Project Title: Establishment of Newer $PM_{2.5}$ Emission Factors with Various Almond Harvesting Machinery

Project No.: **17-AIR3-ESJVAD/Capareda**

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Objectives:

1. Determine any measurable differences in PM emissions between an old harvester and ~~a~~ new low dust emission harvesters
2. Quantity ~~the any~~ improvements (in terms of % reduction) in emissions upon using the new harvesting machinery~~.~~
3. Compare the collection efficiencies between the new and old machinery~~.~~
4. Determine the ratio of the FRM PM_{10} and FRM $PM_{2.5}$

Interpretive Summary:

This project updated the $PM_{2.5}$ emission factors from almond harvesting operators using low dust emissions machinery from major harvest machinery manufacturers in California.

The main goal is to compare the emission factors from older machinery (as control) and determine the percent reduction in dust emissions from the best harvest machinery available from all major manufacturers.

The project also updated the ratio between PM10 and PM2.5 emission factors based from Federal Reference Method (FRM) particulate matter samplers (PM Samplers). These emission factors and dust reduction percentages are necessary to support California's new PM2.5 State Implementation Plan (SIP).

Incentive programs will encourage almond farmers to switch to low emission harvester thereby, lowering the overall dust emission from almond harvesting operations.

Materials and Methods:

Site Selection: We used two orchards in Fresno County (**Figure 1**) to evaluate the emissions from new harvesting systems from all manufacturers in California and compare those from conventional harvester (Flory 480; Flory Industries; Salida, CA). A weeklong harvesting event happened during the month of October 2017. The soil texture was irrigated sandy loam, which were generally composed of sand (63%), silt (20%) and clay (17%), determined using a hydrometer (Soil, Water and Forage Testing Laboratory: Texas A&M Agrilife Extension, 2018). We estimate the trees to be about 15 years old with a spacing of 7.3m (24 ft) between rows and 6 m (20 ft) between trees in the same row. The approximated total area of the first site was 28 ha (70 ac). The second site has an approximate area of 15 ha (37 ac).

Typical varieties in the almond orchard harvested were Nonpareil cultivar together with other cultivars to achieve cross-pollination. In the experimental sites (**Figure 1**), the pollinator of the Nonpareil cultivars were Fritz and Monterey.

Figure 1a: Site 1 used for Replicates 1 and 2

Figure 1b: Site 2 used for Replicate 3
(Images generated using Google Earth, 2018).

Experimental Design: We tested four low dust-emission harvesting machines from four different manufacturers (Flory Industries, Exact, Weiss-McNair and Jack Rabbit). We utilize a control run using the Flory 480 conventional harvester. All manufacturers approved the control machinery. We used the control in between low dust machinery. We assigned a code for each low emission harvester and randomized the order of runs per replicate. There were three replicates for 21 total runs (**Figure 2**).

REP 1	REP 2	REP 3
cA	D	B
A	cD	cB
cC	A	C
C	cA	cA
B	C	A
cB/cD	cC/cB	cA/cD
D	B	D

Figure 2. Order of runs.

Each plot consisted of nine (9) tree rows; however, only the first, fourth and ninth tree rows were harvested which corresponds to the Nonpareil cultivars. We evaluated emissions during the windrow pickup from both sides of the corresponding tree rows.

Emissions Calculations: The data collection and analyses for this study followed a similar approach based on previous almond harvest emission studies (Faulkner et al. 2011; Faulkner and Capareda, 2012; Faulkner, 2013). In summary, there were three sets of samplers deployed on the downwind and one set of upwind samplers on the upwind (**Figure 3**). Each sampler set consist of collocated low-volume TSP and FRM reference method (FRM) PM10 and PM2.5 samplers. We used these samplers to measure the ambient PM concentrations during the nut pick up operations. We positioned each downwind sampler directly perpendicular to the tree rows used for pick-up, with a distance of approximately 8.5m (28 ft) from the edge of the plot.

