dramatically lower risk to 5% of the current risk level, reducing the total risk by 95%. But relative risk reduction alone is not the only aspect critical to health and wellness - these caregiving relationships are also likely critically important to maintain in most cases.

The example of the caregiving relationship reminds us that sometimes, we voluntarily choose to increase our risk for other important reasons, such as physical and mental health. This might include, seeing doctor's appointments, getting groceries, and providing support for or spending time with extended family or friends.

While some of these activities can be done with social distancing, providing support or visiting family while unmasked, eating, and celebrating would require us to pool households. To assess how our risk changes based on an action scenario such as the pooling of households, we would calculate how many times your risk increases by engaging in that scenario. In the case of pooling households, the risk multiplier for a particular household would be the pooled risk/total location-based household risk, or

$$M_h = T_{pool}/T_{h,j}. \quad (7)$$

Using Eq. 7, the risk multiplier in our household models would be:

$$M_1 = 0.00186/0.000037 = 49.16 \text{ times}$$

$$M_2 = 0.00186/0.000125 = 19.26 \text{ times}$$

$$M_3 = 0.00186/0.0000073 = 330.75 \text{ times}$$

$$M_4 = 0.00186/0.00169 = 1.08 \text{ times.}$$

6.3 Strategies for Reducing Risk

Given the above scenario, Household 3 carries the greatest risk for household pooling, with Household 1 as the next most risky. If Household 3 contains individuals at risk for complications from COVID-19, this might be an untenable risk amplification. Until that individual can be vaccinated, we might consider other scenarios which mediate the effect of pooling households. For example gathering socially distanced socially distanced way, having smaller gatherings, or quarantining before gathering. All of these strategies are part of current (May 2020) State of Maine health department coronavirus guidelines [15].

One State of Maine recommendation during peak pandemic was that gatherings be limited to 10 or under. What if we reduce the number of households that congregate to like-risk households? If just the two lowest risk households gather, Households 1 and 3, the new pooled risk is $T_{pool} = 0.000044$, reducing the risk of gathering by nearly 98%. This solution would mean an overall smaller risk for all versus the full pooled risk and comply with current state-level policy.

Another option would be to have high risk individuals and/or households quarantine as much as possible before coming together. Under Maine policy in May 2020, out-of-staters must quarantine for 14 days, so this action would only be mandatory for Household 4 in Rhode Island and voluntary for the other households. A strict quarantine would significantly decrease risk, by bringing C_h , and therefore, $T_{h,j}$ down to 0. This means that pooling would have no added risk to the other household - as if this household had never joined, decreasing T_{pool} . If Household 2 and 4 could strictly quarantine before gathering with Household 1 and 3, that could mean the opportunity to gather in larger groups more safely.

7 Risk to Public Health

We assume that the risk to public health is that each household returns back to the original location with the increased transmission risk now assumed by any temporary pooling. This would increase your risk to the community, but could be mediated by the social risk level. For example, bringing back a higher chance of infection after pooling households may have little impact on overall public health if you observe a strict quarantine upon return or if you live in a location with strict location-based policies. However, bringing a higher chance of infection to a location into a community with relaxed location-based policies or by an households with high social risk may substantively impact community transmission levels [2]. These risks are not captured by the above calculations of risk to the individual household, but these are the risks to one's neighbors. Meeting in a location with lower location-based risk might seem optimal to reduce any increased risk that pooling households might bring. However, in both cases you are adding to the risk load of a community.

One must also consider the limited resources a community may have to deal with an outbreak. Bringing high-risk into a community that operates with low social distancing (due to lack of disease, cultural practices, or policy) that also has a low capacity for dealing with cases (for example as a result of structural racism and/or in rural

communities) could present a serious public health concern [17,20]. Ideally, households that make decisions to pool should consider absorbing the temporary higher risk by quarantining during and after such a gathering to prevent community transmission in high-risk locations.

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