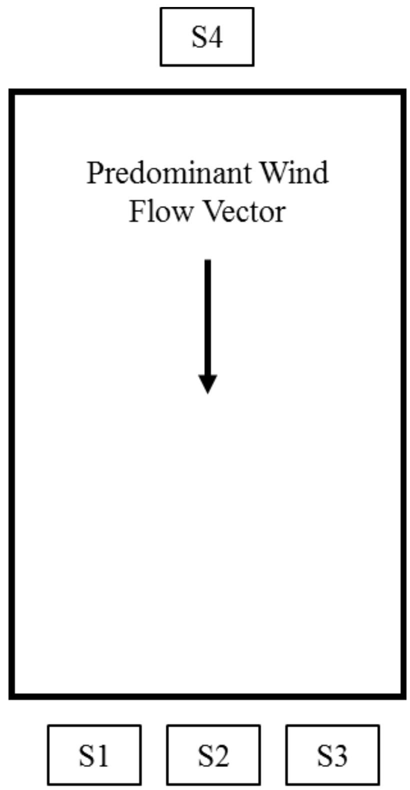


Figure 3. Sampler configuration (not to scale).

We conducted PM10 and PM2.5 concentration measurements using FRM samplers. Each set was equipped with a FRM PM10 sampling inlet (model PQ100 inlet; BGI Inc.; Waltham MA) and a Very Sharp Cut Cyclone (VSCCA, BGI, Inc; Waltham, MA) for PM2.5 collection. We measure TSP concentrations alongside the FRM samplers using a TAMU designed sampler by Wanjura et al. (2005).

We also used the dust collected on the TSP filter to determine the Particle Size distribution (PSD) using Beckman Multisizer 3 coulter counter. We generated the mass median diameter (MMD) and geometric standard deviations (GSD) of the particles from the PSD data. The particles collected were predominantly slightly aspherical in shape, determined by a Vega 3 TESCAN electron microscope (TAMU MIC: College Station, TX) (**Figure 4**) with a particle density of 2.3 g/cm^3 as determined by a pycnometer (AccuPyc 1330, Micrometrics, Norcross, GA).

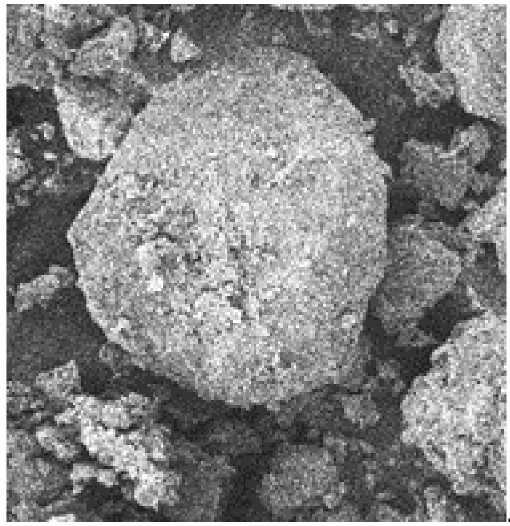


Figure 4. Scanning electron microscope image of collected particles.

To determine the harvester emissions, in terms of kg/km^2, a back-modelling approach (Faulkner and Capareda, 2012; Faulkner, 2013) was used using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) dispersion modelling software provided by Lakes Environmental; Ontario, Canada. We consider the measured downwind net PM concentrations as receptor concentrations. We then used the data to estimate the area emissions coming from each plot. The meteorological parameters used were a combination of on-site data and available meteorological data provided by the National Oceanic and Atmospheric Administration (NOAA) – National Climatic Data Center (NCDC) and Earth System Research Laboratory (ESRL). We estimated additional meteorological and surface parameters according to the U.S. EPA guidance for AERMOD (U.S. EPA, 2018).

We conducted analysis of variance (ANOVA) tests using the model test function in JMP (JMP v. 13; SAS Inc.; Cary, NC) to determine any variations from the emission reduction between harvesters. The null hypothesis tested was that the mean emission reductions were equal.

Size Fractionation: We used a 10-liter resealable plastic container to collect a sample of almonds and foreign material from each harvested windrow for each run. We collect sampled before and after picking of nuts. We used the sample of almonds and foreign materials collected from the load-out stream as it entered the hopper bottom trailer for size fractionation, in terms of mass percentage. Every sample was sealed and transported to the BETA laboratory, Texas A&M University for mechanical fractionation.

The samples were placed in a sieve series in accordance to the ASTM Standard C 136-06 (ASTM, 2006) after the nuts were manually separated. We collected and weighed the materials retained on each sieve series to establish the mass fraction. (**Table 1**) shows the size ranges used as fractionation categories.

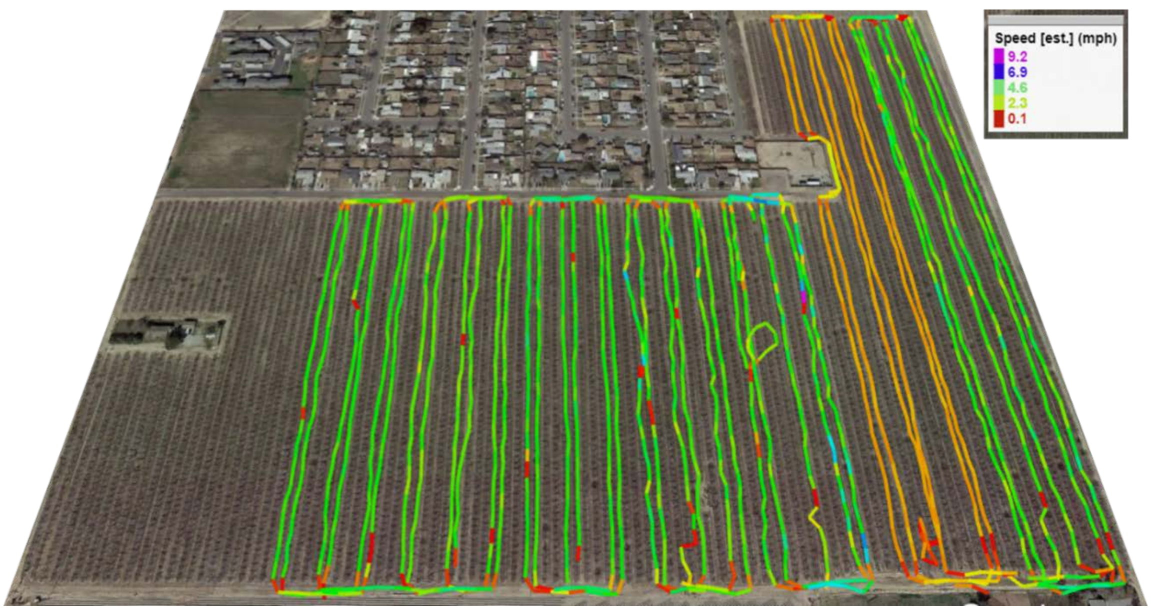
Table 1. Fractionation categories

Particle Size		Category
Minimum	Maximum	
18.5 mm	--	Nuts
10 mm	18.5 mm	Leaves, Small Twigs, Small Nuts
2 mm	10 mm	Leaves and Grasses
--	2 mm	Soil

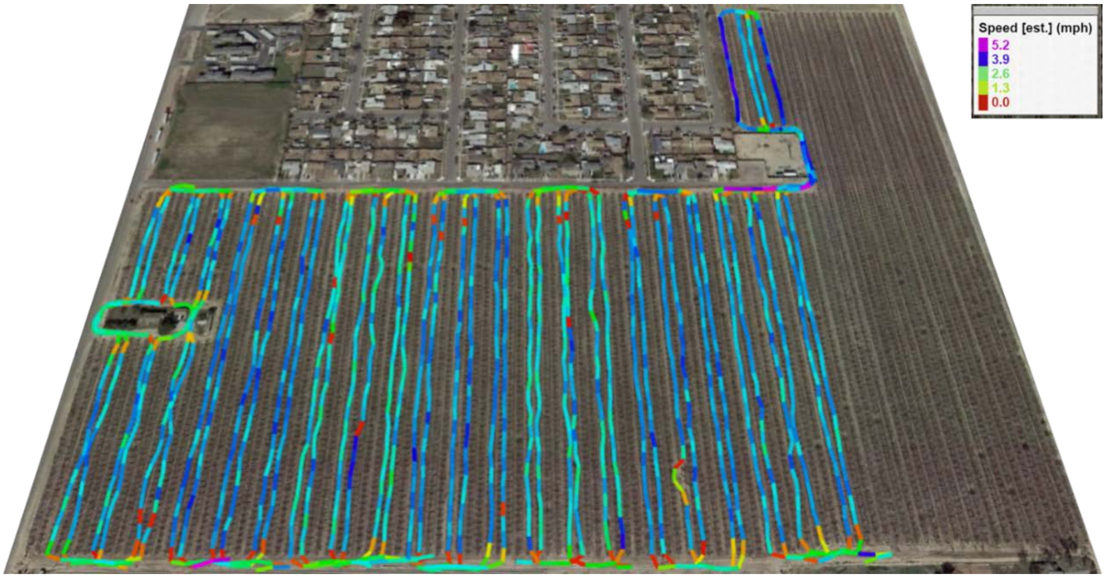
We conducted an analysis of variance (ANOVA) test using JMP Statistical Software (JMP v. 13; SAS Inc.; Cary, NC) to determine whether significant differences existed in the composition of products delivered to the huller between the new and conventional harvesters. The null hypothesis tested was that the mean of each mass percentage for every size range between the two harvesters were equal.

Results and Discussion:

Harvester Speed Profiles: (**Figure 5)** shows the consistency of the speed of harvesters during the entire runs (3 replicates). Almost 90% of the time, the harvester speeds were consistent around an average of 3 mph except during turn-arounds.



(a)



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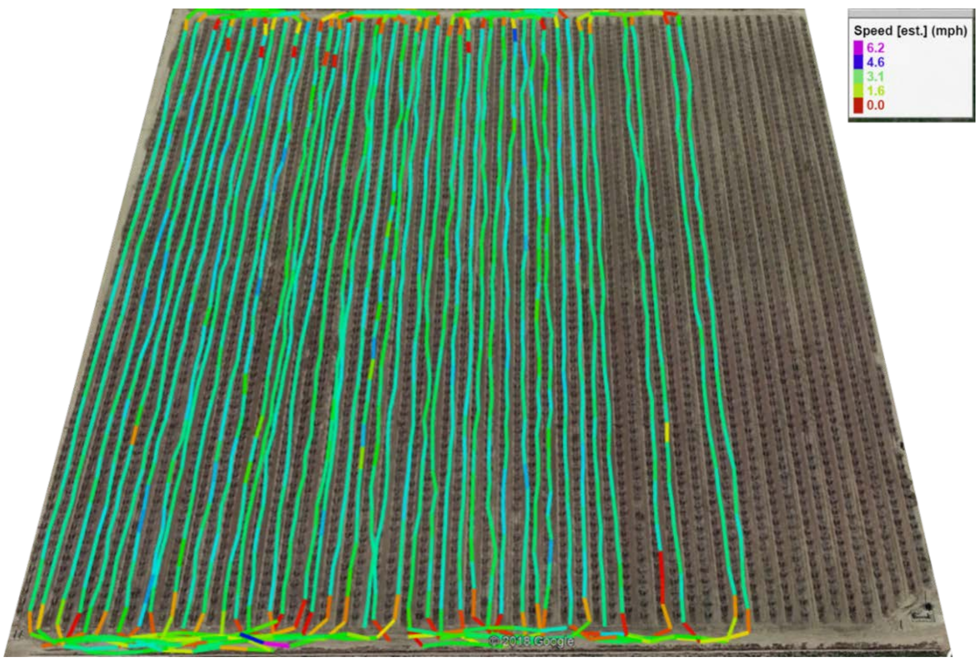

(c)

Figure 5. Harvester speed track profiles for (a) replicate I; (b) replicate II; (c) replicate III

<u>Collection Efficiency:</u> The t-test results showed no significant differences in foreign matter content between the new and the conventional machines. We recover relatively higher amount of soil during the fractionation since we used a maximum of 2 mm size category instead. This slightly differs from sampling method used in previous study (Faulkner, 2013). We have shown size separation results from all machines in (**Tables 2-5**).

Table 2. Size separation results (Machine A)

Size Separation Category	Mass fraction (%)	
	Machine A	Conventional
Nuts	63.2 (2.0) x	58.76(2.4) x
Leaves, Small Twigs, Small Nuts	32.1 (2.0) x	31.2 (0.7) x
Leaves and Grasses	0.4 (0.1) x	0.2 (0.1) x
Soil	4.3 (3.9) x	9.8 (1.9) x

Note: No significant differences were detected in means in the same row followed by the same letter (α = 0.05). We show standard deviations in parenthesis.

Table 3. Size separation results (Machine B)

Size Separation Category	Mass fraction (%)	
	Machine B	Conventional
Nuts	62.4 (3.1) x	62.6 (2.4) x
Leaves, Small Twigs, Small Nuts	29.9 (2.6) x	25.9 (5.5) x
Leaves and Grasses	1.4 (0.7) x	0.2 (0.1) x
Soil	6.3 (2.0) x	11.3 (7.3) x

Note: No significant differences were detected in means in the same row followed by the same letter (α = 0.05). We show standard deviations in parenthesis.

Table 4. Size separation results (Machine C)

Size Separation Category	Mass fraction (%)	
	Machine C	Conventional
Nuts	64.1 (6.6) x	62.0 (5.9) x
Leaves, Small Twigs, Small Nuts	25.5 (3.9) x	23.1 (3.9) x
Leaves and Grasses	1.2 (0.9) x	0.8 (0.7) x
Soil	9.2 (10.8) x	14.0 (9.2) x

Note: No significant differences were detected in means in the same row followed by the same letter (α = 0.05). We show standard deviations in parenthesis.

Table 5. Size separation results (Machine D)

Size Separation Category	Mass fraction (%)	
	Machine D	Conventional
Nuts	62.5 (2.0) x	58.56 (2.8) x
Leaves, Small Twigs, Small Nuts	31.6 (2.1) x	31.2 (0.7) x
Leaves and Grasses	0.6 (0.3) x	0.2 (0.1) x
Soil	5.3 (2.9) x	9.98 (2.3) x

Note: No significant differences were detected in means in the same row followed by the same letter (α = 0.05). We show standard deviations in parenthesis.

Emission Reductions: We calculate and derive the emission reductions from the ambient PM concentration measurements, inverse dispersion modelling, and benchmarked with previous results conducted by Faulkner (2013). We thoroughly analyzed the measured ambient PM concentrations for outliers and tested for normality prior to analysis of variance (ANOVA) tests.

We screened emissions calculated from inverse dispersion modelling based on prevailing wind direction and location of the plume relative to the downwind samplers. Extremely stable ambient conditions would typically result into an unusual estimate of emissions and samplers positioned at the edge of the plume might produce some uncertainties during back-calculation of emission rates (Faulkner, 2013). We further streamlined the emissions for this study by benchmarking the results of the previous low-emission harvester studies (Faulkner, 2013). We have shown the summary of the meteorological conditions considered on this study in (**Tables 6 - 9**). We derived the meteorological data from on-site measurements and U.S. weather agencies.

Table 6. Meteorological parameters considered for emissions calculation (Machine A)

	Machine A			Conventional Harvester		
	Min	Max	Ave	Min	Max	Ave
Sensible Heat Flux (W/m^2)	152.1	196.4	167.5	86.9	174.77	127.8
Albedo	0.19	0.19	0.2	0.19	0.22	0.2
Wind Speed (m/s)	0.50	5.09	2.8	0.68	6.11	2.9
Temperature, K	295.4	300.9	298.7	293.8	300.9	297.2
Relative Humidity, %	20	26	22.3	22	25	23.3

Table 7. Meteorological parameters considered for emissions calculation (Machine B)

	Machine B			Conventional Harvester		
	Min	Max	Ave	Min	Max	Ave
Sensible Heat Flux (W/m^2)	139.9	164	151.6	88.1	175.1	121.7
Albedo	0.19	0.2	0.2	0.19	0.24	0.2
Wind Speed (m/s)	0.50	2.1	2.0	1.77	2.33	2.1
Temperature, K	297	304.2	300.9	294.9	307.5	302.1
Relative Humidity, %	11	15	13.7	8	24	15.0

Table 8. Meteorological parameters considered for emissions calculation (Machine C)

	Machine C			Conventional Harvester		
	Min	Max	Ave	Min	Max	Ave
Sensible Heat Flux (W/m^2)	112.3	164	138.1	101.8	165.8	123.1
Albedo	0.19	0.2	0.2	0.18	0.22	0.2
Wind Speed (m/s)	1.35	5.8	2.9	0.50	2.11	1.9
Temperature, K	302.5	304.2	303.6	294.9	300.4	296.7
Relative Humidity, %	7	18	13.7	19	24	22.3

Table 9. Meteorological parameters considered for emissions calculation (Machine D)

	Machine D			Conventional Harvester		
	Min	Max	Ave	Min	Max	Ave
Sensible Heat Flux (W/m^2)	-22	151.7	83.3	88.1	198.9	159.4
Albedo	0.19	0.74	0.4	0.19	0.24	0.2
Wind Speed (m/s)	0.79	5.39	3.3	0.66	4.34	2.7
Temperature, K	295.9	304.2	300.0	298.8	307.5	303.1
Relative Humidity, %	8	36	23.0	11	32	18.7

Concentrations Reductions and Rations: (**Table 10**) shows the PM2.5 and PM10 concentrations reductions for all harvesting machineries. The $PM_{2.5}$ concentrations reductions ranges from low 40% to slightly above 60%. While for PM 10 concentrations, the range varies from low 30 to above 50%. The table shows no direct correlations between the (collocated) measured PM10 and PM2.5 concentration values. (**Table 11**) shows that ratios of PM2.5 to PM 10 for each machinery as well as for all machineries tested. On the average, the ratio between PM2.5 and PM10 is around 12.5%.

Table 10. $PM_{2.5}$ and PM 10 concentrations reductions for all harvesting machinery.

Machine	% Reduction in $PM_{2.5}$ Concentrations	% Reduction in PM_{10} Concentrations
A	43.5 + 11.9	53.5 + 9.6
B	61.5 + 14.0	37.3 + 18.4
C	57.7 + 13.8	43.6 + 12.1
D	42.1 + 32.5	33.0 + 31.1

Table 11. Ratios of PM2.5 to PM10 concentrations for each harvest machinery as well as average for all machineries.

Machine	Average from All Replicates (%)
Machine A	14.4%
Control for Machine A	15.7%
Machine B	17.9%
Control for Machine B	8.3%
Machine C	8.4%
Control for Machine C	10.7%
Machine A	15.9%
Control for Machine A	11.5%
Overall Average (%)	12.5%

Emission Reductions: (**Tables 1~~1~~2 and 1~~2~~3**) shows the comparison of emissions factors (kg/km^2) and the percentage reductions in emissions. The table also shows previous number from studies done in 2012 and published in 2013 (Faulkner, 2013).

Table 12~~1~~. Emission factors (kg/km^2) from nut-picking operations at two different periods (2010/2011 and 2017) using low-emission and conventional harvesters.

Machine	2017 Almond AQ Sampling			2010-2011 Results by Brock		
	TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
A	2,153	492	326	1,149	561	264
Control	9,360	864	551	4,835	1,981	401
% Reduction	77%	43%	41%	76%	72%	34%
B	1,590	747	225	2,281	1,034	359
Control	2,820	1,706	456	3,891	1,599	280
% Reduction	44%	56%	51%	41%	35%	-28%
C	2,911	1,360	108			
Control	12,800	5,200	281			
% Reduction	77%	74%	62%			
D	2,643	1,530	371	5,095	1,453	121
Control	5,748	4,100	855	6,865	2,628	313
% Reduction	54%	63%	57%	26%	45%	61%

Table 1~~2~~3. Comparative emission factor and percentage reductions.

Machine	Emission Factors (kg/km2)		% Reductions in $PM_{2.5}$ Emissions		
	This Study (2017)	Faulkner (2013)	Concentrations	2017 EF	2011 EF
A	326	264	43.5%	41.00%	34%
B	225	359	62.5%	51.00%	-28%
C	108	na	42.1%	62.00%	na
D	371	121	57.7%	57.00%	61.0%

<u>Summary and Conclusion:</u> Average reductions in PM2.5 emission ranges from around 40% to close to 65% from all low dust machineries. This is an improvement to previous year's results. The average reduction for all machines is around 52.5% or more than half of conventional machines. Hence, if we replace all old machines with newer versions, we will expect to reduce emission factor by half.

Proper machine adjustment is critical in all harvesting processes regardless of model. The yearly improvements may help reduce dust level but it will takes years to achieve the level compared to other agricultural operations. The valley should start phasing-out older machines deliberately while providing incentives to upgrade to newer machines.

Note that the current test episode is for late season harvests with low prevailing wind speed and hence we consider these values rather conservative. Newer harvest machines have the potential to reduce significantly the PM emissions without negatively affecting product quality. We now have the ability to detect differences in PM emissions to the lowest level.

Research Effort Recent Publications:

None.

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